UNIVERSITY OF TWENTE.

MASTER'S THESIS

Designing a Short Term Line Planning Model

Public Report

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Management Summary

This research is conducted at NS (the main railway operator in the Netherlands) in the field of line planning. In line planning, strategic decisions are made concerning which set of line routes to use together with their frequency (called a line plan) for rolling stock equipment. A line route indicates where rolling stocks starts, on which track sections rolling stock drives, which stations the rolling stock visits, and where rolling stock eventually stops. NS tries to fit their line plan as efficient as possible to travel patterns of travelers. Since travel patterns of travelers change over time, NS has to adapt their line plan on these changes.

NS has developed a Line Planning Model to support the line planning process. This model is developed to generate an ideal line plan for over 20-30 years. Using the railway infrastructure and the traveler demands, the Line Planning Model creates this ideal line plan. This research is performed to make the Line Planning Model capable of generating line plans for 0-5 years in ahead. Since the current practice of NS is quite dependent on the line plan, NS is not able to make a lot of changes in 0-5 years in their current line plan. Therefore, the short term Line Planning Model, developed in the research, must be able to suggest small changes in the current line plan of NS. The focus of this research is to define small line plan changes, construct restrictions for a short term line plan, and implement an Algorithmic Search Procedure (ASP) that is able to perform these small changes to create a short term line plan.

For the short term Line Planning Model, four different small changes of a line plan are defined: route changes, head-tail changes, merging or splitting, and changes of connections. In route changes, a small part of the route of a line route is changed in which the start and end station stays the same. Head-tail changes consist of enlarging or shortening the ends of a line route. Merging merges two line routes into one line route and splitting splits a line route into two separate line routes. Finally, changes of connections consist of changing connections of two line routes at a certain station where both line routes pass by.

The second objective of this research is to develop restrictions for short term line plans. The first restriction is a rolling stock restriction, in which the short term line plan may not use more rolling stock than the current line plan of NS. A serving restriction is set to ensure that every station on the Dutch railway network is served. Further, a turbulence restriction is developed to ensure that for most travelers the travel time does not increase. Finally, most line routes of the short term line plan must be exactly the same according to the current line plan of NS and on most track sections the short term line plan may not drive less frequently.

The last element of the short term line planning model is the development of an Algorithmic Search Procedure that is able to suggest the small changes in the current line plan of NS and is able to handle the restrictions. During an experimental and a practical evaluation, we concluded that Steepest Descent is most suitable to implement in the short term Line Planning Model. Steepest Descent evaluates all possible small changes of a line plan and selects the change with the highest improvement. The search procedure continues until no improvements are found in the line plan of NS within the restrictions for short term line plans.

In this research, the short term Line Planning Model is executed on a real life example. The real life example consists of finding improvements in the off-peak line plan of 2019. The short term Line Planning Model is capable of finding a revenue increase of 18,268. In 9 changes these improvements are realized.

Preface

This master thesis in the result of my graduation project at the Netherlands Railways (NS) to finish the master Industrial Engineering and Management at the University of Twente. Although there are always some ups and downs during a graduation project, the overall feeling of the last eight months is certainly good. Working at a complex, real world problem was very challenging and I am very pleased with the result. We reached some interesting insight during this project and we believe this thesis would help the line planning process of NS in the future.

This project would not be so successful without the help of some key persons. First, I thank Pieter-Jan Fioole and Joel van 't Wout of NS. They were always willing to answer my questions. The appointments on Monday morning were always inspiring to get me in the right direction. Besides that, they helped me a lot in some programming problems and in writing my report. Also, I appreciate the time and space they gave me during some hard times. Then, I thank my supervisors at the university: Martijn Mes and Marco Schutten. During the appointments they always gave valuable input for the research. They were able to approach the research from a different perspective, in which new ideas arise.

Last, but not least, I thank my family and friends. They always believed in me to finish this master study. Especially the support of my close family gave me strength to fulfill this mission. Without them, this success would have never been reached.

Martijn Kamphorst

Abbreviations

ASP	Algorithmic Search Procedure
GRT	Generalized Travel Time
LPP	Line Planning Problem
NAP	Network Analysis Procedure
NS	Netherlands Railways
OD pair	Origin Destination pair
OD matrix	Origin Destination matrix
PI department	Process-quality and Innovation department
SCU	Standard Capacity Unit
TRNDP	Transit Route Network Design Problem

Contents

Chapter 1

Introduction

Ever since there is public transport, public transport organizations try to transport travelers to their destination as good as possible. Line planning, the creation of routes that bring passengers systematically to their destination, is an important element in this process. This research supports the Netherlands Railways to optimize the line planning process. In this chapter, we introduce the Netherlands Railways and describe the design of this research. Section 1.1 provides a brief description of the Netherlands Railways. Section 1.2 discusses the research topic. Further, Section 1.3 describes the problem identification and Section 1.4 outlines the scope of this research. Section 1.5 elaborates on the main research goal. Finally, Section 1.6 provides the research questions and the research methodology.

1.1 Netherlands Railways

Since 1917, Netherlands Railways, in Dutch 'Nederlandse Spoorwegen (NS)', is the main passenger railway operator in the Netherlands. Netherlands Railways is a result of a merge between the 'Hollandsche IJzeren Spoorweg-Maatschappij' and the 'Maatschappij tot Exploitatie van Staatsspoorwegen.' Until March 1993, NS was a state enterprise, but in that year the government decided to privatize the enterprise. From that time, managing the Dutch railway infrastructure is the responsibility of ProRail; NS focuses on passenger transport on the Dutch railway network.

NS has a large impact on the Dutch society. Every year, on average 1 million passengers travel on a daily basis by NS (NS website, 2014). Most of the customers travel by NS trains but also by, for example, OV-bicycles and Qbusses. If we take a closer look to important facts of NS in the year 2013, they had a punctuality of 93.6%, 75% of the customers gave NS at least a 7, and the revenue amounted 4606 million euro (NS Annual Report, 2013). In 2013, NS had 32,000 employees, organized according to the organogram in Figure 1.1. This research study takes place in the department 'Proceskwaliteit & Innovatie' (Process-quality and Innovation, in this report called PI department), which we introduce in the next paragraph.

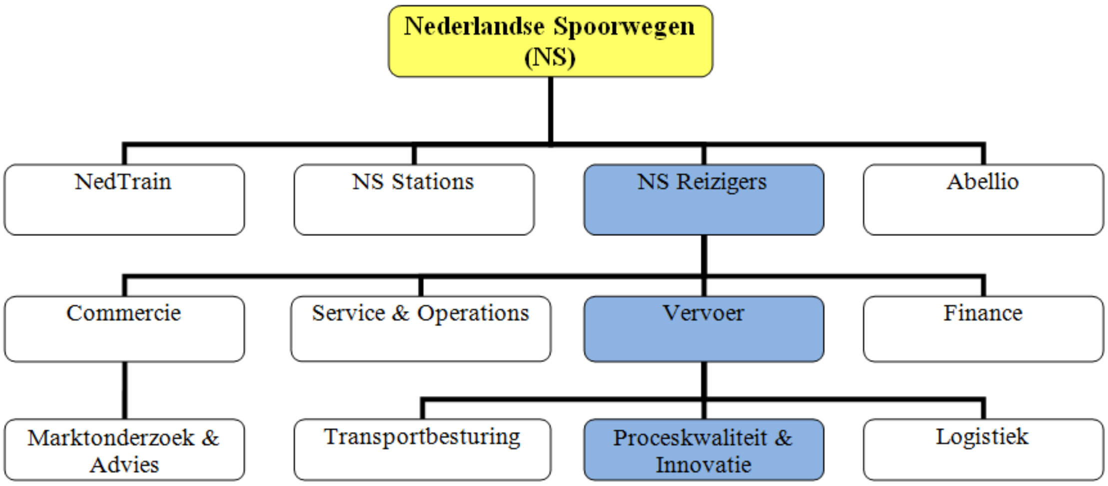

FIGURE 1.1: Dutch Organogram of the Netherlands Railways

The PI department

This research takes place in the PI department of NS. This department is a research department for operational, tactical, and strategic planning models. The PI department creates business decision supporting systems for the creation of train schedules, rolling stock planning, and train crew schedules. One of the supporting models they created (together with the department 'Marktonderzoek en Advies') is the *Line Planning Model*. This Line Planning Model supports the process of line planning for NS. The improvement of the Line Planning Model is the focus of this research study.

1.2 Research Topic

The research topic is the process of line planning at NS. Line planning is a strategical planning method used by public transportation organizations. Section 1.2.1 consists of the introduction of the activity line planning in public transportation organizations. In Section 1.2.2, we explain specific characteristics of line planning at NS.

1.2.1 Line Planning in Public Transportation

In public transportation, line planning is the first activity in creating time schedules for rolling stock and train crews. Figure 1.2 depicts the steps of producing these time schedules. Inputs for the line planning process are the travel demand and the public transport network. Line planning is thereafter used as input for capacity decisions, the creation of timetables, and rolling stock and crew decisions. In this section, we explain the input, the process, and the output of line planning.

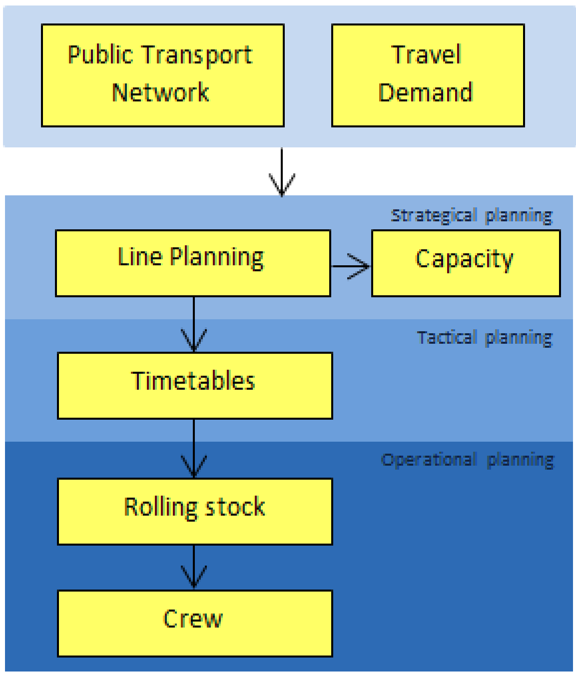

FIGURE 1.2: Position of Line Planning in the Planning Process

Input for Line Planning

The input for line planning is the public transport network and the travel demand. This section outlines both inputs.

Figure 1.3 shows an example of a public transport network. A public transport network consists of lines and stations that could be used by public transport organizations. In train, tram, and metro transportation networks, lines are the tracks located in the region that are used by the public transport organization. In bus transport, lines consist of the roads where the buses could travel. Stations in public transportation networks are the locations where the organizations can pick up and drop off travelers. Besides that, at some stations multiple lines merge or disperse, and some stations are starting/ending locations for rolling stock and train crew.

FIGURE 1.3: Public Transportation Network

Travel demand is the amount of travelers that want to travel from one station to another. In public transportation, the station where a traveler begins is called the origin station and the station where a traveler ends is called the destination station. The amount of travelers between every station pair is displayed in an origin-destination matrix (OD matrix).

Line Planning

Line planning is the process in which public transport organizations create line plans. Figure 1.4 provides an example of a line plan. A line plan consists of several line routes and their frequency. In Figure 1.4, the line routes are the colored lines. These line routes indicate where rolling stock starts, on which tracks rolling stock drives, which stations the rolling stock visits, and where rolling stock eventually ends. The frequency of a line route indicates the number of times in which rolling stock drives back and forth on the line route. Line planning consists of determining the set of line routes and their frequencies used by the public transport organization.

FIGURE 1.4: Line Plan

Output of Line Planning

The output of line planning is a line plan that consists of line routes and their frequencies. The line plan, created during the line planning process, is used as input for capacity decisions and timetable decisions. Using travel demand and the line routes and their frequencies, public transport organizations determine how much capacity they need for executing the line plan. Examples of capacity decisions are the amount of rolling stock and train crews needed.

Creating a timetable is the process of linking time intervals to the line plan. A line plan consists of line routes and their frequency without explicit time intervals. In a timetable these time intervals are determined per line route. The timetable is thereafter used as input for scheduling decisions for rolling stock and train crews.

1.2.2 Line Planning by NS

In this section, we describe the process of line planning by NS. The public transport network that NS uses is the Dutch railway network. The lines of the Dutch railway network are the tracks located in the Netherlands. The stations on the Dutch railway network are divided into intercity stations and stopping stations. The intercity stations are the larger stations on the Dutch railway network. On these stations, most travelers begin or end. Tracks only merge or disperse at intercity stations and some intercity stations are starting and ending locations for rolling stock and train crew. At intercity stations and stopping stations, rolling stock is able to pick up and drop off travelers.

The rolling stock by NS is divided into rolling stock for intercity trains and rolling stock for stopping trains. The rolling stock for intercity trains only visits intercity stations to pick up and drop off travelers. The rolling stock for stopping trains visits both intercity stations and stopping stations. In line planning, NS creates different line routes for intercity trains and stopping trains.

Historically, the line plan for NS is manually designed by balancing different aspects of making train schedules. Using travel information, the current line plan, and the current train schedules, NS adapts the line plan manually. NS constantly searches for improvements in their line plan by changing the line routes and their frequency. NS tries to fit their line plan as efficient as possible to travel patterns of travelers. Since travel patterns of travelers change over time, NS has to adapt their line plan on these changes. To support the decision making in the line planning process, the PI department has developed a model, called Line Planning Model. This Line Planning Model is developed to support line planning decisions.

1.3 Research Motivation

The Line Planning Model is developed to support long term line planning decisions. By long term line planning decisions, NS creates line plans for 20-30 years in the future (called long term line plans). Currently, the Line Planning Model is also used to support short term line planning decisions. By short term line planning decisions, line plans are created for 0-5 years in the future (called short term line plans). However, the Line Planning Model is less suitable to create these short term line plans. To support these short term line planning decisions, the Line Planning Model needs to be redesigned into a short term line planning model that creates short term line plans.

1.4 Problem Identification

In this section, we identify the reasons why the Line Planning Model is less suitable to produce short term line plans. First, we broadly explain the functioning of the Line Planning Model. Second, we provide the main differences between short term and long term line plans. Then, we explain the reasons why the Line Planning Model is capable in creating long term line plans but is less suitable in producing short term line plans. Finally, we give the problem statement for this research.

The Line Planning Model

Figure 1.5 schematically shows the functioning of the Line Planning Model. The first step of the model consists of generating candidate line routes. In this step, line routes are generated that could be suitable for the line plan. In the second step, line plans are created using an Algorithmic Search Procedure (ASP). In this ASP, line plans are

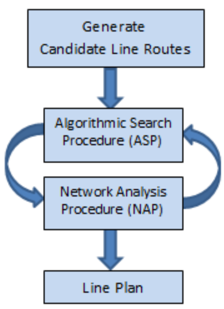

FIGURE 1.5: Line Planning Model

created by choosing line routes out of the set of candidate line routes. Then, the line plan is evaluated using a Network Analysis Procedure (NAP). Based on the result of the NAP, a new line plan is created using the ASP. The output of the loop of the ASP and NAP is the final created line plan. For a more detailed description of the Line Planning Model, we refer to Chapter 2.

Long Term vs Short Term Line Plans

In long term line plans, the current line plan and the current capacity of NS is fully adaptable. For the long term, NS is able to make big changes in the current line plan. NS is able to gradually implementing these big changes in their current practice. By gradually implementing big changes in the current line plan, NS can gradually adapt their current practice on these changes. Also, for the long term, NS can adapt their current capacity on these big changes by, for example, purchasing rolling stock or hiring new train crews.

In short term line planning, NS tries to find improvements in the current line plan by making small changes. For the short term, there are more limitations on creating line plans. In some cases, making a specific change in the line plan is not possible because NS is not capable of implementing the change in the short term. Changes in the current line plan cause the need of making changes in the current practice of NS. Changes in the current practice of NS are, for example, rescheduling rolling stock and train crew. Besides that, sometimes a change in the line plan causes the need of more capacity, for example, rolling stock. NS is not able to purchase a lot of new rolling stock in the short term. Besides that, some changes are not preferred by NS, for example changes that impact a lot of travelers. Some changes leads to confusion of a lot of travelers and NS wants to prevent this.

Shortcomings of the Line Planning Model

The Line Planning Model is designed to create long term line plans. In the Line Planning Model, the line plans are created with the ASP and are evaluated by the NAP. Currently, the ASP creates long term line plans. This means that the ASP is not designed to make small improvements in the current line plan, what is required to create short term line plans. Besides that, the line plans, created by the ASP, are evaluated by the NAP on being good long term line plans. The NAP is not able to evaluate the line plan on being good short term line plans. Therefore, the Line Planning Model is not able to create short term line plans that support short term line planning decisions.

This leads to the following problem statement:

> "The Line Planning Model used by the PI department is not able to support short term line planning questions."

1.5 Research Scope

In this section, we give some boundaries of our research. The boundaries of this research are:

- The method of creating long term line plans is out of scope of this research. In this research, we redesign some elements of the Line Planning Model to create a short term Line Planning Model.
- As stated in Section 1.4, the Line Planning Model first generates candidate line routes. The functioning of this first step in the model is beyond the scope of this research. We believe the method of generating candidate line routes, which we describe in Section 2.1, works well. Nevertheless, the redesigned ASP and NAP has to deal with this step of the Line Planning Model.
- In the NAP of the Line Planning Model, different calculations are made to analyze the line plans. The functioning of these calculations is out of scope of this research. In Section 2.3, we explain the functioning of these calculations.
- In the Line Planning Model, the Dutch railway network and the number of travelers are inputs. The structure of the network and the determination of the number of travelers are not part of this research.
- A line plan consists of line routes with their frequencies. In the current line plan, the frequencies of the line routes are, except for some fixed line routes, always two per hour. For this research, we assume NS does not want to change the frequencies of line routes. Changing frequencies result in problems in linking time intervals to line routes. We assume that NS does not want to change frequencies of line routes in the short term.

- The Line Planning Model is a strategic planning model and is used as input for tactical and operational models such as train schedules and material planning. These tactical and operational models are beyond the scope of this research.

1.6 Research Goal

The goal of this research is to design a planning methodology that creates short term line plans. Currently, the Line Planning Model is designed to create long term line plans. In this research, the Line Planning Model is redesigned into a short term Line Planning Model. Hereby, the ASP of the short term Line Planning Model must be capable of making small changes in the current line plan and the NAP must be able to evaluate the line plans on being feasible for the short term. This evaluation needs to take into account the limitations of short term line planning decisions. This brings us to the following main research goal:

> “To redesign the ASP and the NAP of the Line Planning Model, such that short term line planning problems can be solved.”

