# Algorithm-based design of line and timetable variants for long-distance trains in Switzerland

Joël Amstutz
Institute for Transport Planning and Systems
Swiss Federal Institute of Technology, ETH
Zurich, Switzerland
jamstutz@student.ethz.ch

*Abstract*—**For a long time, the planning of railway systems had to be done manually. Along with the rise of computers and the progress in the field of operation research, tools and algorithms capable of designing and optimizing the supply emerged. Still, the planning of the Swiss railway network until horizon 2035 was entirely done by hand. In this work, we aim to design valuable alternative line and timetable variants for long-distance trains and to compare them with the planned 2035 supply. To this extent, we build a model of the Swiss long-distance railway network and design various variants using OpenBus, an optimization toolbox, to tackle the tasks of line planning, vehicle scheduling and timetabling. We find that none of the designed variants clearly outperform the planned 2035 supply. Thus, its quality is confirmed. One of the variants using rather short lines seems to yield economic advantages and could be further investigated.**

***Keywords—Line planning, timetabling, mathematical optimization, Swiss long-distance railway network, Ausbauschritt 2035***

## I. Introduction

For a long time, the planning of railway systems had to be done by hand. The line design, timetabling, vehicle and crew scheduling were huge tasks that mobilized lots of people and took time. Along with the rise of computers, specific tools to assist the planer emerged, but the planning and the optimization were still done manually. The recent progress in the field of operation research open new possibilities. Today, timetables computed by mathematicians are already being operated in Berlin and in the Netherlands.

The first railway line of Switzerland started its operations in 1847 between Zürich and Baden [1] The rise of cars in the second half of the 20th century changed the transportation landscape as public transport lost its position as leading mobility provider [2]. Some railway companies went bankrupt, whereas other reacted by increasing their service attractiveness and their cost-efficiency. As part of this process, the fixed-interval timetable was firstly introduced in 1982. In 2004, in the course of the first step of the program Bahn 2000, the integrated fixed interval timetable (IFIT) was introduced. The combination of modern rolling stock and an expansion of the supply led to an increase in the amount of passengers and contributed to strengthen the railway system in Switzerland.

The future development and extension of the railway infrastructure in Switzerland is coordinated in development programs called "Ausbauschritte". The infrastructure measures contained in the Ausbauschritt 2035 (AS 2035) are derived from the target supply for horizon 2035, which is a precise timetable [3]. Although a lot of different variants and combinations were analyzed, the whole planning process was entirely done manually. As a result, the timetable structure of the AS 2035 supply remains similar to the current timetable.

In this context, the question arises whether valuable alternatives to the AS 2035 supply exist. Especially, could the use of modern optimization techniques facilitate the finding of such alternatives, as it was the case in the Netherlands? Thus, this thesis aims to look for alternative line and timetable variants for Switzerland and to compare them with the target supply of AS 2035. The variants shall be designed using algorithmic tools for line planning and timetabling. To this extent, a model of the Swiss railway long-distance network will be built based on the expected infrastructure state on horizon 2035.

In order to be feasible within the time available and to limit the complexity of the problems to be solved (from a computational point of view), the thesis is restricted to inland long-distance traffic. The analysis of the demand reaction to the modified supply is not part of the work. Only periodic timetables of an hour shall be investigated, considering the benefits for the passengers (noticeability and availability) and for the operator (regular processes) [4] as well as the planning practice in Switzerland.

We first present the theoretical background related to the research goal of this work. We then present the tools and methods used to build the model. Then, the generic design process of the variants is presented, followed by a description of the variant-specific principles guiding their design. We then present a comparison of aggregated key figures and summarize the comparison with AS 2035. The obtained results and used methodology are then discussed. Finally, a conclusion summarizes the findings and presents possible future research topics.

## II. Theoretical Background

### *A. Public transit network and supply design*

The main goal of a public transport system is to provide a mobility supply for the whole population. The supply should be affordable to ensure its broad accessibility across the population. This implies that the operational productivity must be maximized [2].