1.7 Research Questions and Methodology

In order to solve the stated problem, we compose several research questions. We divide the research questions into five main elements of this research: context analysis, literature review, model design, model evaluation, and implementation advice. These five research elements are supplemented with the conclusions and recommendations. We give the research questions, the chapter structure, and the methodology for each research element separately.

Context Analysis

Chapter 2 of this report consists of the context analysis. Using interviews with the PI department of NS, we analyze the context of the Line Planning Model. In these interviews, we analyze the functioning of the Line Planning Model.

1. How does the current Line Planning Model function?
    (a) How does the model generate candidate line routes?
    (b) How does the Algorithmic Search Procedure function?
    (c) How does the Network Analysis Procedure function?

Literature Review

Chapter 3 consists of the literature review. This literature review includes building a theoretical framework for this research. In this literature study we consult articles, reports, and other useful documents. This literature study consists of the determination of the ASPs that are suitable for solving short term line planning problems.

2. Which ASPs proposed in literature are suitable for solving short term line planning problems?
    (a) Which ASPs are proposed in literature to solve line planning problems?
    (b) Which ASPs are suitable for solving short term line planning problems?

Model Design

In Chapter 4, we design the ASPs and the NAP for the Line Planning Model of NS. We design the ASPs, described in Chapter 3, for the short term Line Planning Model. This is done by making the ASPs capable of making small changes in line routes of a line plan. The NAP is designed to be able to evaluate a line plan on being feasible for the short term.

3. How can we design the NAP for the short term Line Planning Model?
4. How can we design the ASPs for the short term Line Planning Model?

Model Evaluation

In Chapter 5, we evaluate the performance of the designed ASPs and NAP in the Line Planning Model. We give the performance of the ASPs and the NAP in the short term Line Planning Model. We analyze this performance using an experimental and a practical evaluation. In the experimental evaluation, the ASPs are compared by running the ASPs on different scenarios. In the practical evaluation, the ASPs are evaluated on practical issues, such as running time.

5. How well do the implemented ASPs in the short term Line Planning Model perform?

Implementation Advice

In Chapter 6, we give an implementation advice for creating a short term Line Planning Model. Based on the findings of this research, we give recommendations for implementation and further research.

6. How can we implement the short term Line Planning Model?

Conclusions

Chapter 7 of this report consists of the conclusions. In this chapter, we give the main conclusions of this research by answering the research questions.

Chapter 2

Line Planning Model

In this chapter, we describe the functioning of the Line Planning Model currently used by NS. As shown in Figure 2.1, the Line Planning Model consists of four elements: generate candidate line routes, the Algorithmic Search Procedure (ASP), the Network Analysis Procedure (NAP), and the final line plan. In Section 2.1, we describe the generation of candidate line routes. Section 2.2 consists of a description of the ASP and in Section 2.3, we describe the NAP. Section 2.4 elaborates on the software platform of the Line Planning Model. Finally, Section 2.5 gives the main conclusions.

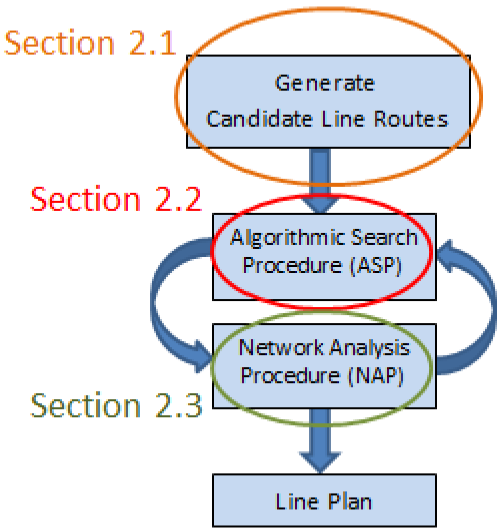

Figure 2.1: Overview of the Line Planning Model

2.1 Generate Candidate Line Routes

The first step in the Line Planning Model is to generate candidate line routes. In this step, potential line routes for the line plan are generated. To generate these candidate line routes, the Line Planning Model uses some rules to choose potential line routes. Without these rules, the set of line routes becomes too large for the ASP. These rules restrict the set of candidate line routes by only generating line routes that are an option to implement for the line plan of NS. For example, NS would not implement a stopping train line route from the north of the Netherlands (Groningen) to the south of the Netherlands (Maastricht). Using the simple network in Figure 2.2, we explain some rules.

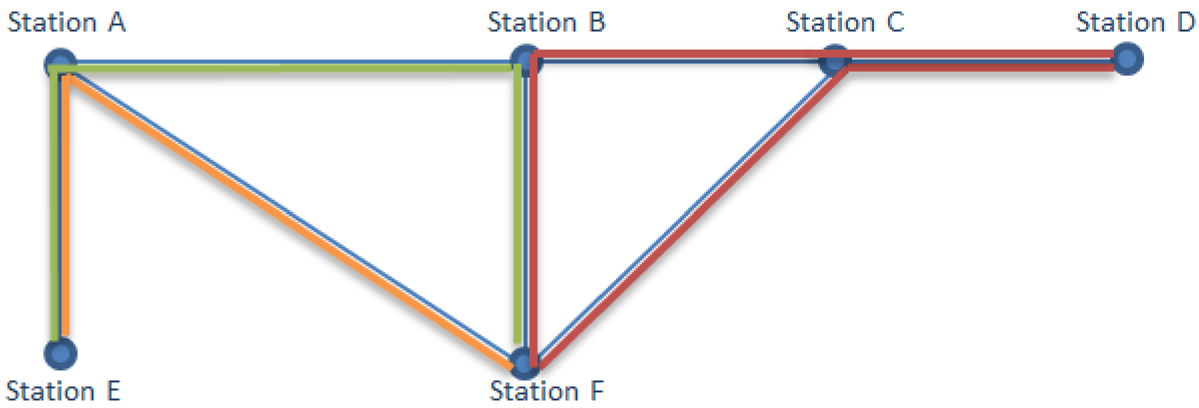

FIGURE 2.2: Simple network

- A line route may use a track at most once. In Figure 2.2, a line route that goes from Station D back to Station D on the red line route may not be generated, because the track from Station C to Station D is used twice.
- A line route can only be generated if this line route can be used in practice. For example, in Figure 2.2, it may happen that a line route from Station E to Station F on the green line route is not possible. The reason could be that it is not possible to make a turn at Station B to Station F.
- A line route may not be longer than a predefined distance. In Figure 2.2, if the green line route from Station E to Station F is longer than the predefined distance, the line route is not generated.
- A line route is deleted if the line route has a detour of a predefined distance in comparison with the shortest route. In Figure 2.2, the shortest route from Station

E to Station F is the orange line route. The green line route, also from Station E to Station F, may only be generated if the number of detour kilometers are smaller than the predefined distance.

The set of generated candidate line routes are input for the ASP, explained in Section 2.2.

2.2 Algorithmic Search Procedure

In this section, we explain the ASP that creates line plans in the long term Line Planning Model. The input for this step is the set of candidate line routes that are generated, as explained in Section 2.1. From this set of candidate line routes, a Genetic Algorithm is used to select line routes which form line plans. A Genetic Algorithm is a search algorithm that mimics the process of natural selection. In this section, we explain the functioning of the Genetic Algorithm.

The Genetic Algorithm consists of different elements which are illustrated in Figure 2.3. The first element, Generate Initial Population, consist of randomly choosing line routes to form a initial line plan. Then the Genetic Algorithm uses different iterations (generations) to create a final line plan. The iterations consist of repeating the elements: Determine Scores Individuals, Select Individuals for reproduction, and Reproduction by Mutation or Crossover. We now explain the different elements in the Genetic Algorithm.

Generate Initial Population

Generate initial population is the initialization step in the Genetic Algorithm. During this first step, random line plans are proposed. From the set of candidate line routes, explained in Section 2.1, line routes are randomly chosen to be in the line plan. The outputs of this initialization step are randomly generated line plans.

Determine Scores Individuals

In this step, each proposed line plan is evaluated. This evaluation is done in the NAP of the Line Planning Model. We explain the NAP in Section 2.3.

Select Individuals for Reproduction

Based on the scores of the line plans, some line plans are selected for Reproduction by

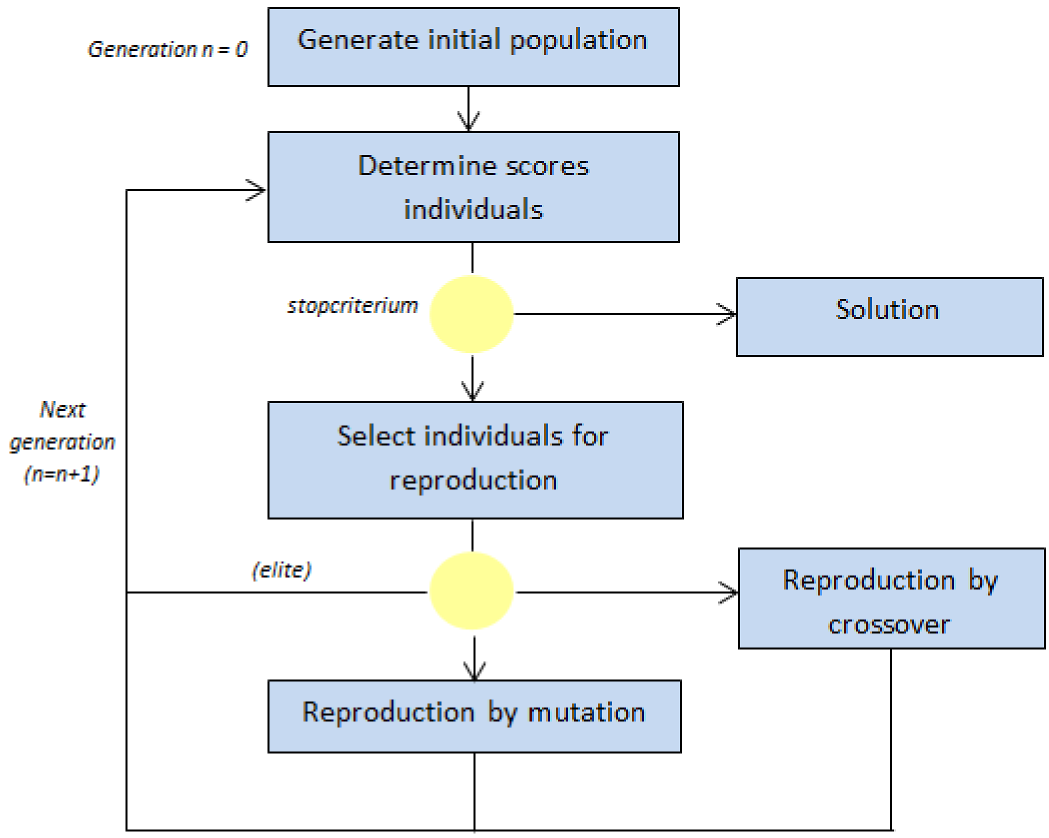

FIGURE 2.3: Genetic Algorithm (Guis, 2011)

Mutation or Crossover. With a certain probability a line plan will be selected, in which the best scoring line plans have the highest probability to be selected.

Reproduction by Mutation or Crossover

The last step in the ASP is to change the selected line plans for the next iteration. Two different changes are possible: Reproduction by Mutation and Reproduction by Crossover. In both changes, the selected line plans are changed by adding candidate line routes or deleting line routes from the line plan. In this section, we explain the functioning of both changes, supported by the line plans and the candidate line routes displayed in Figure 2.4 (in which each colored line represent a different line route).

Reproduction by Mutation consists of swapping existing line routes in the line plan, by a candidate line route. With a certain probability, an existing line route in the line plan will be switched by a candidate line route to form a new line plan. For example, the green line route (from Station E to Station B) in line plan 1 from Figure 2.4 can be swapped with the red and the dark blue line route from the candidate line routes.

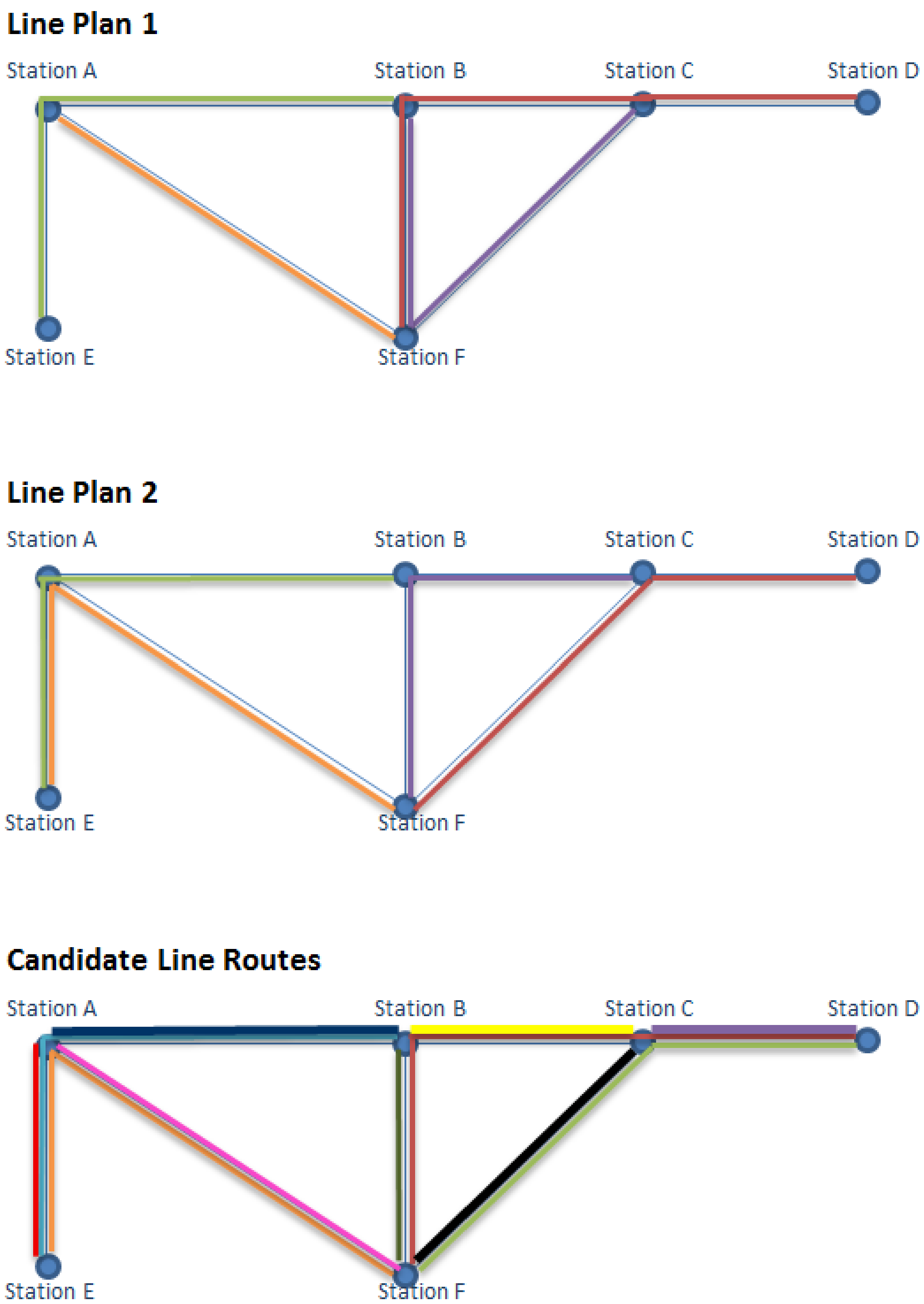

FIGURE 2.4: Example of two line plans and candidate line routes

Another example is swapping the orange line route (from Station E to Station F) in line plan 2 by the pink line route from the candidate line routes.

Reproduction by Crossover consists of interchanging line routes between line plans. The line plans are cut into two different parts; two sets of line routes per line plan are created. With a certain probability these sets of line routes are interchanged to create new line plans. For example, in Figure 2.4, the line plans can be cut in a left and a right part, where by the left part consists of stations A and E and the right part consists of stations B, C, D, and F. When the line routes in the right part are interchanged between the line plans 1 and 2, the red and the purple line routes are interchanged. The right line routes of line plan 1 are combined with the left line routes of line plan 2 and vice versa. This results in two new line plans.

2.3 Network Analysis Procedure

After the ASP proposes a line plan (Section 2.2), the quality of the proposed line plan is evaluated using the NAP. In the NAP, the line plan could be evaluated on multiple objectives, depending on the targets of NS. To determine the value of these multiple objectives, multiple calculations are needed. In Section 2.3.1, we describe which objectives are used. In Section 2.3.2, we explain the calculation steps for these objectives.

2.3.1 Objectives in the NAP

The objectives in the NAP in the long term Line Planning Model are set by the PI department and depend on the targets for the line plan. The main targets for NS are to create high customer satisfaction with as high as possible financial income. We divide these main targets in objectives for traveler satisfaction and financial objectives.

Objectives for Traveler Satisfaction

- Number of Travelers: The inputs for the NAP are the current line plan and the current number of travelers. For every proposed line plan, the NAP predict the total number of travelers for that specific line plan. The better the line plan, the more travelers will travel with NS.

- Turbulence: Turbulence indicates the number of travelers for whom the travel time increases. The proposed line plan has an impact on the travelers who nowadays travel with NS. The turbulence measures the number of travelers for whom the travel time increase more than a predetermined threshold (such as 3, 5, or 10 minutes). NS uses this measure because travelers become unsatisfied when their travel time increases.

Financial Objectives

- Rolling Stock Cost: Costs for the insurance, the depreciation, and the maintenance of rolling stock.
- Infra Charges: NS pays per rolling stock kilometer and per stop at a station a charge for using the tracks and the stations of ProRail. These charges are indicated as infra charges and must be paid to ProRail.
- Energy Charges: Rolling stock needs electricity to move over a track. These electricity costs depend on the travel kilometer of each rolling stock.
- Train Crews Costs: The train crew costs are the personal costs for driving rolling stock. On each rolling stock, a train driver and at least one train conductor is needed. The number of train conductors needed depend on the length of rolling stock.
- Revenues: The revenues for a line plan are the charges the traveler pays for traveling by train. These charges depend on the amount of kilometer the traveler travels and the number of travelers.

2.3.2 Calculation of the Objectives in the NAP

To determine the values of the objectives in the NAP, several calculations are needed. The input for these calculations are the proposed line routes and their frequencies determined by the ASP, the current line routes, and the number of travelers for each origin destination pair (OD pair).

In Figure 2.5, we give a schematic view of the calculation steps. The calculation steps consist of the determination of travel routes and the distribution of travelers among these

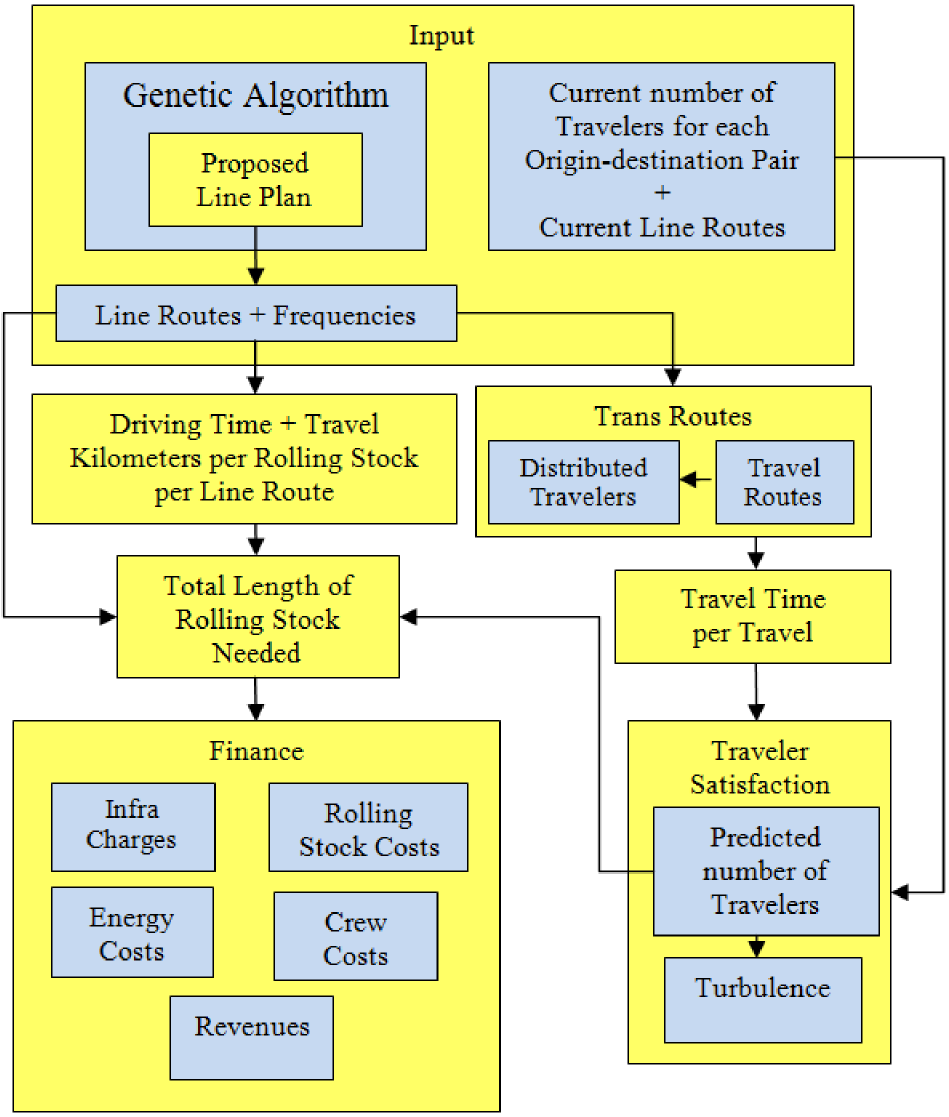

FIGURE 2.5: Calculation of Objective Value

travel routes, travel time for travelers, driving time and travel kilometers for each line route, and the length of rolling stock needed. In this section, we describe the calculation steps and their relation to the objectives.

Determination of Travel Routes and Distribution of Travelers

The Generic Algorithm proposes a line plan, which consists of line routes and their frequencies. The travel route for a traveler for each origin-destination pair (OD pair) depends on the line plan. This is the reason why for every proposed line plan the travel routes and the distribution of travelers to the travel routes are determined for each OD pair.

The determination of travel routes and the distribution of travelers is done with *Trans*

Routes calculations. In this section, we broadly explain the functioning of Trans Routes. Exact calculations are explained in the document: 'Specificaties TRANS Toedeler (Warmerdam, 2004)'. Trans Routes calculations are divided into two steps. In the first step, all the travel routes for each OD pair are determined. The second step consists of distributing the travelers among these travel routes.

To determine the travel routes for each OD pair, a Breadth First Search is used. In the Breadth First Search, possible routes between an OD pair are created without transition. Then, routes between an OD pair are created with one transition, then with two transitions, and so on. After each creation of routes, the newly created route is compared with the previous created routes. With some constraints, such as a detour of 5 kilometers more than the previous created routes is not allowed, the newly created routes are accepted or declined.

After the determination of the travel routes for each OD pair, the travelers are distributed among these routes. Most travelers will choose the route between an OD pair with the least travel time, but some travelers prefer other routes. The reason for preferring another route could for example be: traveling on a route with a transition is experienced as less comfortable than traveling a route without a transition, even when it is slightly longer. In the distribution of travelers amongst routes, the model uses a Logistic Regression method. In this Logistic Regression, the utility per travel route is determined. Travel routes with transitions are, for example, less favorable for travelers than routes without transitions, and will have lower utility. A lower utility leads to less expected travelers on these routes.

Travel Time per Travel

The travel time per travel is the time to travel between an OD pair. To calculate the travel time for each OD pair, NS does not use real travel time but perceived travel time. Perceived travel time is the real travel time of traveling between an OD pair raised by a penalty when a traveler has waiting time. Waiting time arises when a traveler has to wait on a station, for example by making a transition. Waiting on a station is perceived as less comfortable than sitting in a train. NS uses the Generalized Travel Time (GRT) to indicate the perceived travel time. Using the travel routes and the distribution of travelers, determined in the Trans Routes calculation, this GRT is calculated.

The GRT is based on real travel time and travel comfort of a traveler. In Formula 2.1, we give the calculation of the GRT between an OD pair. The real travel time is the average travel time the traveler needs to travel between an OD pair. In Formula 2.1, the real travel time depend on the number of travel opportunities per hour (Ntravelopportunities), the time in the rolling stock (Tinvehicle), and the transition time (Ttransition).

Using the number of travel opportunities per OD pair, the average waiting time for a traveler on the origin station is calculated. For example, if a traveler has 3 opportunities per hour to travel from Amsterdam to Rotterdam, the average waiting time will be 30/3=10 minutes.

The other elements that influence the real travel time between an OD pair are the average time in the train and the average transition time (both measured in minutes). When a travel route for an OD has transition time, the GRT is increased with perceived travel time because waiting at a station is experienced more uncomfortable than traveling in a train. The GRT is increased, for every transition, by 20 minutes (perceived travel time per transition, determined by the department Market Research and Advice (MOA).

$$GRT_{O,D} = 30/N_{travelopportunities} + T_{invehicle} + T_{transition} + 20 * N_{transitions;O,D} \tag{2.1}$$

The GRT is used to predict the number of travelers on an OD pair.

Prediction of Number of Travelers and Turbulence

To predict the number of travelers per OD pair, the current number of travelers per OD pair and the GRT are used as input. Per OD pair, the current number of travelers is increased or decreased whether the GRT for that OD pair is more or less favorable for the traveler. If the GRT between an OD pair become more favorable for the traveler, more travelers will use that OD pair and the predicted travelers on that OD pair increases. The increase or decrease of GRT for an OD pair will not lead to a proportional increase or decrease of travelers. Instead, the increase or decrease is corrected by an elasticity percentage to calculate the increase or decrease of the number of travelers.

Turbulence Calculation

For each proposed line plan, the GRT is calculated for each OD pair. There is turbulence if the GRT for an OD pair in the proposed line plan is larger than the GRT in the current line plan. The turbulence for an OD pair is the difference between the GRT of the proposed and the current line plan of NS. A higher GRT of in OD pair in the proposed line plan compared to the current line plan of NS causes turbulence. Using the number of travelers that make use of the OD pair, the number of turbulent travelers is calculated. NS wants to minimize the number of turbulent travelers that have turbulence more than a certain threshold (3, 5, or 10 minutes).

Calculation of Driving Time and Travel Kilometers

The Genetic Algorithm proposes a line plan, consisting of line routes and their hourly frequencies. Using these line routes and their hourly frequencies, the driving time and the travel kilometers per line route are calculated. The total driving time and the total travel kilometers for all line routes together are input for the financial calculations.

Total length of Rolling Stock needed

The predicted number of travelers for each OD pair and the frequency and driving time per line route are input for the calculation of the length of rolling stock needed on a line route. The length of rolling stock is indicated with the term Standard Capacity Unit (SCU). One SCU is a train bin, which has a capacity of approximately 100 passengers. Using the prediction of the number of travelers for each OD pair, the number of required SCUs per rolling stock is calculated. The total rolling stock needed is calculated using the circulation time per line route.

The number of SCUs needed per rolling stock per line route is calculated using the predicted number of travelers per OD pair. To explain the SCU calculation, we use the line route Amsterdam, Rotterdam via Den Haag. If, for example, the predicted number of travelers from Amsterdam to Den Haag is 200, the predicted number travelers from Den Haag to Rotterdam is 100 and the number of travelers from Amsterdam to Rotterdam is 300, the maximum number of travelers for that line route is 500. The number of SCUs needed for the rolling stock for the line route Amsterdam, Rotterdam via Den Haag is 500/100=5 SCUs.

The circulation time per line route is calculated using the driving time of rolling stock for the line route. For example, if the driving time for the line route Amsterdam to Rotterdam is 60 minutes, the circulation time for that line route is 2*60=120 minutes (driving back and forth). If the frequency of the line route Amsterdam Rotterdam is 2 per hour, NS needs 4 rolling stocks for this line route (because after 1 hour the first rolling stock is still driving, after 2 hours the first rolling stock is back in Amsterdam and can be reused).

The total number of SCUs needed per line route is calculated by multiplying the SCUs per rolling stock and the number of rolling stocks needed. For the example line route Amsterdam, Rotterdam this is 2*5=10 SCUs.

Calculation of Financial Objectives

The financial objectives consist of five different components: infra charges, crew-, energy- and rolling stock costs, and revenues. These financial objectives depend on the total length of rolling stocks needed, the total driving time and total travel kilometers, and the predicted number of travelers for each line route. We explain the calculations of each different financial objective separately.

The crew costs are calculated using the total driving time of rolling stocks and the costs of staff per unit of time. The costs for train crews (train conductors and train machinists) per driving minute are assumed fixed.

The infra charges are payments for using the tracks and the stations of ProRail. For every kilometer that a rolling stock drives and for every stop that the rolling stock makes, a fixed charge is paid to ProRail. The calculation of the travel kilometers is therefore input for calculating the infra charges. The number of stops are calculated using the proposed line plan.

The energy costs are calculated using the costs per kilometer and the total distance traveled. The energy costs per kilometers are a assumed fixed, which is determined by NS.

The costs for rolling stock are the costs for using SCUs. These costs consist of depreciation, insurance and maintenance of SCU. Inputs are the total number of SCUs needed and the travel kilometers per SCU. Costs for depreciation and insurance are assumed fixed per SCU. Costs for maintenance are partly assumed fixed per SCU and partly assumed fixed per travel kilometer.

The last financial objective is the revenues for NS. For every traveler NS transports, NS earns revenue. This revenue is calculated using the predicted number of travelers for each OD pair times the distance traveled. It is assumed that every traveler pays a fixed charge per travel kilometer.

2.4 Software Platform of the Line Planning Model

The Line Planning Model is a Java application programmed in Eclipse. In this section, we give a broad description of the Java application, supported by some screen shots that show the Line Planning Model. The terms in the Java application are in Dutch.

The Java application consists of different tabs: 'Netwerk', 'Instellingen','Kandidaatlijnen', 'Lijnvoering', and Optimizer. In the 'Netwerk' tab, the input network that is loaded in the Line Planning Model is shown. In Figure 2.6, we give an example of an input network (the Dutch railway network). In the 'Instellingen' tab, settings for generating candidate line routes and settings for the NAP can be entered. In the 'Kandidaatlijnen' tab, the generated candidate line routes are show. In Figure 2.7, we give an example of a candidate line route in the 'Kandidaatlijnen' tab. The bold black line is an example of a candidate line route. In the 'Lijnvoering' tab, the Java application shows the created line plan. In Figure 2.8, we give an example of a created line plan. The right framework shows the corresponding objective value for the line plan. On the left, the line plan is drawn. The different colored lines represent the line routes of the line plan. In the optimizer tab, settings for the ASP can be entered and the ASP can be carried out.

This information is not available in the public version of this report.

Figure 2.6: Network of the Netherlands in the Line Planning Model

This information is not available in the public version of this report.

Figure 2.7: Generating Candidate Line Routes in the Line Planning Model

This information is not available in the public version of this report.

Figure 2.8: Example of a line plan in the Line Planning Model

2.5 Conclusions

In this chapter, we explained the functioning of the Line Planning Model used by NS and we analyzed the steps of the Line Planning Model on being usable for the short Term Line Planning Model. The Line Planning Model consists of three steps: generate candidate line routes, the Algorithmic Search Procedure (ASP), and the Network Analysis Procedure (NAP). In the first step, a set of candidate line routes is generated that is input for the ASP and the NAP. In the ASP, a Genetic Algorithm creates line plans for NS. This Genetic Algorithm iteratively proposes line plans which are evaluated using the NAP. In the NAP, the PI department can optimize different objectives of NS, that are divided in financial and traveler satisfaction objectives. Ultimately, this process leads to a final line plan.

Chapter 3

Literature Review

In this chapter we construct a theoretical framework for this research. This theoretical framework consists of the determination of the Algorithmic Search Procedures (ASPs) for the creation of line plans in the Line Planning Model. First, in Section 3.1, we describe different methods in literature to tackle the line planning problem. Then, in Section 3.2, we explain the most promising ASPs suggested in literature for the Line Planning Model and we explain their functioning. Section 3.3 elaborates on which ASPs are usable for the short term Line Planning Model, based on their functioning. Section 3.4 gives the main conclusions.

3.1 Methods to Solve Line Planning Problems

In literature, designing a cost and service efficient public transportation network is indicated with the Transit Route Network Design Problem (TRNDP). Line planning problems and TRNDP are used interchangeably in literature. Kepaptsoglou et al. (2009) made a review on the TRNDP studies from 1967 to 2007. They divide the methods in conventional methods and heuristics. Fan and Machemehl (2008) and Sadrsadat et al. (2012) make a similar distinction between solution methods for the line planning problem. Figure 3.1 shows the classification of the different TRNDP studies. In this section, we give the main characteristics of these methods and analyze whether these methods are suitable for implementing in the Line Planning Model.

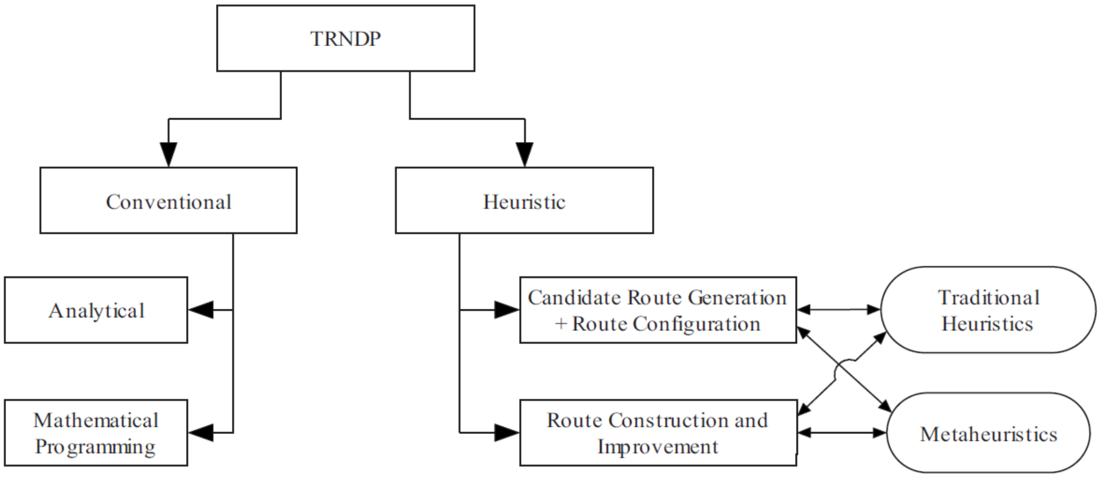

FIGURE 3.1: Classification of methodologies for the TRNDP (Kepaptsoglou et al. (2009)

3.1.1 Conventional Methods

Conventional methods have a strong focus on a mathematical technique in route design under idealized situations. The methods often use the characteristics of the network to design routes, such as route lengths and distances between stops.

The conventional methods use simple, idealized structures to develop relationships between the elements of a public transport network. Bussieck et al. (1995), Goossens (2004), and Borndorfer et al. (2004) suggest Integer Programming (IP) models to solve the line planning problem. The IP models have different objectives, for example, maximize service level or minimize costs. These objectives are supported by constraints such as capacity and frequency constraints. To solve the IP problems, the researches use different solution approaches, such as Branch-and-Bound and Lagrangian Relaxations.

In the IP models, different assumptions are made to solve the problems in reasonable time. For example, Bornforder et al. (2004) assume that travelers always choose the shortest path from origin station to destination station and they ignore transfers between line routes. Goossens (2004) only takes Intercity Stations and Intercity Trains into account to reduce the size of the network. On the one hand, these assumptions result in reducing the complexity of the models in which the models are able to solve the line planning problem. On the other hand, the assumptions lead to a less accurate representation of reality.

The advantage of conventional methods is that they search for the optimal solution in the solution space. The disadvantage is that conventional methods need a lot of assumptions to be able to solve the line planning problem. Kepaptsoglou et al. (2009) state that conventional methods are mostly used for analyzing networks, not for designing networks, and can be used for theoretical interest only. The Line Planning Model is a complex model that is used to optimize a large size network. Therefore, these conventional methods are not taken into account in this research.

3.1.2 Heuristics

In many recent researches, heuristics are used to solve the line planning problem. Baaj and Mahmassani (1991) and Bussieck (1998) prove that the TRNDP is a discrete, NP-hard combinatorial optimization problem. Therefore, heuristics are often used in solving line planning problems. A remark for the heuristics is made by Sadrsadat et al. (2012): 'Although their results may not be the best, depending on the complexity of the problem, they are often close to the optimal solutions and found quickly. Since in most cases the optimal solution can never be found, the main advantage of using heuristic methods is finding good results in a short time.'