Supply planning shall maximize the attractiveness of public transport for the customer while keeping the production costs as low as possible. The attractiveness of the supply is influenced by many elements. The following belong to supply planning: accessibility, frequency, travel time and direct connections [2], whereas by travel time we denote the time elapsed between the start and the end of the trip, i.e. the sum of driving times and possible intermediate transfer and waiting times. The supply planning also influences the production costs : fleet and personal requirements as well as the productivity of vehicle and personal deployment [2].

Transport demand is induced by the wish of people to perform different activities that cannot be performed at the same point in space. Each time somebody travels, it has chosen one variant out of the available transport supply. This choice includes departure time, mode(s) and route. When it comes to model the choice process, random utility theory is the most often used theoretical framework. Among other elements, it postulates that people make rational decisions under perfect information in order to maximize their net personal utility. Also, the modeler doesn't know every aspect of every considered decision parameter, leading to the introduction of an error term in the utility function [5].

The net personal utility is made of benefits and costs of the chosen alternative. Hence, from a passenger's point of view, optimality is maximizing the net benefit. Thus, considering what can be influenced by the supply planning, goals regarding passenger optimality can be derived:

- Maximize the service frequency, i.e. the number of travel options per hour, the noticeability and regularity of the service intervals.
- Minimize the transport time, i.e. minimize the driving time and the waiting time at transfers.
- Minimize the number of transfers.

The operator generally has the goal to maximize its profitability. Quantifying it requires to distinguish between efficiency and effectiveness [6]:

- Efficiency is the ratio between the invested resources (costs) and the produced output. For example, the efficiency increases if we can produce the same service at lower costs. However, efficiency does not tell if we are producing the right service.
- Effectiveness is the evaluation of the degree of goal achievement. For example, the effectiveness increases (in case of public transportation) the closer the seats supply is to the effective demand. Effectiveness tells if we are producing the right service

Thus, we formulate the goals of the supply planning for the operator: Minimize the costs by maximizing the effectiveness, i.e. producing a supply that matches the demand, and minimizes the amount of needed vehicles and personal. The second goal is to maximize the service attractiveness to attract new customers.

### *B. Mathematical optimization in public transit planning*

Mathematicians often divide the planning process into the following subprocesses: The line planning problem (LPP), the timetabling, the scheduling of vehicles and the scheduling of the crew. These subproblems are traditionally solved sequentially. However, such a sequential approach leads to suboptimal solutions. For example, a timetable that produces short travel times might produce cost-intensive vehicle schedules. Hence, integrative approaches look very promising since they allow to optimize many stages together [7].

The line planning is the process of determining the lines to be operated and to choose their service frequency. The lines are chosen from a line pool which can be generated by hand or using algorithms. The generation of the line pool is an important step, as it influences the quality of the resulting line plan [8].

Timetabling is the process of fixing the time at which trains arrive and leave a specific operating point. The periodic event scheduling problem (PESP) introduced in [9] is the commonly used formulation of the problem of designing periodic timetables. The idea is to schedule a set of periodic events within a fixed period $T$ of specified duration.

Mathematically generated timetables are already operated in practice. The 2005 timetable of the Berlin Subway was the first optimized timetable to be operated in daily usage [10]. In the Netherlands, a complete redesign of the timetable was done in 2006 to improve the robustness and the punctuality of the timetable. The new timetable was a success: the train punctuality and the number of passengers increased while the number of train drivers per train-kilometer was reduced by approximately 15 percent. All these improvements illustrate the potential of benefits arousing from mathematically generated solutions with respect to classical approaches [11].

## III. METHODOLOGY AND MODEL

For this thesis, OpenBus [12] and LinTim [13] are taken under consideration. Due to a better implementation of infrastructure constraints (single-track sections), the possibility to consider different stopping patterns on the network and to define station- and train-specific values for driving times, minimal dwells and transfer times, OpenBus was chosen to tackle the challenge of this work.

### *A. OpenBus*

The following elaborations are base on [12] to which we generally refer to for more details. OpenBus is entirely written in MATLAB and uses the Gurobi solver [14]. OpenBus is relying on an Eigenmodel in order to solve the tasks of line planning, timetabling and vehicle scheduling in an integrated way.