Heuristics that are most often used for solving the line planning problem are: Steepest Descent e.g. Nachtigall et al. (1995) and Zhao (2004), Tabu Search e.g. Fan and Machemehl (2008) and Martins et al. (1996), Simulated Annealing e.g. Zhao (2006), Lianbo (2008), and Bing et al. (2014), and a Genetic Algorithm e.g. Shrivastava and O'Mahony (2006) and Bielli et al. (2000). In Section 3.2, we explain how these most promising heuristics are used to solve the line planning problem.

3.2 ASPs suitable for the Line Planning Model

In Section 3.1, we determined that the following ASPs are considered as most promising for this research: Steepest Descent, Tabu Search, Simulated Annealing, and a Genetic Algorithm. In this section, we first describe how each ASP is used for solving line planning problems followed by the theoretical functioning of the heuristic.

3.2.1 Steepest Descent

Nachtigall et al. (1995) and Zhao (2004) propose Steepest Descent to solve small network problems. Nachtigall et al. (1995) use Steepest Descent to make initial line plans as input for a Genetic Algorithm. Zhao (2004) uses Steepest Descent for improving network designs.

Functioning of Steepest Descent

Steepest Descent is a local search method developed by Pirlot (1996). Figure 3.2 depicts the functioning of Steepest Descent. In the first step, an initial solution is created. This initial solution is an already existing solution for the problem. Then, neighborhood solutions are created by making small changes in the current solution. Steepest Descent evaluates all neighborhood solutions, in which the best neighborhood solution is compared to the current solution. If the best neighborhood solution is better than the current solution, the current solution is replaced by the neighborhood solution. Otherwise, Steepest Descent stops.

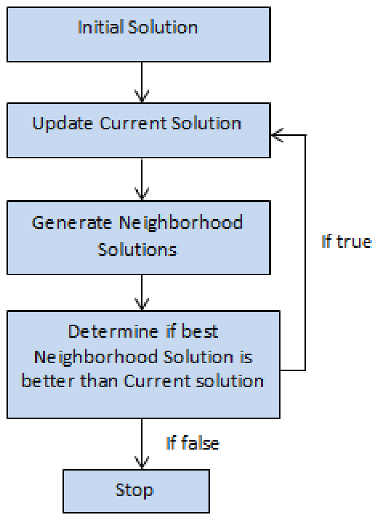

FIGURE 3.2: Steepest Descent

3.2.2 Tabu Search

Fan and Machemehl (2008) use Tabu Search to solve bus network design problems. They implement Tabu Search with the same neighborhood structure as the Simulated Annealing approach of Fan and Machemehl (2006). The difference is that the model of Fan and Machemehl (2008) deals with a variable number of travelers in the network. The number of travelers in the network is recalculated per line plan and depends on the line routes in the line plan.

Martins et al. (1996) implement Tabu Search in a feeder bus network design. The problem has strong similarities with line planning problems. For example, the objectives in the feeder bus network design problem is to minimize the cost function with the consideration of passenger and operation interest (Martins et al., 1996).

Functioning of Tabu Search

Tabu Search is a local search technique developed by Glover (1989,1990), which is able to escape from local minima. Figure 3.3 displays the functioning of Tabu Search. The first step of Tabu Search is an initialization step. In this step, the length of the tabu list and the stop criterion are determined. The value for these parameters is different for every problem. Then, a random solution is created. This random solution is stored as the current solution. Then, Tabu Search generates all neighborhood solutions by making small changes in the current solution. The best solution of the neighborhood solutions, that is not tabu, is stored as the current solution. A change is tabu when the change is stored in the tabu list. The last performed changes are stored in a tabu list. If the tabu list has reached his predetermined length, the oldest entry in the tabu list is removed. When Tabu Search does not find improvements in the best solution found after a predetermined number of iterations, Tabu Search stops. The output of Tabu Search is the best solution found.

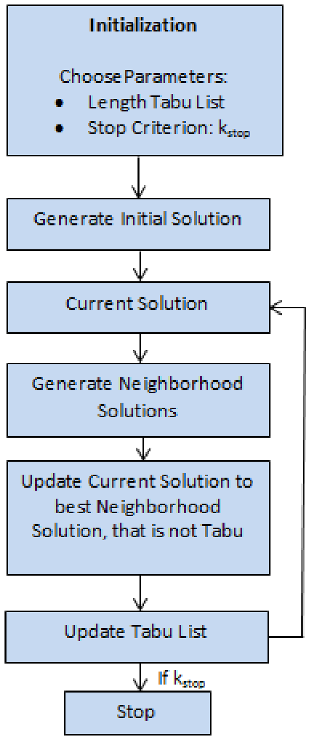

FIGURE 3.3: Tabu Search

3.2.3 Simulated Annealing

Zhao (2006), Lianbo (2008), and Bing et al. (2014) use Simulated Annealing to solve network problems in railway optimization. The network problems have strong similarities with line planning problems. Zhao (2006) and Lianbo (2008) recommend Simulated Annealing to solve transit network problems and Bing et al. (2014) to solve stock based problems.

Fan and Machemehl (2006) use Simulated Annealing to solve the line planning problem. The method that Fan and Machemehl (2006) use, shares many similarities with the Line Planning Model of the PI department. The model that they propose, also consists of two steps: generating candidate line routes and an ASP. For the ASP, they compare the Genetic Algorithm with Simulated Annealing. They implement the ASPs on different virtual rail networks and conclude that Simulated Annealing performs significantly better than the Genetic Algorithm.

Fan and Mumford (2008) use Simulated Annealing in making small changes to the line routes of a line plan. These small changes are: adding a node to a line route and deleting the first or the last node of a line route. After the small change, the line plan is evaluated. Based on the evaluation, the line plan will be accepted or not. The method used by Fan and Mumford (2008) is applicable for this research because NS also wants to make small changes in their line plan.

Functioning of Simulated Annealing

Metropolis et al. (1953) created Simulated Annealing, based on simulating the annealing of solids. Kirkpatrick et al. (1983) and Cerny (1985) were the first that used Simulated Annealing to solve combinatorial optimization problems. Simulated Annealing is a heuristic that starts with a random search which converges into a local search.

Figure 3.4 displays the functioning of Simulated Annealing. Simulated Annealing starts with an initialization step. In this step the values of the parameters for Simulated Annealing are determined. These values of the parameters is for each optimization problem different. The second step consist of generating an initial solution. This initial solution is a random, feasible solution for the problem.

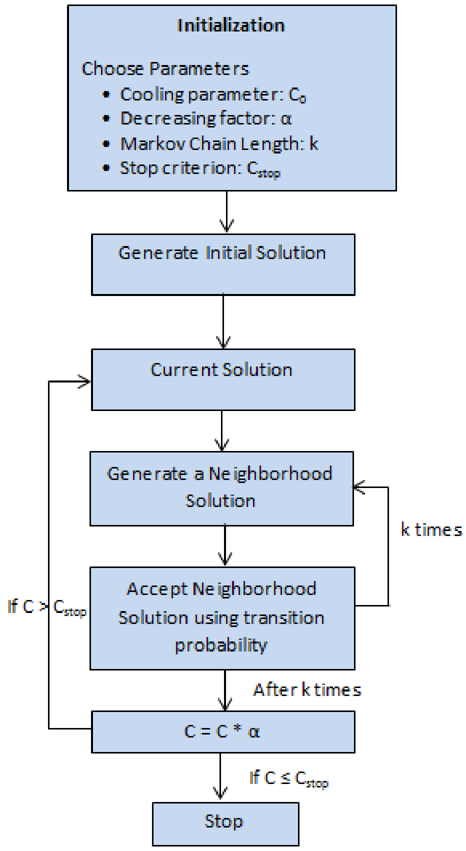

FIGURE 3.4: Simulated Annealing

After these first two steps, Simulated Annealing uses several iterations to search for better solutions than the initial solution. During the iterations, Simulated Annealing creates a neighborhood solution by making a random, small change to the current solution. A neighborhood solution is accepted using a transition probability. This transition probability depends on the difference in objective value between the current solution and the neighborhood solution, and the control parameter (C). At the beginning, Simulated

Annealing accepts almost every neighborhood solution (also a worse solution). At the end, the probability of accepting a worse solution becomes smaller. This is due the fact that after k times, the control parameter (C), which influence the transition probability, is decreased by the decreasing factor. This process leads to the effect of converging from a random search to a local search. The output of Simulated Annealing is the best solution found during the iterations.

3.2.4 Genetic Algorithm

Shrivastava and O'Mahony (2006) and Bielli et al. (2000) use a Genetic Algorithm to solve line planning problems. They use the Genetic Algorithm in a similar way as the Line Planning Model of NS. In both researches, the line planning problem is solved by first generating an initial set of candidate line routes. Second, line plans are created by selecting line routes from the set of candidate line routes using reproduction by Mutation or Crossover. Then, these line plans are evaluated whereby the most promising line plans are selected.

Guis (2011) proposes a Genetic Algorithm as ASP in the Line Planning Model for NS. The PI department currently uses this Genetic Algorithm. In Chapter 2, the functioning of this Genetic Algorithm was explained.

3.3 ASPs suitable for the short term Line Planning Model

In this section, we analyze which ASPs, described in Section 3.2, are suitable to be implemented in the short term Line Planning Model. As stated in Section 1.5, the ASP must be able to make small improvements in line plans. We evaluate the ASPs on this criterion.

Genetic Algorithm, Simulated Annealing, Steepest Descent, and Tabu Search are all able to make changes in line plans. The Genetic Algorithm uses reproduction by mutation or crossover to make changes in line routes of the line plan. In reproduction by mutation, a line route of the line routes is swapped between a candidate line route. By reproduction by crossover several line routes between line plans are interchanged. We believe that these methods of changing line routes are not suitable for making small improvement in line plans. The reproduction by mutation does not take into account whether changes of line routes are small or big. The method randomly swaps line routes between the candidate line routes and the line route in the line plan. Besides that, reproduction by crossover provides line plans consisting of completely different line routes. Therefore, the crossover of line plans is not able of making small changes in line plans. Since the Genetic Algorithm is not able to make small improvements in the line plan, it less suitable for the short term Line Planning Model.

Simulated Annealing, Steepest Descent, and Tabu Search use neighborhood solutions to make changes in the line plans. The neighborhood solutions provide the possibility to decide which changes of line routes in the line plan are included. Therefore, we can only propose small changes of line routes in the line plan in the neighborhood solutions. For this research, we decide to use all three local search heuristics. In Chapter 4, we give the design of the neighborhood solutions of these heuristics.

3.4 Conclusions

In literature, conventional methods and heuristics are proposed to solve the line planning problem. The conventional methods are not suitable to create line plans in the Line Planning Model, since they are only applicable in small sized networks and are often used for theoretical interests.

The most suitable heuristics for solving line planning problems are: Steepest Descent, Tabu Search, Simulated Annealing, and a Genetic Algorithm. Although the optimum is not guaranteed to be found, the heuristics can solve the line planning problem to near optimal results in reasonable time. Given the complexity of the Line Planning Model, we need a heuristic.

For the short term Line Planning Model, we need a heuristic that is capable of making small changes in line routes of a line plan. The Genetic Algorithm is less suitable for this purpose. The changes made by the Genetic Algorithm, i.e. reproduction by mutation or crossover, are not able to make these small changes. However, Steepest Descent, Tabu Search, and Simulated Annealing all make use of neighborhood solutions. The neighborhood solutions provide the possibility to make these heuristics suitable for making small changes in line routes of line plans.

Chapter 4

Model Design

This chapter describes the design of the short term Line Planning Model. Figure 4.1 depicts an overview of the short term Line Planning Model. Input for the short term Line Planning Model are the Dutch Railway network, the corresponding OD matrix, the candidate line routes, and the line plan of NS. Section 4.1 elaborates on the input for the short term Line Planning Model. Section 4.2 outlines the design of the ASPs (Steepest Descent, Tabu Search, and Simulated Annealing) that are selected in Chapter 3 for the short term Line Planning Model. Section 4.3 provides the design of the NAP for the short term Line Planning Model. Finally, Section 4.4 provides the main conclusions.

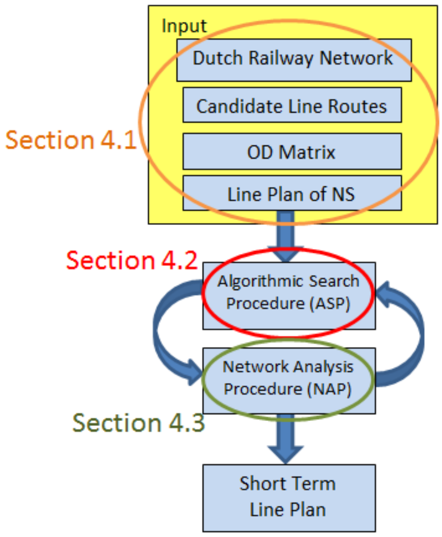

FIGURE 4.1: Overview of the short term Line Planning Model

4.1 Input of the Short Term Line Planning Model

The input for the short term Line Planning Model are the Dutch railway network, the candidate line routes, the line plan of NS, and the corresponding OD matrix. The Dutch railway network consists of the tracks and the stations, located in the Netherlands, in which NS is able to operate. The Line Planning Model creates candidate line routes on the Dutch railway network that NS is capable and willing to use. Chapter 2 describes the creation of these candidate line routes.

The short term Line Planning Model searches for small changes of line routes. Since the candidate line routes are all the line routes that NS is capable and willing to use, small changes in the line route must be one of the candidate line routes. Therefore, the candidate line routes are input for the ASP. The ASPs may only select a candidate line routes to be in the line plan.

The input of the OD matrix and the line plan of NS depend on the line planning problem that NS wants to solve. NS creates different OD matrices and line plans for peak hours, off-peak hours, and weekends. Peak hours are the hours during weekdays where most travelers travel by NS and off-peak hours are the hours in which less travelers travel by NS. These off-peak hours are during weekdays between 9.00 and 16.00 hours and between 18.30 and 6.30 hour. During peak hours, more travelers travel by NS and therefore NS drives more frequently on line routes and rolling stock on these line routes are larger. Besides that, some line routes are different in off-peak hours and weekends, for example the line route for the stopping train from Enschede to Apeldoorn is split into a line route from Enschede to Almelo and a line route from Almelo to Apeldoorn. The input for the short term Line Planning Model is one of the line plans of NS with the corresponding OD matrix.

4.2 ASPs Designed for the Short Term Line Planning Model

This section elaborates on the design of the ASPs (Steepest Descent, Tabu Search, and Simulated Annealing) for the short term Line Planning Model. During several iterations, the ASPs create a short term line plan. During each iterations, the ASPs create neighborhood solutions in which a small change is performed in a line plan by making a small change in the current line route (noted as a change from L to L'). In Section 4.2.1, we explain how the model create these neighborhood solutions. Section 4.2.2 elaborates on the specific design elements of the ASPs.

4.2.1 Creating Neighborhood Solutions

In the neighborhood solution, a line plan L' is created out of a line plan L by making a small change in a line route of line plan L. There are different changes that are indicated as small. We have developed four types of small changes in line routes: route changes, head-tail changes, merging & splitting, and changing connections.

In this section, we explain these four line route changes using the virtual network displayed in Figure 4.2. To describe a line route change in detail, we use the terms track sections and stations. A track section consists of a track between two consecutive stations. In the virtual network displayed in Figure 4.2, a line route is drawn from station A to station D. This line route consists of three track sections: the track section from station A to station B, the track section from station B to station C, and the track section from station C to station D.

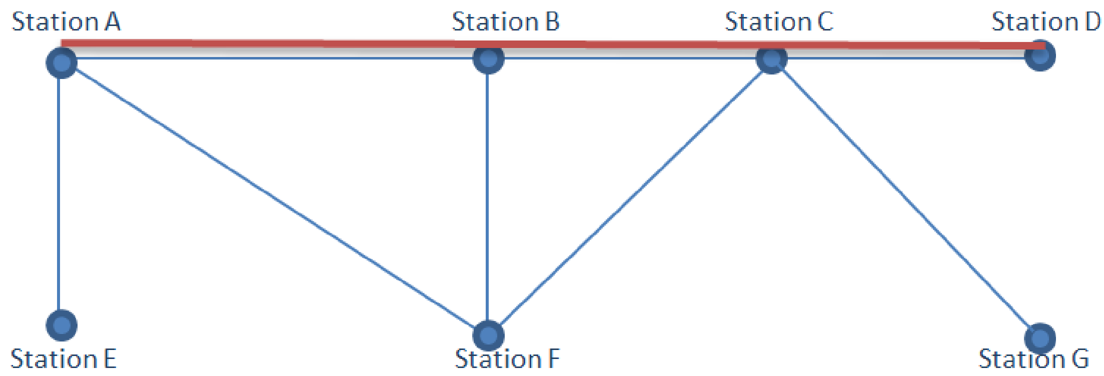

FIGURE 4.2: Virtual Network

Route Changes

A route change is a change of path of the line route from the origin station to the destination station. By route changes, the origin and the destination station of the line route remain the same. The change of the line route L consists of a difference in path between the origin and the destination station. The line route in L' must use 1 or 2 different track sections than the line route in L. The rest of the track sections used remain the same. In Figure 4.3, changing the green line route into the orange or the red line route is an example of a route change.

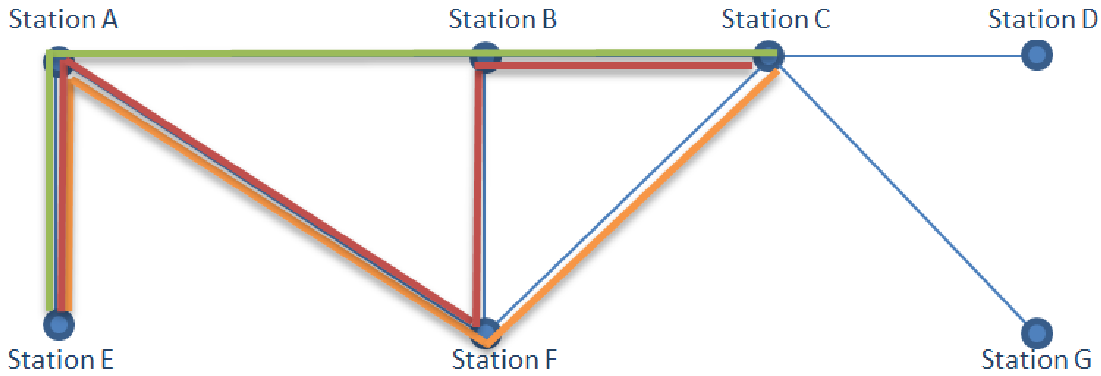

FIGURE 4.3: Example of a Route Change

Head-Tail Changes

Head-Tail changes are changes of the origin or the destination station of a line route. The head-tail change of the line route in L to the line route in L' consists of shortening or enlarging the line route by one track section and by one station. The rest of track sections and stations between the line route in L and the line route in L' remain exactly the same. Per line route in L, two types of head-tail changes are possible: shortening the line route by one track section and one station, or enlarging the line route by one track section and one station. In Figure 4.4, changing the green line route in L into the orange or the red line route in L' is an example of a shortening head-tail change. In Figure 4.5, changing the green line route in L to the orange or the red line route in L' is an example of enlarging the line route.

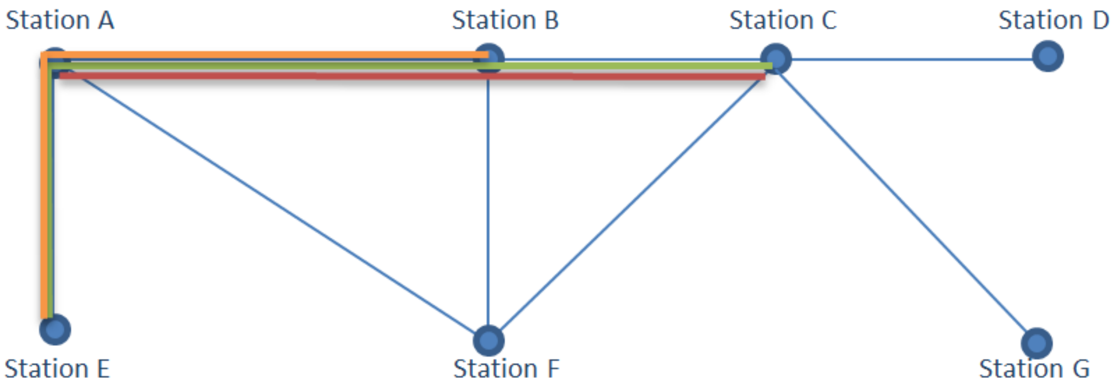

FIGURE 4.4: Example of a shortening Head-Tail Change

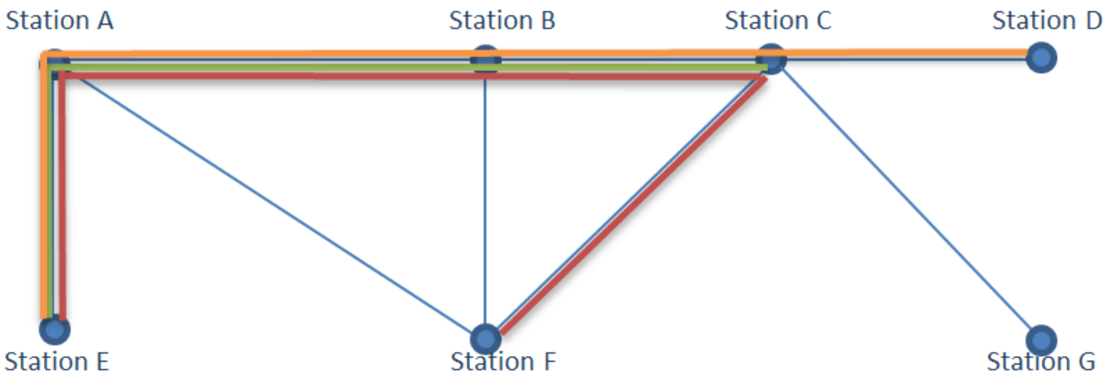

FIGURE 4.5: Example of an enlarging Head-Tail Change

Merging & Splitting

In merging line routes two line routes in L merges into one line route in L'. The line route in L' must use the same track sections and stations as the two line routes together in L. In Figure 4.6, changing the green and purple line routes in L into the red line route in L' is an example of a merge.

Splitting a line route is the opposite operation of merging line routes. By Splitting, one line route in L is split into two separate line routes in L'. The two line routes in L' together use the same track sections and stations as the line route in L. Besides that, the two line routes in L' do not use the same track sections and have one mutual station. In Figure 4.6, changing the red line route in L into the green and the purple line route in L' is an example of a split with mutual station B.

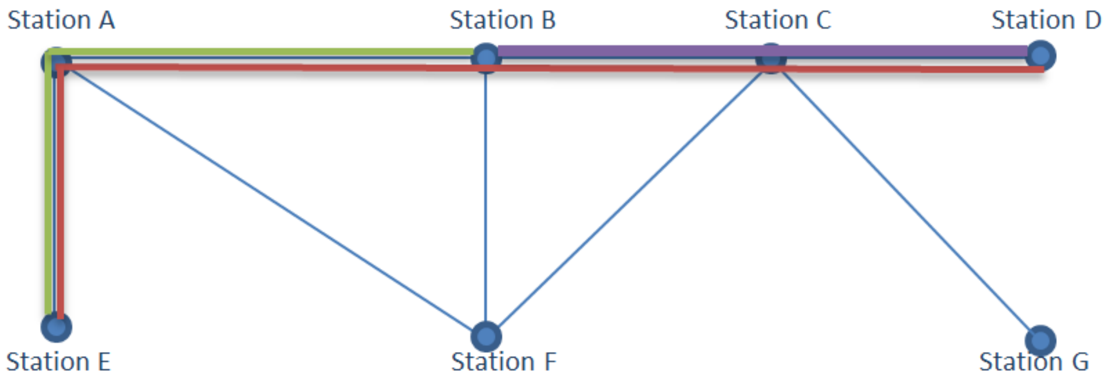

FIGURE 4.6: Example of a merge & split

Change Connections

Change connections consist of changing a connection of two line routes in L at a station that both line routes make use of. We divide these changes of connections into two types: T-splits and X-splits. By a T-split, a line route that ends on a station in L is combined with a line route in L that does not start or end at that station but moves along the station. The line route in L that moves along the station is split into two parts at that station. Thereafter, one part of the line route is merged with the line route in L that ends on the specific station to create a line route in L'. The other part of the line route in L forms the other line route in L'. In Figure 4.7, changing the green and purple line route in L into the red and the orange line route in L' is an example of a T-split at station B.

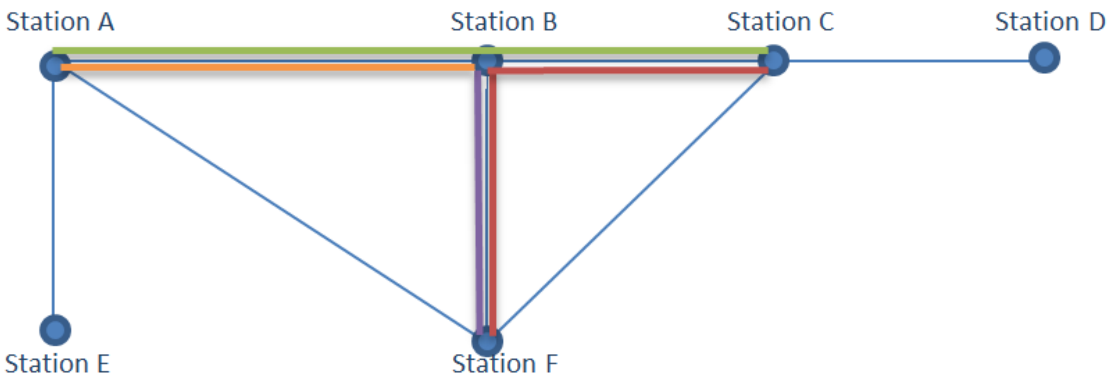

FIGURE 4.7: Example of a T-split

A X-split consists of changing the connections of two line routes in L that both contain the same station. In both line routes, this station is not the start or the end station. Both line routes in L are split into two separate line segments at the identical station. Two line routes in L' are created by merging the line segments occurred out of the line routes in L. In Figure 4.8, changing the green and purple line route into the orange and red line route is an example of a X-split at station C.

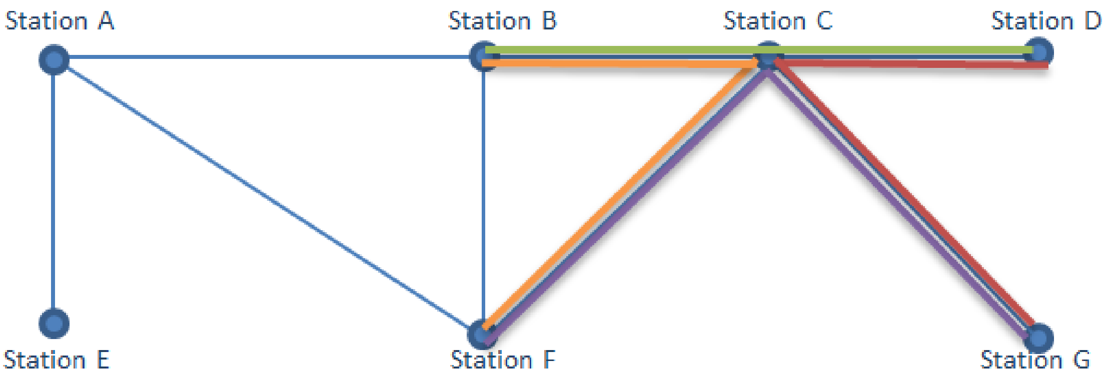

FIGURE 4.8: Example of a X-split

4.2.2 ASP Design

In this section, we give the design of the ASPs (Steepest Descent, Tabu Search, and Simulated Annealing) to create a short term Line Planning Model. In Figure 4.9, we give the functioning of the ASPs. In this section, we explain the differences of the design between the ASPs.

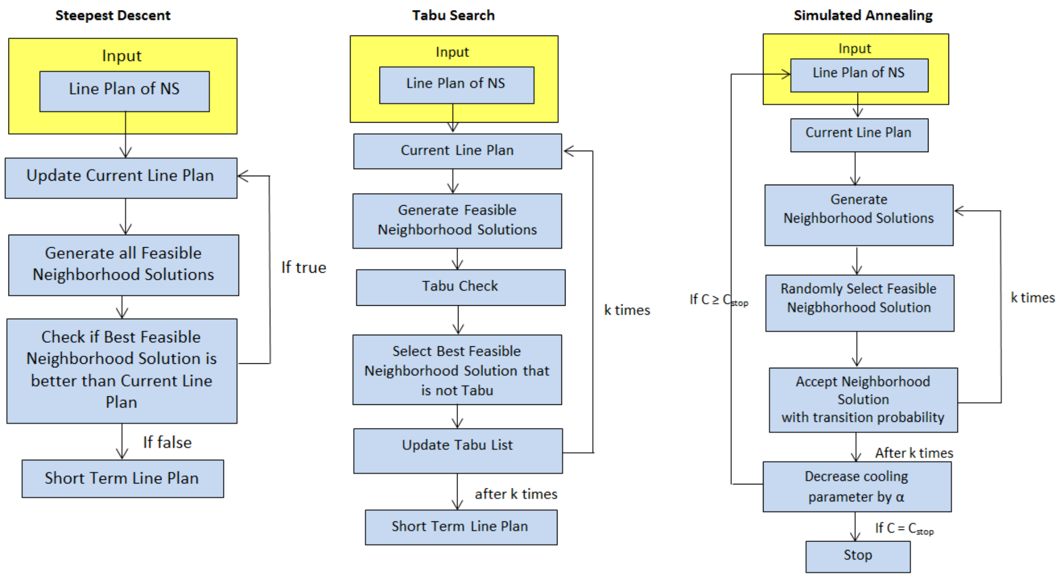

FIGURE 4.9: Design of Steepest Descent, Tabu Search, and Simulated Annealing

Steepest Descent

Since the short term Line Planning Model searches for small changes in the line plan of NS, the initial solution for Steepest Descent is the line plan of NS. In each step, Steepest Descent generates all neighborhood solutions possible and chooses the best neighborhood solution based on the evaluation in the NAP. Steepest Descent can only choose a neighborhood solution if this line plan is feasible. The neighborhood solutions are compared to the current line plan. If the best feasible neighborhood solution is better than the current line plan, the current line plan is replaced by the best neighborhood solution. If the best feasible neighborhood solution is worse than the current line plan, Steepest Descent stops.

Tabu Search

Also for Tabu Search, the initial solution is the line plan of NS. In each step, Tabu Search determines the best feasible neighborhood solution that is not tabu. First, Tabu Search creates a list of all neighborhood solutions of the current line plan. Then, the non tabu neighborhood solutions are evaluated by the NAP on their feasibility. The best feasible neighborhood solution is chosen as current line plan. A neighborhood solution is tabu if the change performed by Tabu Search is on the tabu list. The tabu list consists of the last changes performed. Besides that, Tabu Search consists of an aspiration criterion. This means that a change that is on the Tabu List but is evaluated as the best solution found so far, this change is accepted as the current solution. Appendix A elaborates on the choice of the parameter settings for Tabu Search.

Simulated Annealing

Normally, the initial solution of Simulated Annealing is a random solution. For the short term Line Planning Model, the initial solution is the line plan of NS. In every step of Simulated Annealing, a random neighborhood solution is selected. This neighborhood solution is a small change of a line route in the current line plan. Thereafter, the NAP evaluates the neighborhood solution on being feasible. If so, the neighborhood solution is accepted using the transition probability. Otherwise, another neighborhood solution is chosen.

Simulated Annealing has the characteristic to converge from a global search to a local search method. The global search is used to be able to explore the entire search space. By allowing Simulated Annealing to perform the global search phase, the entire line plan of NS will become unrecognizable, because in that phase most neighborhood solutions are accepted. Since the goal of the short term Line Planning Model is to stay close to the line plan of NS, we only make use of the local search part of Simulated Annealing.

This is done by choosing a start temperate in which only a small part of neighborhood solutions are accepted by the transition probability. Appendix A elaborates on the input parameters of Simulated Annealing. Besides that, after each Markov chain, we have chosen to reset the current solution to the line plan of NS. This makes Simulated Annealing able to search in other corners of the search space.

The adaptations we have made for Simulated Annealing provide that the method differs a lot from normal Simulated Annealing. The strength of Simulated Annealing is however that the method mostly accept better solutions but also sometimes worse solutions. This property of Simulated Annealing provides that we implement Simulated Annealing in this way.

4.3 NAP Designed for the Short Term Line Planning Model

In this section, we make the NAP capable of evaluating a line plan on being feasible. The NAP in the short term Line Planning Model consists of an objective function and restrictions. The objective function determines the quality of the line plans and the restrictions evaluates the line plan on being feasible. In this section, we describe the design of the objective function and the restrictions.

4.3.1 Objective Function in the NAP

For the short term Line Planning model, we assume that the model needs to maximize the financial income of using a line plan. Chapter 2 describes the calculation of the financial income of using a line plan. As stated in Chapter 2, the financial income of a line plan consists of revenues minus costs (infra charges, energy, crew, and rolling stock costs). For the short term Line Planning Model, we exclude the rolling stock costs, because these costs involve purchasing rolling stock and NS already purchased the rolling stock for the short term. In this section, we describe the relation of the different elements in the objective function to determine the financial income of using the line plan.

Infra Charges

The infra charges are the costs of using the tracks and stations, payed to ProRail. These charges consist of an assumed fixed charge per driving kilometer and an assumed fixed charge for stopping at a station.

Energy Costs

The energy costs are the electricity costs of driving rolling stock on a track. These energy costs are assumed fixed per driving kilometer.

Crew Costs

The crew costs are salary costs for train conductors and train drivers. These costs are assumed fixed per driving minute.

Revenues

The revenues are the payments of the travelers for traveling by NS. These payments are assumed fixed per traveler per driving kilometer. Before the calculation of the financial income of using a line plan, *Trans Routes* determines the travel routes for travelers. These travel routes are determined independently of the financial income, otherwise the model will choose a detour for travelers to get high revenues.

4.3.2 Restrictions in the NAP

To be able to judge if a line plan is feasible, we created restrictions in the NAP. Feasible line plans are defined as line plans that could be implemented by NS in 0-5 years ahead. In this section, we explain the restrictions for short term line plans.

Rolling Stock Constraints

Short term line plans are line plans that are executable by the current capacity of NS. By capacity, we mean rolling stock and train crews of NS. NS uses the term Standard Capacity Unit (SCU) for defining rolling stock capacity. One SCU is a train bin, which has a capacity of approximately 100 passengers. NS has a fixed amount of SCUs available. A short term line plan must be operated by the amount of SCUs currently available by NS. Further, NS is capable of hiring new crew in the short term. Therefore, we assume in this research that the available amount of train crews is unlimited for the short term.

We constructed constraints for rolling stock because NS is not capable of an increase of rolling stock in the short term. The capacity constraints for rolling stock are constructed for rolling stock for stopping trains and rolling stock for intercity trains separately. The

NAP calculates the amount of rolling stock needed for executing a line plan. We compare the increase or decrease of rolling stock needed for the line plan currently capacity of NS with the amount of rolling stock needed for the short term line plan. The calculation of the current rolling stock available is an estimation because it is, for example, hard to calculate how many rolling stock is in repair. That is why for this research, we assume NS is capable of a 5% increase of rolling stock for stopping trains and intercity trains.

Serving Constraint

The line routes of the short term line plan must serve every station of the Dutch railway network. Serving a station means stopping at least once an hour at the station. The serving constraint checks if every station is served by the short term line plan. The Dutch Government provide a rule that every station must be served on the Dutch railway network at least once an hour. Some stations do not serve many travelers and it will be cost efficient for NS to not serve these stations. This is especially the case in the east of the Netherlands. For some stations, NS set higher serving requirements to increase traveler satisfaction. Short term line plans must satisfy these minimal serving requirements.

Turbulence Constraint

The turbulence constraint checks if not too many travelers become dissatisfied with the short term line plan. For this constraint, we measure the turbulence of the short term line plan (introduced in Chapter 2). Turbulence is the number of travelers for whom the travel time increases. Changing line routes of the line plan of NS could result in turbulence. For example, if a connection at a station is changed, some travelers have to make an extra transition at that station. This results in extra travel time for these travelers.

The NAP calculates the amount of turbulence of the short term line plan according to the line plan of NS. We measure the number of travelers that have turbulence larger than a certain threshold. This threshold can for example be 3, 5, or 10 minutes. The maximum percentage of travelers that may be turbulent can be set by the PI department. In this research, we assume that a maximum of 5% of the travelers may be 5 minutes turbulent.

Maximum Change of Line Routes

Most line routes in a short term line plan must be exactly the same as the line routes in the line plan of NS. Only a few line routes in the short term line plan may have changes compared to the line routes in the line plan of NS. By implementing a short term line plan, some travelers who use the changed line routes need to adjust their travel pattern. Sometimes these changes cause confusion of the traveler. NS does not want to cause too much confusion of their travelers. That is the reason why NS does not want to change too much line routes. Changing only a few line routes is easier to communicate to the traveler than changing a lot of line routes. For this research, we assume that 30% of the line routes in the short term line plan may be different compared to the line plan of NS. This 30% of changes in line routes only applies for line routes that can be changed. For example, we assumed in this research that line routes with a frequency of 1 can not be changed. These line routes are therefore not taken into account for this calculation. This provides that only 10 of the 98 of the line routes of the line plan of NS may change.