The LPP is solved in two steps. Firstly, the total travel time of the passengers is minimized under a cost constraint $c_{max}$. Secondly, the operating costs are minimized under the constraint that the minimal total travel time achieved in the first step cannot be exceeded. After the LPP, the lines operated (inclusive frequency and vehicle type) and the passenger routes are fixed. The timetabling process begins with a feasibility check to verify if a feasible timetable exists for the computed LPP solution. If not, a new solution is computed and the previously found solution is forbidden. The timetabling is done in two steps: First, the vehicles are scheduled such that the amount of needed vehicles and thus the resulting operating costs are minimal. Then, the timetable is further optimized such that the total travel time of the passengers is minimal under the constraint that the minimal amount of vehicles achieved in the previous step cannot be exceeded.

It is important to mention that the travel times estimated during the line planning process are frequency-dependent, i.e. the waiting times are estimated with half the frequency of the next coming line. In the timetabling process, the number of trains that can simultaneously dwell at a station is not constrained. All junctions are assumed to be conflict-free, i.e. built as flyover.

## B. *Network and infrastructure*

Since this study is restricted to long-distance trains, the long-distance network must first be defined. To define the relevant network sections, we start from the proposed long-distance network and relevant centers in [15] and adapt it slightly. At first, every cross-border section between Switzerland and another country is removed. Sections going to Broc-Fabrique, Locarno, Le Locle and Konstanz are added. Also, the lines Vevey – Puidoux and Thalwill – Sihlbrugg – Litti are included. In total, 90 stops are considered for the study.

The infrastructure is basically a graph with nodes representing operating points and edges representing the lines (we distinguish single, double and quadruple tracks). The state considered in this study corresponds to today's state completed with the measures to be realized on horizon 2035 after completion of AS 2035. Only projects and measures playing a role regarding the level of modeling detail are considered. Today's infrastructure state is collected using available network data [16] as well as online-maps such as [17] and [18]. The modeled network can be seen in Fig.1.

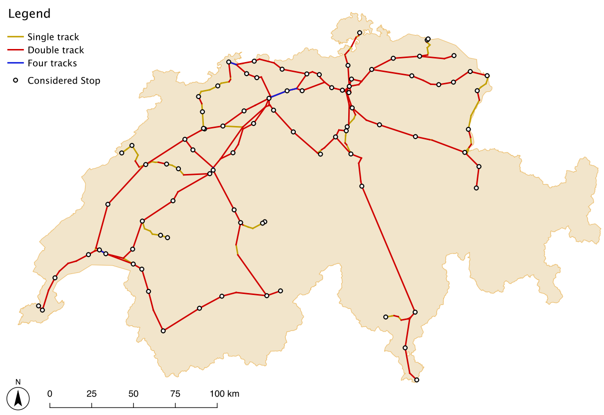


Fig. 1. Modell of the Swiss long-distance network. Boundaries: [19].

## C. *Timetabling*

To compute a timetable, various parameters must be estimated. The driving times are estimated using the netgraphs of the AS 2035 supply. When different values exist for the same route, the most frequent value is used. If the driving time is not equivalent in both directions, the mean is used. A difference is made between WAKO- and normal driving times between Lausanne and Bern.

A uniform value of 30 s is used for driving time supplements due to acceleration and braking processes. For long-distance trains (we an acceleration capability of 0.6 $m/s^2$ according to [20]), this means that the time supplement is underestimated for line speeds above 125 km/h, which is an acceptable compromise.

A uniform value of 2 minutes is assumed for headways between subsequent trains. For opposite trains on single-track sections, a value of 1 minute is used. The minimum dwell and transfer times are extracted from the netgraphs of the AS 2035 supply. We discretize the dwell times in 30 s steps, from 30 to 120 s depending on the importance and size of the station. Finally, a turn-around time of 5 minutes is assumed.

The travel times are calibrated by computing a timetable for the variant SAME (see below) and comparing the resulting travel times with the AS 2030 supply.

## D. *Rolling Stock and Operating costs*

Since the exact future state of the long-distance fleet is unknown, a set of four different train types is considered. The fleet is segmented in two double- and single-deck trains and in premium and standard vehicles. Considered types are a FV Dosto, a Giruno, an IR Dosto and a Flirt. All vehicle types can be operated in single and in double heading.