Maximum Frequency Change on Track Sections

NS wants to drive approximately the same frequency on track sections. NS does not want to travel less frequently on most track sections. Driving less frequently on a track section will cause more travel time for some travelers. For example, if NS currently drives four times an hour on the track section from station A to station B and in the short term line plan NS only drives two times an hour, the average waiting time for travelers on station A increases. Therefore, the average travel time for these travelers increases. Driving more frequently on a track section is acceptable for NS.

In Figure 4.10, changing the green line route into the red line route causes driving less frequently on the track section from station A to station B. This results in driving less frequently on one track section. Changing the green line route in the orange line route causes driving less frequently on the track sections from station A to station B and from station B to station C, which results in driving less frequently on 2 track sections. Driving more frequently on the track section from station C to station D does not matter, driving more frequently is acceptable.

For this research, we assume that the short term line plan may only cause a decrease in driving frequency on at most 20 track sections compared to the current line plan of NS.

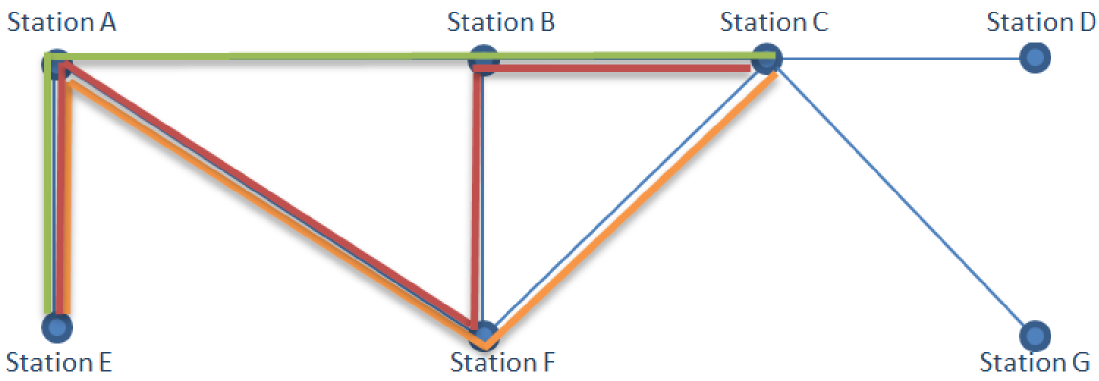

FIGURE 4.10: Example of changes on track sections

4.4 Conclusions

In this chapter, we constructed the short term Line Planning Model for NS. We made the ASP capable of making small changes in line routes of the line plan of NS and made the NAP capable of evaluating a line plan on being feasible.

We designed the ASPs Steepest Descent, Tabu Search, and Simulated Annealing for the short term Line Planning Model. The neighborhood solutions of the ASPs proposes small changes in line routes of a line plan. We constructed four types of small changes: route changes, head-tail changes, merging & splitting, and connecting changes. Based on the score of the neighborhood solution, the ASPs create short term line plans by accepting several neighborhood solutions of the line plan of NS.

We made the NAP able to evaluate a line plan on being feasible. The NAP consists of an objective function and restrictions. The objective value is used to measure the quality of the line plan. The objective for the short term Line Planning Model is to maximize revenues minus costs. Next to the objective, five constraints are constructed to judge a line plan on being feasible. The five constraints consider the rolling stock, serving, turbulence, maximum changes of line routes, and maximum changes in track sections. These five constraints check if a line plan can be executed by NS in 0-5 years ahead.

Chapter 5

Model Evaluation

In this chapter, we evaluate the performance of the alternative ASPs, created in Chapter 4. We perform an experimental and a practical evaluation on the models. Section 5.1 consists of the experimental evaluation. This evaluation consists of the comparison of the models based on several experiments. Section 5.2 elaborates on the practical evaluation for the ASP in which we describe the usage of the ASPs on a real life example of NS. Finally, Section 5.3 outlines the main conclusions.

5.1 Experimental Evaluation

In this section, we give the results of the experimental evaluation between the designed ASPs in the short term Line Planning Models in Chapter 4 (Steepest Descent, Tabu Search, and Simulated Annealing). In Section 5.1.1, we give the experimental design. Section 5.1.2 consists of the results and Section 5.1.3 gives the conclusions of the experiments.

5.1.1 Experimental Design

In this research, we implemented three ASPs in the short term Line Planning Model: Steepest Descent, Tabu Search, and Simulated Annealing. To evaluate the performances, we use a virtual network, displayed in Figure 5.1, and a fictional OD matrix. This is because the calculation time of the ASPs on the Dutch railway network is too time expensive to carry out a sufficient number of experiments. This section first elaborates on the design of the fictional network and the fictional OD matrix and then provides the set up of the experiments.

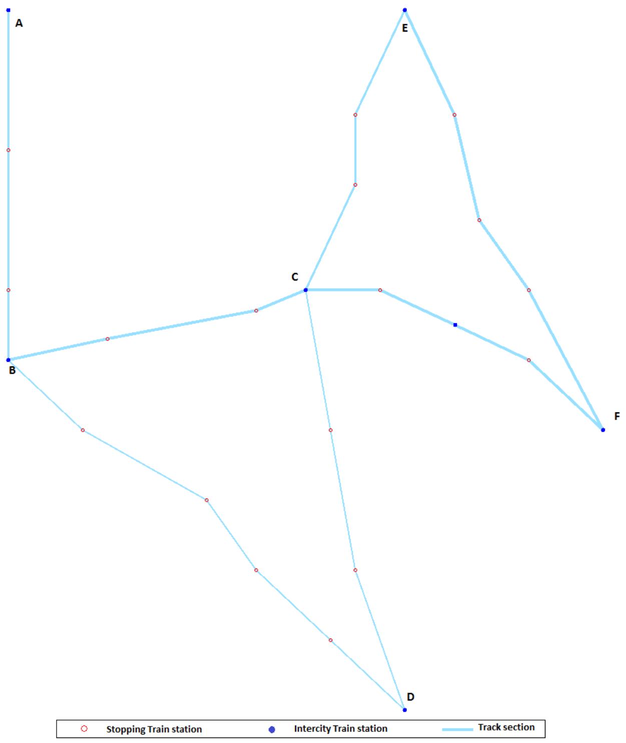

FIGURE 5.1: Virtual Network

Design of Fictional Network and OD Matrix

In the virtual network of Figure 5.1, the ASPs can produce short term line plans rather fast, so we can perform multiple experiments on this network. The virtual network is designed based on the Dutch railway network. The virtual network also consists of stopping stations and intercity stations. At the stopping stations, only stopping rolling stock can stop. At the intercity stations, both stopping rolling stock and intercity rolling stock can stop and rolling stock is only able to start or end at intercity stations. In the OD matrix, travelers between the stations are randomly generated. Since on the Dutch railway network, most travelers travel between intercity stations, we generated a random number between 500 and 1000 travelers between two intercity stations. Between the other stations (two stopping stations or a stopping station and a intercity station) a number between the 0 and 500 travelers is generated. Further, the structure of the virtual network is designed such that all neighborhood solutions could be generated (route changes, head-tail changes, merging & splitting, and changing connections). Appendix B outlines the choice of the structure of the virtual network.

Experimental Set Up

In the experiments, we perform 100 different replications by applying the ASPs on 100 input line plans. These 100 input line plans are generated by randomly selecting candidate line routes to form a line plan. The only restriction for the input line plan is that the line plan is a feasible line plan, which means that every station of the small sized network must be served. Since we want to mimic the real situation by NS as good as possible and we assume that the line plan of NS is already a good line plan, first 1000 input line plans are generated, in which the best 100 line plans are selected. The choice for using different input line plans is that the performance of the ASPs highly depends on the input line plan, because the NAP restrict changes based on the input line plan.

For every input line plan, the revenues of using the line plan are calculated (objective function in the NAP). Then, the ASPs produce short term line plans for every input line plan. The difference in objective function between the input line plan and the short term line plan gives the performance of the ASP. The larger the difference, the better the ASP function. For every input line plan, we measure which ASP produces the best short term line plan.

The parameter settings for the NAP are the settings determined in Chapter 4. Since we use a virtual network and there are less track sections in the virtual network compared to the Dutch railway network, we adapted the maximum frequency change on track sections to 10 instead of 20. To perform a sensitivity analysis, we also evaluate the performances of the ASPs using more strict and loose settings of the NAP. Table 5.1 outlines the parameter settings for the normal, loose, and strict NAP settings. The parameters settings for Simulated Annealing and Tabu Search are given in Appendix A.

	Normal Settings	Loose Settings	Strict Settings
Max Capacity Increase (%)	5	8	2
Max Turbulence Minutes	5	8	2
Max Turbulence Percentage	5	8	2
Max Line Route Changes (%)	30	40	20
Max Changes of Track Sections	10	15	5

Table 5.1: NAP settings for the experiments

5.1.2 Results

In the experiments, we executed the three ASPs on the 100 input line plans. Since Steepest Descent is the easiest method to execute, we compare Tabu Search and Simulated Annealing with Steepest Descent. The comparison consists of measuring which ASP perform best per input line plan and checks whether Tabu Search or Simulated Annealing are able to outperform Steepest Descent.

Steepest Descent vs Tabu Search

Figure 5.2 and Figure 5.3 provide the results of the comparison of Steepest Descent and Tabu Search under the normal NAP settings. Figure 5.2 shows per input line plan how much improvement Steepest Descent and Tabu Search make and in which cases Tabu Search is able to outperform Steepest Descent. In all replications, Steepest Descent and Tabu Search are able to find improvements. The maximum improvement is 6.3% and the minimal improvement is 0.3%. It often applies that a high input objective value causes a low improvement percentage of the ASPs. By a lower input value there is more room for improvement than by a higher input value. Based on the input objective value, there is no clear pattern when Tabu Search outperforms Steepest Descent. Figure 5.3 depicts a pie diagram that shows in how many percent of the cases, Tabu Search outperforms Steepest Descent. Tabu Search is in 13% of the cases better than Steepest Descent. In the rest of the cases, Tabu Search and Steepest Descent give an exactly equal result. The explanation that Steepest Descent and Tabu Search often finds equal results is that the first iterations of Tabu Search and Steepest Descent are exactly the same (they both accept the best neighborhood solution). If the best neighborhood solution is not better than the current solution, Steepest Descent stops. Then, Tabu Search tries to find a global optimum by using the tabu list. Since in the short term Line Planning Model the ASPs are restricted by constraints in the NAP, Tabu Search is often not able to escape from the local minimum. That is the reason why Steepest Descent and Tabu Search give exactly the same results in 87% of the cases.

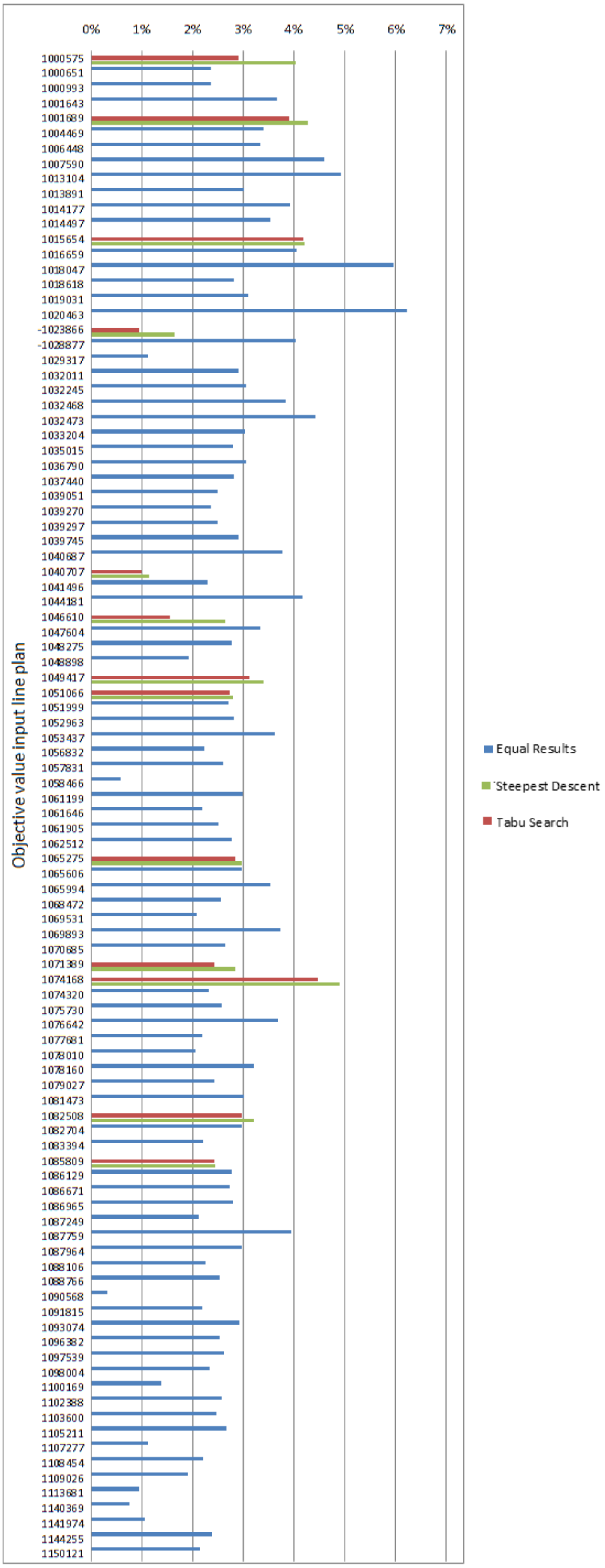

Figure 5.2: Percentage Improvement in Objective Function

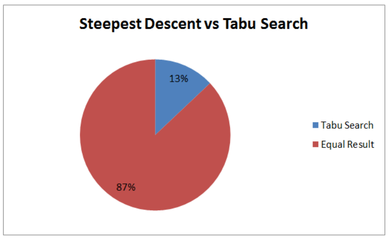

FIGURE 5.3: Steepest Descent vs Tabu Search

Figure 5.4 provides the pie diagrams of the performances of both ASPs in strict and loose NAP settings. Appendix C outlines all the results of the sensitivity analysis. In the strict settings, Tabu Search is only able to find a better optimum in 3% of the cases. In the loose settings, this is in 23% of the cases. Looser settings of the NAP provide a larger search space, in which Tabu Search is better able to escape from the local optimum. Stricter settings of the NAP provide a smaller search space, in which Tabu Search is in most cases not able to escape from the local optimum. Even more, very strict NAP settings provide in some cases such small search spaces that Steepest Descent and Tabu Search are not able to find a better solution than the starting solution.

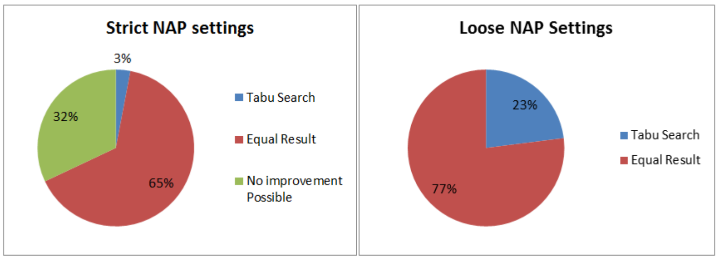

FIGURE 5.4: Sensitivity Analysis Steepest Descent vs Tabu Search

Steepest Descent vs Simulated Annealing

Figure 5.5 and Figure 5.6 depict the comparison of Steepest Descent and Simulated Annealing for the normal NAP settings. Simulated Annealing consists of several restarts, in which the best restart is selected for the comparison with Steepest Descent. As well as by Tabu Search, Simulated Annealing is often not able to outperform Steepest Descent (23%). In 74% of the cases, Steepest Descent and Simulated Annealing give an equal result and in 3% of the cases Steepest Descent outperforms Simulated Annealing. We believe that the small size of the network and therefore the small size of the search search is the reason for these results. Simulated Annealing is almost always capable of finding at least the same local optimum of Steepest Descent because the virtual network probably consists of little local optimums.

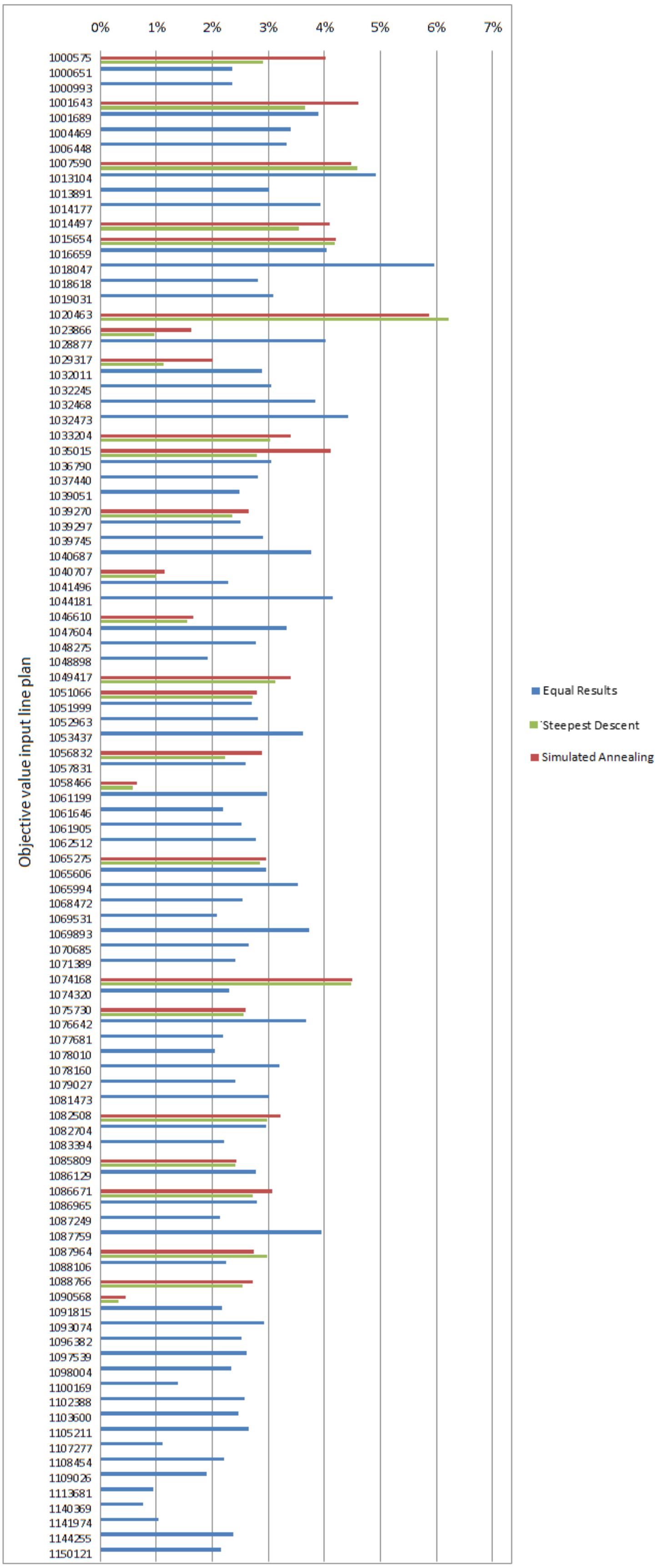

FIGURE 5.5: Percentage Improvement in Objective Function

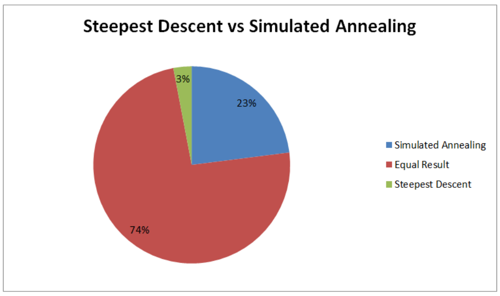

FIGURE 5.6: Steepest Descent vs Simulated Annealing

Figure 5.7 consists of the sensitivity analysis of the comparison of Steepest Descent and Simulated Annealing. In this sensitivity analysis it becomes clear that the larger the search space (loose settings), the more capable Simulated Annealing is to outperform Steepest Descent. We explain this due the fact that the larger the search space becomes, the more local optimums arise. Then, Simulated Annealing is more capable of searching in different corners of the search space. Appendix C shows all the results of the sensitivity analysis.

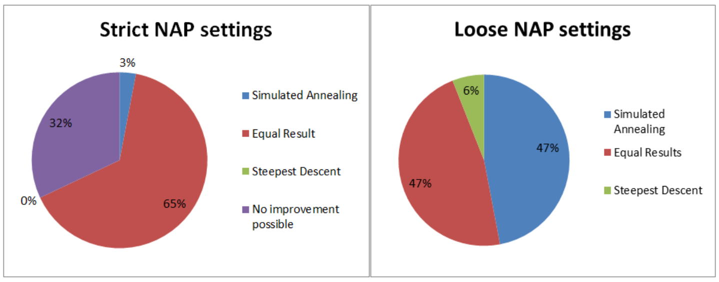

FIGURE 5.7: Sensitivity Analysis Steepest Descent vs Simulated Annealing

5.1.3 Conclusions

In the previous section, an analysis was made to compare the ASPs Tabu Search and Simulated Annealing to Steepest Descent. The goal was to determine whether Tabu Search or Simulated Annealing is able to outperform Steepest Descent. The conclusion is that for both ASPs it is hard to outperform Steepest Descent. In most cases, Steepest Descent, Tabu Search, and Simulated Annealing find equal results. However, Simulated Annealing is more often capable of outperforming Steepest Descent than Tabu Search. The sensitivity analysis showed that Tabu Search and Simulated Annealing are more often capable of outperforming Steepest Descent by looser NAP settings. In this case, the search space of the ASPs become larger, which results in better performances of

Tabu Search and Simulated Annealing. Also in this case, Simulated Annealing has the biggest potential to outperform Steepest Descent.

5.2 Practical Evaluation

In this section, we run the ASPs (Steepest Descent, Tabu Search, and Simulated Annealing) that are implemented in the Line Planning Model on a real life example of NS. The real life example is the off-peak line plan for 2014. First, Section 5.2.1 elaborates on the general complications that are encountered when running the short term Line Planning Model on the real life example. Section 5.2.2 provides the insights for the ASPs that we acquired from the runs. Finally, Section 5.2.3 gives the conclusions.

5.2.1 General Complications

Running the ASPs implemented in the short term Line Planning Model on the real life example results in some complications. In this section, we describe these complications and we discuss the solutions for these complications.

- On some line routes of the line plan of 2014 rolling stock operates on a frequency of 1 per hour. The short term Line Planning Model is not able to deal with these line routes. For this research, we assumed that rolling stock operates 2 times an hour on line routes. We solved this by only searching for improvements in line routes where rolling stock operates 2 times an hour. However, the line routes where rolling stock operates 1 times an hour are taken into account in the NAP.
- The short term Line Planning Model is not able to make small changes in all line routes of the line plan of 2014. The input for the short term Line Planning Model are the line routes of the line plan of 2014 and the candidate line routes. For this research, we assume that all possible changes in line routes are candidate line routes. This is not the case for all line routes in the line plan of 2014. Some line routes are so specific that the line route and their neighborhood solutions are not a candidate line route. Examples of a specific line route is a line route for stopping rolling stock that does not make a stop at every station on the route or a line route for intercity rolling stock that stops at a stopping station. We solved this by

exclude these specific line routes in the search procedure of the short term Line Planning Model. However, these specific line routes are taken into account in the NAP.

5.2.2 Acquired Insights

Running the ASPs on the real life example provided several insights. This section outlines these insights. In succession, we describe insights regarding the objective function, calculation time, the constraints in the NAP, and other issues for implementation.

Objective Function

Table (N.A) gives the increase of the objective function after running Steepest Descent, Tabu Search, and Simulated Annealing on the real life example. Steepest Descent and Tabu Search generate an equal short term line plan and therefore they have an equal increase in revenue. Steepest Descent and Tabu Search create a short term line plan with approximately 2000 more revenue than Simulated Annealing.

Table is not available in the public version of this report.

That Steepest Descent and Tabu Search give an equal increase in revenue is not a surprising result after the experimental evaluation described in Section 5.1. In the first iterations, Steepest Descent and Tabu Search both select the best neighborhood solution as current solution. If all neighborhood solutions are worse than the current solution, Steepest Descent stops. Normally, Tabu Search will continue by always selecting the best neighborhood solution (independent whether the neighborhood solution is better than the current solution). Since the short term model is unable to select infeasible solutions, the search space of Tabu Search becomes so small that Tabu Search is not able to find better solutions anymore.

That Simulated Annealing gives a worse solution than Steepest Descent and Tabu Search is more surprising. In the experimental evaluation, Simulated Annealing was almost always able to find at least an equal solution according to Simulated Annealing. We provide three possible reasons for this result:

- The optimal parameter settings for Simulated Annealing are not determined. Appendix A consists of the determination of the parameter settings. These parameter settings are based on the virtual network of the experimental evaluation. A better determination of the parameters of Simulated Annealing could result in better performances. Since the calculation time of one run (approximately 4.5 hours) is high, the determination of these parameters is hard.

- To perform a descent comparison between the three ASPs, we must execute Simulated Annealing several times because the search method is a probabilistic heuristic. Different runs will produce different short term line plans. Since the high calculation time of Simulated Annealing (4.5 hours), we are not able to execute Simulated Annealing many times and the results are therefore based on one run.
- We have tried to design the virtual network in the experimental evaluation such that the results for this network are representative for the Dutch railway network. Because the Dutch railway network is much larger than the virtual network. The search space for the ASPs is therefore much smaller on the virtual network than on the Dutch railway network. The Dutch railway network consists therefore of more local optima than the virtual network. On the virtual network, Simulated Annealing and Steepest Descent ended up very often on the same local optimum. On the Dutch railway network the chance of finding the same local optimum is much smaller.

Calculation Time

Table 5.2 outlines the calculation time for running the ASPs on the real life example. Since the short term Line Planning Model is a strategical model for decisions for 0-5 years ahead, calculation time is not a big issue. Although, running Simulated Annealing needs a lot of calculation time (approximately 4.5 hours), which causes problems for a good implementation of Simulated Annealing in the short term Line Planning Model. For example, determining the optimal parameters needs several runs and this is hardly possible with this amount of calculation time.

	Steepest Descent	Tabu Search	Simulated Annealing
Average Calculation Time per Iteration (Min)	1.8	1.9	8.3
Number of Iterations	9	11	17
Total Calculation Time (Min)	16.3	20.4	266.8

Table 5.2: Calculation Time per ASP

Constraints in the NAP

Table 5.3 consists of the values of the constraints in the NAP after running the ASPs on the real life example. In every run, the values of the rolling stock constraints is far from reached. In fact, all short term line plans need less rolling stock. We explain this by the fact that all costs are in the objective function and driving less rolling stock results in less costs. Therefore, the ASPs search for line plans with less rolling stock.

Besides the rolling stock constraints, the ASPs come close to the boundaries of the other constraints. For Steepest Descent this is not a problem. This search method converges to the best feasible local optimum. For the other two ASPs, Simulated Annealing and Tabu Search, approaching the constraints could result in bad performances. Since we restrict the ASPs by only accepting feasible solutions, it will be hard to escape for these ASPs to escape from local minimums. For Tabu Search, this became clear because very often Steepest Descent and Tabu Search produce the same short term Line Plans. For Simulated Annealing, we tried to eliminate this problem by restarting the procedure.

	Max increase	Steepest Descent	Tabu Search	Simulated Annealing
Capacity Increase (%) IC Rolling Stock	5	-4.3	-4.3	-2.0
Capacity Increase (%) Stopping Train Rolling Stock	5	-4.1	-4.1	-6.3
Turbulence (%)	5	3.8	3.8	2.9
Line Route Changes (%)	30	27.8	27.8	27.8
Changes of Track Sections	20	18	18	14

Table 5.3: Changes in Constraint Values

Implementation Issues

In this research, we create a short term Line Planning Model that produces short term line plans. These short term line plans are line plans that could be implemented in 0-5 years ahead. This section outlines some insights according to implementing the ASPs in the short term Line Planning Model.

- Steepest Descent is a search procedure that does not need any parameter settings and is easy to understand. Tabu Search in general and Simulated Annealing in particular are much complexer search procedures to understand and have complex parameter settings. It is preferable to have a search procedure that is easy to understand and to implement. At NS, the decision makers for line plans will sooner accept a line plan that is created using a search method that they understand. Besides that, a search method with complex parameter settings needs much set up time because the parameters needs to be determined for each separate instance.

- The changes made in line routes between the input line plan and the output line plan is easy to identify by Steepest Descent but hard to identify by Tabu Search and Simulated Annealing. For this real life example, Steepest Descent makes only 9 changes in line routes to create a short term line plan. Tabu Search makes 11 changes and Simulated Annealing makes 17 changes. Figure (N.A) shows the development of the objective value for Steepest Descent. Such figures increase the power of persuasion for the changes made by Steepest Descent.

  Figure is not available in the public version of this report.

  Another advantage of Steepest Descent is that the changes in line route in an iteration can be very easy displayed. Per iteration, the current line route can be displayed together with the changed line route. For example, Figure 5.8 depicts the change of line route made in the first iteration. In this iteration, the black line route on the left line plan is changed by the black line route in the right line plan. By showing these changes, the decision makers of line plans get a good understanding in which changes of line routes has to be made to accomplish the increase in objective value.

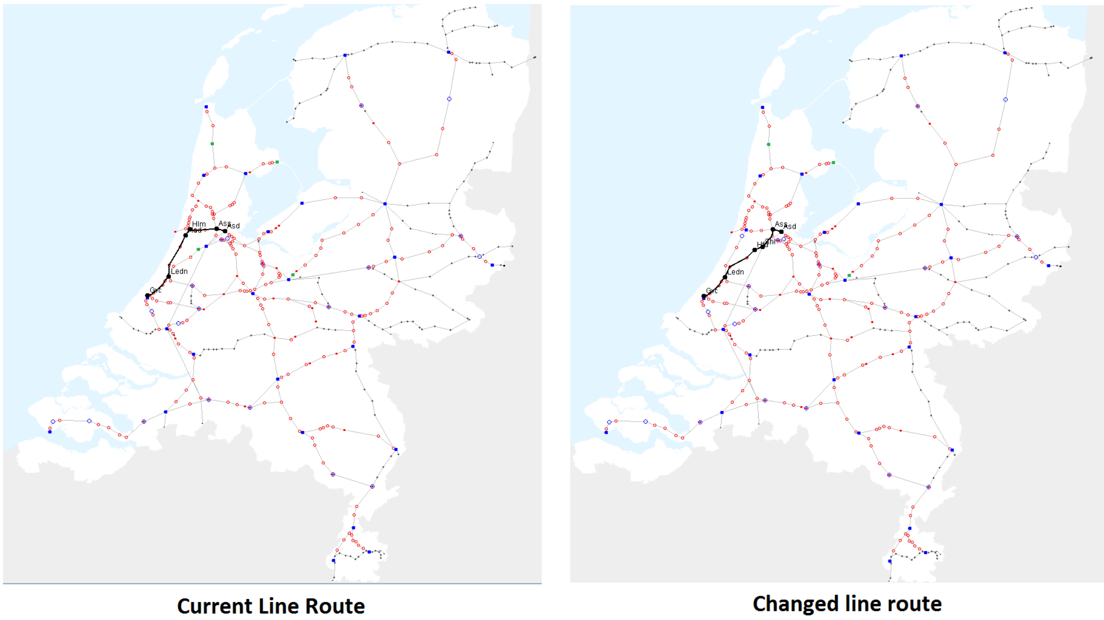

FIGURE 5.8: Changed line route in the first iteration of Steepest Descent

5.2.3 Conclusions

In the practical evaluation, the ASPs developed for the short term Line Planning Model are executed on a real life example. From the practical evaluation it becomes clear that Steepest Descent is the most suitable ASP to implement in the short term Line Planning Model. Steepest Descent found the highest increase in objective function, has the least calculation time, is easy to understand, and is relatively easy to implement. Besides the analysis of ASPs, we gained some insights about the constraints in the NAP. The ASPs never reach the boundaries of the rolling stock constraints, most short term line plans need less rolling stock.

5.3 Conclusions

In this chapter, we evaluated the ASPs implemented in the short term Line Planning Model on their performances. The evaluation consisted of an experimental evaluation and a practical evaluation, in which we compared the ASPs, Steepest Descent, Tabu Search, and Simulated Annealing. In the experimental evaluation, we researched whether Tabu Search or Simulated Annealing is able to outperform Steepest Descent. The conclusions of the experimental evaluation is that the differences in performance between the three ASPs are small, so we cannot conclude that one of the three ASP outperforms the others. However, Simulated Annealing has the highest potential to find the best solution. In the practical evaluation, the ASPs are executed on a real life example of NS. In this evaluation it becomes clear that Steepest Descent is currently the best option to implement in the short term Line Planning Model. Steepest Descent found the best solution, has the least calculation time, is easy to understand, and is relatively easy to implement.

Chapter 6

Implementation Advice

In this chapter, we give an implementation advice for NS for creating a short term Line Planning Model. In this research, we implemented three ASPs (Steepest Descent, Tabu Search, and Simulated Annealing) and recreated the NAP to create a short term Line Planning Model. We use the findings of this research to give an implementation advice for the creation of a short term Line Planning Model for NS. Section 6.1 outlines an implementation advice for the ASP and Section 6.2 consists of the implementation advice for the NAP.

6.1 Advice for ASP Implementation

In this research, we implemented Steepest Descent, Tabu Search, and Simulated Annealing in the short term Line Planning Model. In Chapter 5, we evaluated these ASPs on their performances, using a experimental and a practical evaluation. The findings of these evaluations are input for the implementation advice for the ASPs. In this section, we give several advices for implementing the ASPs.

Implement Steepest Descent and perform more research on Simulated Annealing and Tabu Search

In Chapter 5, we evaluated the performances of the ASPs in the short term Line Planning Model. In the experimental evaluation it turned out that it is hard for Tabu Search and Simulated Annealing to outperform Steepest Descent. The practical evaluation also confirmed that Steepest Descent is the best method to implement in the short term Line

Planning Model. Advantages of Steepest Descent are that the method does not need complex input parameters and the method is easily understandable. Besides that, the method converges quickly to an optimum which provides clear insight in the decisions made by Steepest Descent to create short term line plans. Therefore, we advice to use Steepest Descent in the short term Line Planning Model. For Tabu Search and Simulated Annealing, more research need to be performed to ensure better performances. This research can be, for example, determining the optimal parameter settings.

More research on Neighborhood Solutions

In Chapter 4, we constructed route changes, head-tail changes, merging & splitting, and change connections as neighborhood solutions. Although, we believe these neighborhood solutions are a good representation of small changes in line plans, we recommend more research on this subject. For example, we considered every neighborhood solution as an option for the short term line plan. In reality, this is not the case. Some neighborhood solutions are definitely not an option because this results in planning problems by, for example, making timetables. Also, it is possible to predict in advance that some neighborhood solutions are bad and therefore should not be included in further calculations. For example, splitting a line route at a station where a lot of travelers remain in the rolling stock is probably a bad idea (these travelers all have to make an extra transition after the split). Besides that, other neighborhood solutions can be included. For example, in this research we assumed that every intercity rolling stock on a line route only makes a stop at intercity stations. In reality, some intercity rolling stock on a line route make stops at stopping stations. Such decisions can also be indicated as a small change in a line route and can therefore be included as a neighborhood solution. Also, adding a line route, deleting a line route, or other variants of neighborhood solutions can be options for NS.

Create Neighborhood Solutions instead of Candidate line routes

For this research, we stated that only candidate line routes are an option to implement in the line plan of NS. In the real life example, executed in Chapter 5, we recognized that this is for practical cases not true. NS has implemented line routes that are more complicated than the candidate line routes. In the short term Line Planning Model, neighborhood solutions of an existing line route are only created if the existing line route is a candidate line route. This results in not creating neighborhood solutions for the line routes that are not in the candidate line routes. A solution for this problem could be that in further development of the model, the neighborhood solutions are created without using the candidate line routes. The neighborhood solution can therefore be created out of the current line routes in the line plan of NS.

Research the Frequency Problem

For this research, we assumed that every line route has a frequency of 2 times an hour. However, in practice, some line routes have a frequency of 1 times an hour. We did not researched the option of increasing or decreasing the frequency of operating on a line route. In creating a complete model that supports line planning decisions, it is recommended to take these frequency changes into account. The frequency changes can be performed during the creation of neighborhood solutions. Since frequency changes of line routes often cause problems for timetable decisions, NS must create strict rules for frequency changes in the neighborhood solutions.

6.2 Advice for NAP Implementation

In Chapter 4, we created the NAP for the short term Line Planning Model. The calculations in the NAP, which are described in Chapter 2, remained the same compared with the long term Line Planning Model. In this research, we extended the NAP by constraints for short term line plans. This section outlines the implementation advice for the NAP in the short term Line Planning Model.