In order to optimize the line plan the timetable, the operating costs have to be quantified. Only the operating costs on side of the railway undertaking (RU) are considered. Furthermore, only the costs directly related to the moving of a train are considered. To estimate the costs, the findings of [21] where a universal train model was built to compute the different cost parts depending on the characteristics of the train, are used. Following [21] we consider the path price, the energy price, the capital costs, the maintenance costs as kilometer-dependent costs and the personal costs as time-dependent costs.

The estimated operating costs should not be taken as absolute since they lie below literature values. They are nevertheless useful as relative value to compare the variants.

## E. *Demand*

In order to optimize the network during the automated timetabling process, an OD-matrix is needed. The demand is extracted from the *Prognosezustand 2040* of the Swiss National Model of Passenger Transport (NMPT) [22]. The NMPT is a classical aggregated transport model. The space and thereby the demand is divided into zones that are punctually linked with the transport network. To compute a demand between the considered stops, the passenger trip-chains are investigated.

The long-distance demand is divided into two categories: the direct demand and the supply-induced demand. The first is the direct demand between zones directly linked to a considered stop. The latter corresponds to passengers which start or end their trip at a non-considered stop, but will travel via at least two considered stops. Both categories are extracted from the NMPT.

Given the aim to design a periodic timetable of an hour, the maximum of the morning and evening peak-hour demand is considered. Furthermore, the demand is made symmetric by taking the maximum of both directions with the aim to improve the symmetry of the resulting timetable.

The resulting demand is concentrated on short-distance connections. 72.6 % of the demand is on connections with less than 30 minutes of gross travel time (i.e. considering only the driving times along the network). The demand for longer connections is in general clearly lower.

# IV. GENERATION OF THE VARIANTS

## A. *General approach*

Ideally, a large line pool is given as an input to OpenBus, which computes a solution. However, the first experiences using a line pool with reduced vehicle choice shows that the sole computation of an optimal line plan for which a feasible timetable can be found can take more than 14 hours. Since we aim to benefit from flexibility regarding the vehicle choice and have a limited time budget, another approach is developed. The two-phase approach combines the optimization in OpenBus with heuristics.

The first phase aims at finding which lines shall be operated and which not. At first, a line pool is generated according to the guiding principle of the variant. At this point, only one vehicle type is allowed per line, and the size of the line pool is kept around 50 – 60 lines to keep the computation time in an acceptable range. The resulting set of chosen lines is analyzed under consideration of the initial line pool to understand which line was preferred over others. Also the loads of the lines can be observed to detect potential inadequate configurations of lines. The line pool is then adapted to test other aspects of the line design. To effectively learn from previous results, the adaptations must be done stepwise such that the line pools remain relatively similar to each other. This iterative process shall improve the quality of the line pool by keeping lines that are often chosen and removing lines that are not.

The second phase is the final computation of the solution. After learning from 10 to 15 different line pools, the final line pool is assembled by including the lines that were found most useful in phase 1. Lines that must be chosen are signaled to OpenBus. Still, not all lines are mandatory such that some flexibility remains in the LPP. All possible vehicles types given the infrastructure (clearance profile and length of crossing-points) and variant-specific constraints are allowed to choose from. Vehicle sharing is enabled for every line to give space for cost improvements. As a consequence, the value of the cost constraint is lowered to its target value, i.e. the estimated operating costs of the variant SAME.

### *B. Variants*

The variant SAME replicates the AS 2035 supply by including the same lines and frequencies. Thus, its costs can be seen as an approximation of the costs of the AS 2035 supply. However, the stop set defined in Section 3.2.1 does not contain all long-distance stops of the AS 2035 supply. This leads to shorter travel times compared the AS 2035 supply.

The variant METRO follows the guiding principle to reduce the number of lines and to uniform the stopping pattern together with a higher service frequency: at least two trains per hour shall be operated per line. Thus the time period of the timetable is reduced to 30 min instead of 60 min. All lines stop everywhere, are as long and straight as possible with a minimum amount of turn-arounds. Also, tangential connections (e.g. Vevey – Palézieux) are included.

The variant LEVEL introduces a separation of the long-distance system in two distinct levels: Express (E) and Local (L). The E-level is advertised as a fast, premium service. It is characterized by a sparse stopping policy and almost double track sections. Thus, the set of E-level stops is limited to a few larger cities and some network relevant stops selected under consideration of [15]. The lines of the L-level stop at each station.

## V. RESULTS

Passenger-oriented key-figures do consider only attractive connections, i.e. connections that are at most 10% or 3 minutes slower than the fastest available connection. Furthermore, the number of connections is computed under the consideration of the time distribution of the connections at the start and end point of the trip. Thus, for each interval (between any attractive connection) smaller than 3.5 times the longest interval, the number of connections is reduced by 1.

### *A. Comparison of key figures*

Table 1 shows the key figures of the three developed variants. The travel times refer to the actual travel time given the timetable. Regarding passenger-oriented figures, the variant SAME dominates the other variants with the exception of the mean number of connections per hour. Beside the percentage of direct travelers and the mean number of transfers, the variant LEVEL dominates the variant METRO.

As all variants were generated with the same cost constraint of 245'000 CHF. As a result, the costs do not significantly differ. The variant LEVEL achieved more savings during the optimization and is thus the cheapest. The variant SAME has the highest global load factor (0.68), followed by the variant LEVEL.

TABLE I. KEY FIGURES OF THE VARIANTS

| **Key figure** | **Variant** | | |
|---|---|---|---|
| | ***SAME*** | ***METRO*** | ***LEVEL*** |
| Mean Travel Time [min] | 27.9 | 29.2 | 28.9 |
| Mean Number of Transfers | 0.12 | 0.15 | 0.17 |
| Direct Travelers [%] | 89.9 | 86.6 | 84.7 |
| Mean Number of Connections / h | 2.44 | 2.90 | 3.93 |
| Total Operating Costs [kCHF] / h | 240 | 239 | 232 |
| Global Load Factor | 0.68 | 0.60 | 0.63 |
| Mean Cost per Seat-km [ct. CHF] | 2.95 | 2.58 | 2.64 |
| Total Fleet Length [km] | 33.6 | 34.2 | 23.0 |
| Mean Vehicle Capacity [seats] | 449 | 523 | 438 |

The variant LEVEL has the shortest fleet and generally smaller vehicles. The Variant METRO has the longest fleet and more double-deck trains than the variant SAME and LEVEL.

### *B. Comparison of OD-pairs.*

Two different sets of OD-pairs are compared to the AS 2035 supply regarding travel times, number of transfers required and number of connections available. Considered are 20 highly demanded OD-pairs and 20 long-distance OD-pairs. For the first set, travel times and number of transfers do not significantly differ from the AS 2035 supply. However, the variant SAME and METRO provide fewer connections per hour and the variant LEVEL provides more connections per hour.

The evaluation of long-distance OD-pairs shows that the variants METRO and LEVEL induce generally higher travel times and more transfers. Again, the variant LEVEL provides more connections, whereas the variant SAME provides less, a consequence of the irregular intervals between the single travel options.

## VI. Discussion

### A. Two-phase approach and optimality

By combining the optimization in OpenBus with the heuristic two-phase approach, optimality is sacrificed compared to a single optimization round starting from a larger line pool. A possible approach to quantitatively estimate the losses in optimality would be to compute a solution with a line pool combining all tested lines during phase one of the generic generation process and to compare it with the final solution of the two-phase approach. In any case, it would be preferable to generate the solution in one step, starting from a larger line pool

It should not be forgotten that the optimality of a solution is limited by the set of possible solutions, i.e. at first by the size and quality of the line pool. Thus, it is inappropriate to speak of optimality in a global sense, as the optimality of a solution would imply that the line pool contains *all* possible lines of the considered network.

A few days before the submission of the thesis, we found an error in the timetabling process of the OpenBus version used for the thesis: The preparation of the *E AN* for the optimization of passenger travel times after the optimization of the vehicle schedules overwrites some vehicle transfer edges at terminus stations. As a result, there is more freedom during the optimization of the passenger travel time.

This can lead to an increase of the operating costs of the final solutions presented in this work. Given the short time remaining, only little investigation was done. To assess the impact, the vehicle schedules were recomputed for the variant LEVEL only, while keeping the event times fixed. As a result, one additional vehicle is needed. Thus, the impact on the costs is relatively small in this case, but further verifications are necessary. The computed number of vehicles and costs presented in this thesis are thus probably slightly underestimated.

### B. Improvements of OpenBus

In manual planning, it is usual practice to overlap different lines with a similar stopping pattern along a shared corridor such that the course interval is regular. Currently, OpenBus does not identify lines with similar stopping pattern on a particular corridor and thus does not try to optimize their overlapping, which especially impacts the variant SAME. In contrast, the headway between different realizations of a line is fixed such that these are evenly distributed along the period.

### C. Feasibility of the variants

The feasibility of the computed variants is not comparable to that of the AS 2035 supply, which has been verified along the lines and in the nodes [3] including track occupancy. Overall, there is no guarantee that the variants are feasible across all junctions and stations of the network. To assess it, more precise driving times and the verification of critical spots is necessary.

### D. Recommandation for the long-distance supply

The definition of a good supply differs whether one adopts the point of view of passengers or of the operator. Thus, the determination of the best alternative implies the combination of rational evaluation criterions and political preferences. We do not intend to select a best variant, but rather to provide decision-support for the future evolution of the long-distance train supply in Switzerland.

In their current state, none of the developed variants can be recommended for use and must be further developped. Nevertheless, it can be said that the variants SAME and LEVEL both have their advantages. The first maximizes the quality of the connections, while the second maximizes the quantity. As SAME is already well developed (it is the AS 2035 supply), it could be interesting to develop it further since it yields potential economic advantages

## VII. Conclusion

In this work, line and timetable variants for the long-distance supply on the Swiss railway network are designed using mathematical optimization techniques. The goals for passenger and operator are first defined. An appropriate tool, OpenBus, is then chosen under consideration of the thesis objective and the required level of detail. After that, the relevant long-distance network is defined and modeled in OpenBus. Thereby, only publicly available information is used. Several variants are generated, each of them following a leading idea. Variant SAME replicates the line design of AS 2035, variant METRO uniforms the stopping pattern and variant LEVEL explores a two-level system. The variants are evaluated and compared to each other as well as to the planned stated of AS 2035. Finally, strengths and weaknesses of the variants and of the chosen approach are highlighted.

None of the generated variants dominates the others. The line design of the variant SAME is the best in terms of travel quality, i.e. travel time and required number of transfers. However, the timetable computed from it could be improved, as the spacing between similar overlapped lines lacks regularity. The variant LEVEL hints that it is possible to offer more connections per hour on several relations with operating costs similar to those of the variant SAME. Thus, it might be interesting to develop it further. Although only a small part of the solution space was explored, the fact that in general none of the generated variant outperforms the AS 2035 supply across all the considered criterions strengthens its pertinence.

Although still in development, OpenBus proved to be a capable tool to solve the tasks of line planning and timetabling. However, improvements are recommendable. Among them, the consideration of overlapping similar lines both in the LPP and in timetabling is crucial. Due to the assumptions and simplifications made, the timetables generated in this work must be further developed and verified to assess their technical feasibility. Thereby, the inclusion of constraints at junctions and in stations (number of tracks) is recommendable.

The methods used are useful to enlarge the solutions space and to test new designs. Once the model is built, testing different line designs can be done in much less time than manual planning would require. Thus, we expect optimization methods to gain further significance in the timetabling process in the future.

## ACKNOWLEDGMENT

This work would not have been possible without the involvment of several persons to whom I would like to express our gratefulness. I would like to thank Prof. Dr. Francesco Corman, Dr. Valerio De Martinis and Florin Leutwiler for the valuable feedbacks and supervision of the thesis. Also, a huge thank goes to Florian Fuchs who provided me OpenBus and supported me during its utilization. Thanks also to Peter Lorch, the leader of the IVT computer environment for the support regarding computer facilities and to Andreas Justen (ARE) who provided the national passenger transport model. Thanks also to Lukas Ballo for the helpful insights regarding operating costs and Lukas Regli (SMA und Partner AG) for the feedback from the industry.

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