Make Calculations Less Complex

The NAP calculates for every line plan the ASPs proposes, the traveler diffusion among the network, the travel time of each traveler, the number of rolling stock needed, etc. These calculations are complex and specific, and need therefore approximately 1 second calculation time. Since the NAP is often used by the ASPs, the total calculation time of the ASPs becomes large. For the short term Line Planning Model, the ASPs only propose small changes in the line plan. Therefore, we believe it is unnecessary to make every calculation in the NAP, most outcomes of the calculations remain exactly the same. For example, if an ASP suggest a small change in a line route in the north of the Netherlands, it is unnecessary to recalculate the NAP values for the south of the Netherlands. The values of the NAP for the south of the Netherlands will probably stay the same or will change just marginally.

More Research on Constraints

In this research, we have set constraints for rolling stock, serving, turbulence, and so on. Although, we believe that these constraints are necessary to ensure that the short term Line Planning Model creates feasible short term line plans, further research on this subject can be performed. In the practical evaluation, we already concluded that the boundary of the rolling stock constraint is never reached. Therefore, this constraint can be removed. Further, more research can be performed to ensure that all important constraints are taken into account. Besides that, in this research the values of the constraints are estimated. The real values of the constraints are subject for further research.

Different Settings for Short Term Decisions

In this research, we used the same settings for the NAP in the short term Line Planning Model as for long term Line Planning Model. Examples of settings are: the elasticity percentage for travel growth, the costs per travel kilometer per SCU, or the revenue per travel kilometer per traveler. These settings are for the short term different than for the long term. It is recommended to perform more research on these settings.

Chapter 7

Conclusions

This chapter outlines the main conclusions of this research. The main conclusions consist of answering the research questions determined in Chapter 1. In the chapter, we give the answer of each research question.

How does the current Line Planning Model function?

The current Line Planning Model generates line plans using an input network and OD matrix. To create these line plans, the Line Planning Model first generates candidate line routes. These candidate line routes consist of all potential line routes to implement in a line plan for the input network. Then the Line Planning Model uses an Algorithmic Search Procedure (ASP) and a Network Analysis Procedure (NAP) to create line plans. The ASP that is used in the Line Planning Model is a Genetic Algorithm. This Genetic Algorithm selects line routes from the set of candidate line routes to form a line plan. The NAP evaluates the quality of the created line plan. The NAP can evaluate the line plans on different criteria, depending of the objectives of NS (traveler satisfaction and/or financial objectives). Then, based on the quality of the created line plan, the Genetic Algorithm iteratively proposes new line plans. Finally, the Genetic Algorithm proposes a final line plan that has the highest NAP value.

Which ASPs proposed in literature are suitable for solving short term line planning problems?

In literature, Steepest Descent, Tabu Search, Simulated Annealing, and the Genetic Algorithm are most often used to solve the line planning problem. Since the short term Line Planning Model should only perform small changes in a line plan, we concluded that Steepest Descent, Tabu Search, and Simulated Annealing are most suitable to solve a short term line planning problem. By making small changes in a line plan in their neighborhood solutions, these ASPs use local search to find the best neighborhood solution.

How can we design the NAP for the short term Line Planning Model?
The NAP for the short term Line Planning Model consists of an objective function and constraints. The objective function is used to evaluate the quality of a line plan. For this research, we assumed that NS wants to optimize the financial income of a line plan. The revenues minus costs are therefore determined per line plan. The revenues of a line plan consist of the payments of travelers, and the costs consist of energy and crew costs and infra charges. The higher the financial income, the higher the quality of a line plan.

Next to the objective function, the constraints determine which line plans are feasible. We define feasible line plans as line plans that could be implemented in 0-5 years ahead. The first constraint consists of a rolling stock constraint, in which the feasible line plan must use at most the same amount of rolling stock compared to the current line plan of NS. Further, a serving constraint provides that all stations on the Dutch railway network are served. A turbulence constraint ensures that most of the current travelers of NS do not have much increase in travel time. Finally, a feasible line plan may travel less on at most 20 track sections and 70% of the line routes of the current line plan of NS must be exactly the same. These constraints ensure that a feasible line plan does not variate much from the current line plan of NS.

How can we design the ASPs for the short term Line Planning Model?
For the short term Line Planning Model, we constructed the neighborhood solutions for the ASPs Steepest Descent, Tabu Search, and Simulated Annealing. The neighborhood solutions consist of small changes in line routes of a line plan. Four changes are defined: route changes, head-tail changes, merging & splitting, and changes of connections. Route changes consists a change of the route in a small part of the line route. The start and the end station of the line route stays the same. By head-tail changes, a line route is enlarged or shortened in which the rest of the route stay the same. By merging, two line routes are merged into one line route and by splitting one line route is split into two line routes. Finally, changes of connections consist of changing connections of two line routes that both affect the same station.

The ASPs are designed using the neighborhood solutions. The start solution of all ASPs is the current line plan of NS. Then by Steepest Descent, all neighborhood solutions are evaluated by the NAP and the best feasible neighborhood solution is selected as the current solution. Steepest Descent stops when neither of the neighborhood solutions is better than the current solution. By Tabu Search, also the best of the neighborhood solution is accepted as current solution. The difference with Steepest Descent is that by Tabu Search the last accepted changes are tabu and may not be accepted. Tabu Search stops after a predetermined number of iterations.

For Simulated Annealing, we made some adaptations to made the ASP suitable for implementation in the short term Line Planning Model. Simulated Annealing starts normally as a global search method in which a random neighborhood solutions is accepted as current solution. Since the current line plan of NS is input and we assumed that this line plan is already a good starting solution, we only use the local search part of Simulated Annealing. This is done by setting the starting temperature of Simulated Annealing already quite low, in which only a better neighborhood solution or a slightly worse neighborhood solution is accepted as current solution. Further, we restart Simulated Annealing after each Markov chain. These restarts enable Simulated Annealing to not deviate too much from the current line plan of NS.

How well do the implemented ASPs in the short term Line Planning Model perform?

An experimental and a practical evaluation is used to evaluate the performance of the ASPs. Since Steepest Descent is the easiest method to implement and to understand, the experimental evaluation consisted of estimating whether Simulated Annealing or Tabu Search is able to outperform Steepest Descent. We concluded that Simulated Annealing and Tabu Search often yield similar results compared to Steepest Descent.

In the practical, the ASPs are tested on a real life example. In this practical evaluation, it became clear that Steepest Descent is the most promising ASP to implement in the short term Line Planning Model. Steepest Descent was able to find the highest objective value and is the easiest to implement.

How can we implement the short term Line Planning Model?

In this research, we already implemented Steepest Descent in the short term Line Planning Model. NS is able to use this short term Line Planning Model on different line planning problems. For future research, we recommend NS to perform more research on neighborhood solutions. In this research, neighborhood solutions are created but probably more neighborhood solutions are available. Further, research can be performed on the settings of the Line Planning Model for short term line planning problems. Currently, the Line Planning Model is adjusted to long term line planning problems.

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Appendix A

Parameter Settings

In this appendix, we explain the determination of the parameter settings for Tabu Search and Simulated Annealing in the experimental and the practical evaluation.

A.1 Tabu Search

Tabu Search consists of two parameter settings: the length of the tabu list and the number of iterations. We use the research of Fan and Machemehl (2008) to estimate the parameters. Fan and Machemehl (2008) use Tabu Search to solve the line planning problem and made a research on the parameter settings. They propose a optimal length of the tabu list of 10 swaps and 100 number of iterations. For this research, we use these settings for the experimental and the practical evaluation for Tabu Search.

A.2 Simulated Annealing

Simulated Annealing consists of four different parameters: the start temperature, end temperature, length of the Markov chain, and the decrease factor. The start and the end temperature are determined using the transition diagram, displayed in Figure A.1 This transition diagram is made by creating a short term line plan out of a random input line plan in the experimental analysis. Since we restart the method after each length of Markov chain, we start the method already at a low temperature. The start temperature that is used is therefore 500 and the end temperature is 100. The length of Markov chain that is used is equal to the number of neighborhood solutions, which are often around 50 in the experimental design and 150 in the practical evaluation. The decrease factor is set to 0.95, because this temperature provides a running time of approximately 2 minutes in the experimental evaluation.

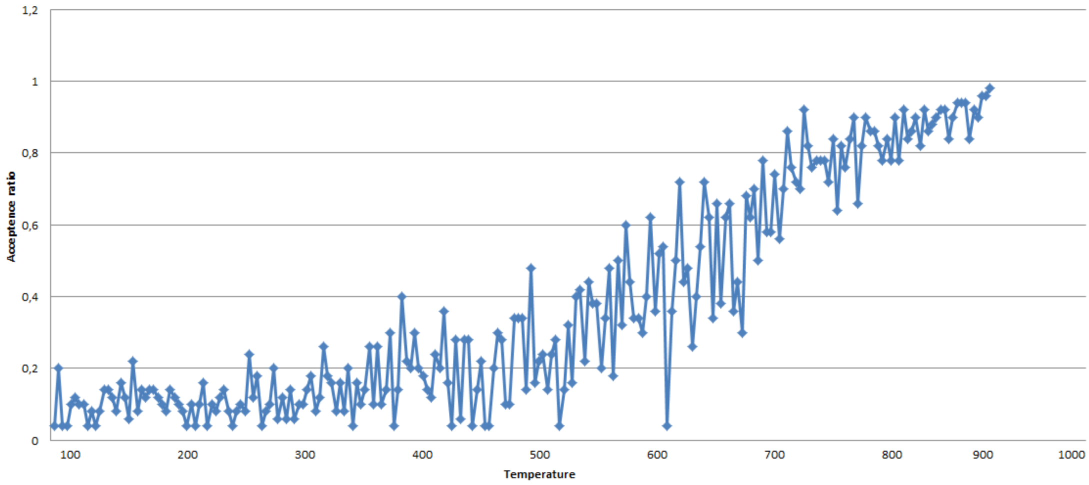

FIGURE A.1: Transition Diagram

Appendix B

Structure of Virtual Network

This appendix explains the structure of the virtual network used in the experiments. The structure of the virtual network is designed such that all neighborhood solutions could be generated (route changes, merging & splitting, head-tail changes, and changing connections). Figure B.1 shows for each neighborhood solution an example on the virtual network. These neighborhood solutions consist of changing the green and the purple line route in the red and the orange line route. The line routes are all intercity line routes.

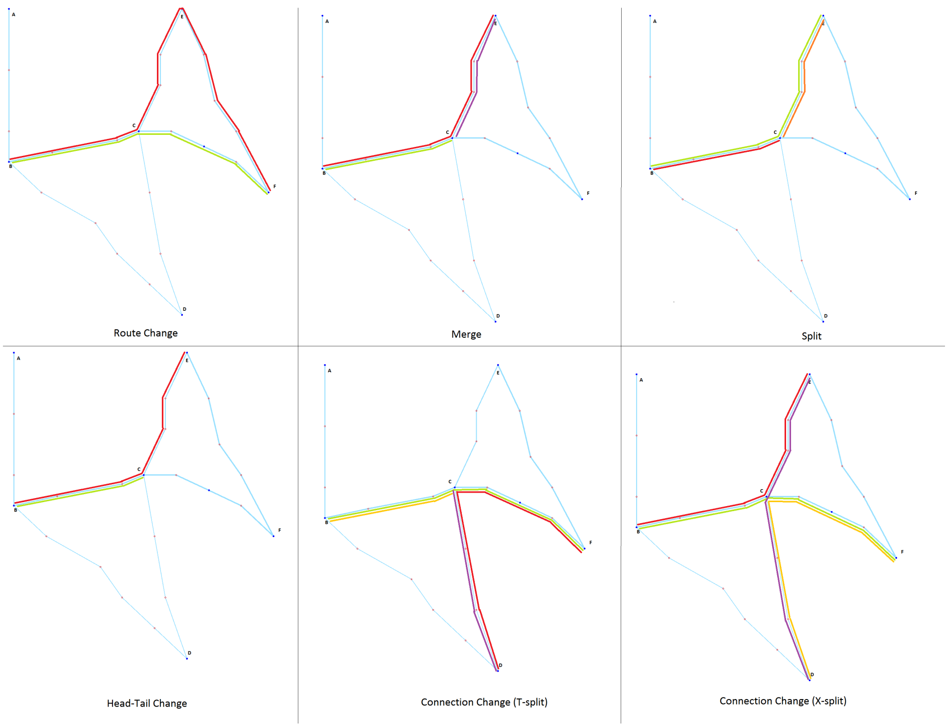

FIGURE B.1: Neighborhood Solutions in Virtual Network

Appendix C

Results of the Experiments

This appendix shows the results of the sensitivity analysis of the experimental design. First we give the results of the comparison of Steepest Descent and Tabu Search and then the results of the comparison of Steepest Descent and Simulated Annealing.

Figure C.1 and Figure C.2 provide the results of the sensitivity analysis of Steepest Descent vs Tabu Search. Figure C.1 shows the improvement percentage of Steepest Descent and Tabu Search under the loose NAP settings and Figure C.2 shows the improvement percentage of Steepest Descent and Tabu Search under the strict NAP settings.

Figure C.3 and Figure C.4 provide the results of the sensitivity analysis of Steepest Descent vs Simulated Annealing. Figure C.3 shows the improvement percentage of Steepest Descent and Simulated Annealing under the loose NAP settings and Figure C.4 shows the improvement percentage of Steepest Descent and Simulated Annealing under the strict NAP settings.

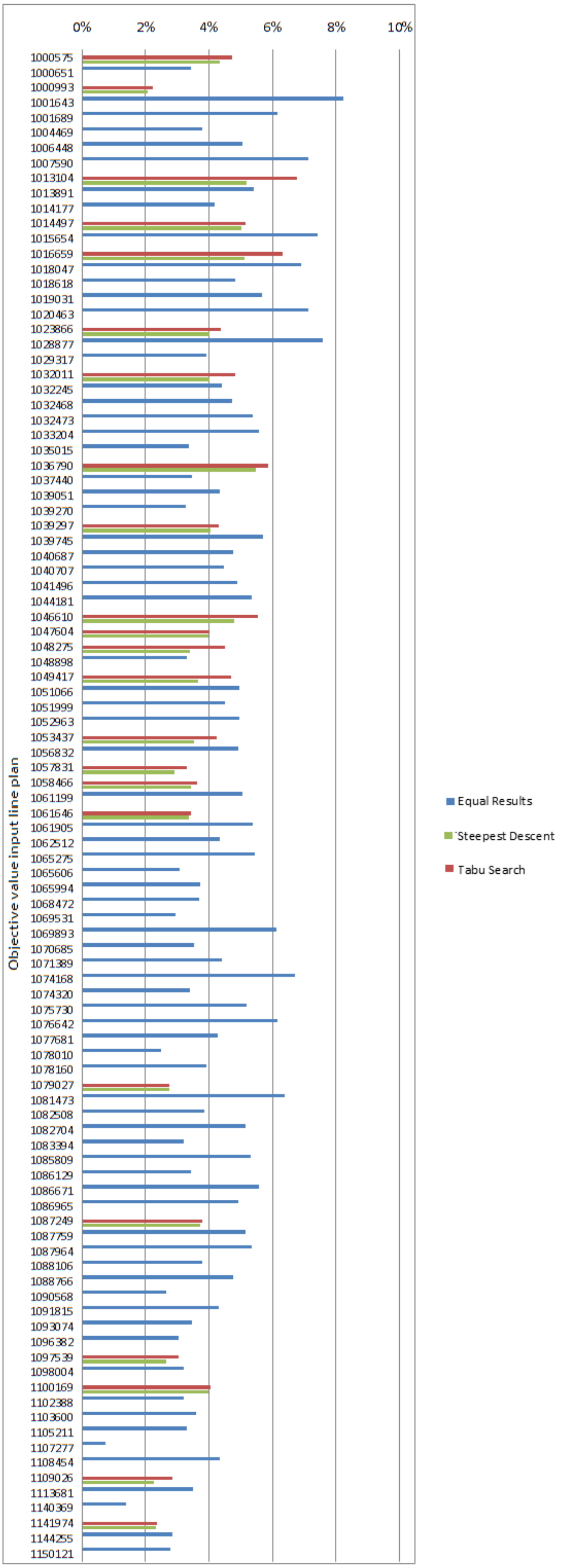

FIGURE C.1: Steepest Descent vs Tabu Search under loose NAP settings

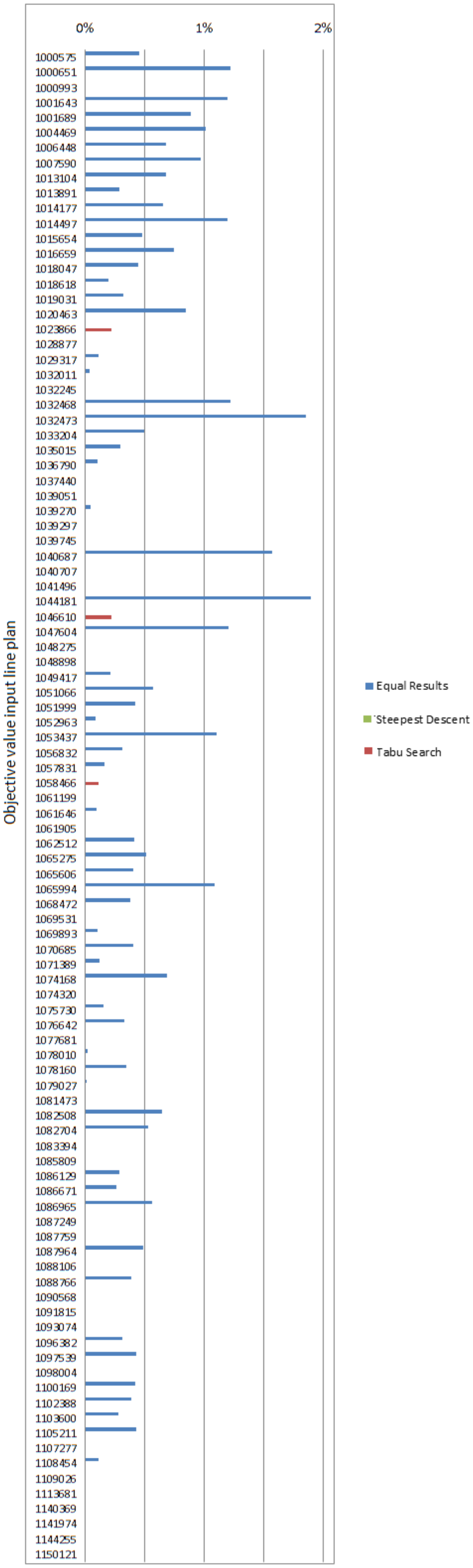

Figure C.2: Steepest Descent vs Tabu Search under strict NAP settings

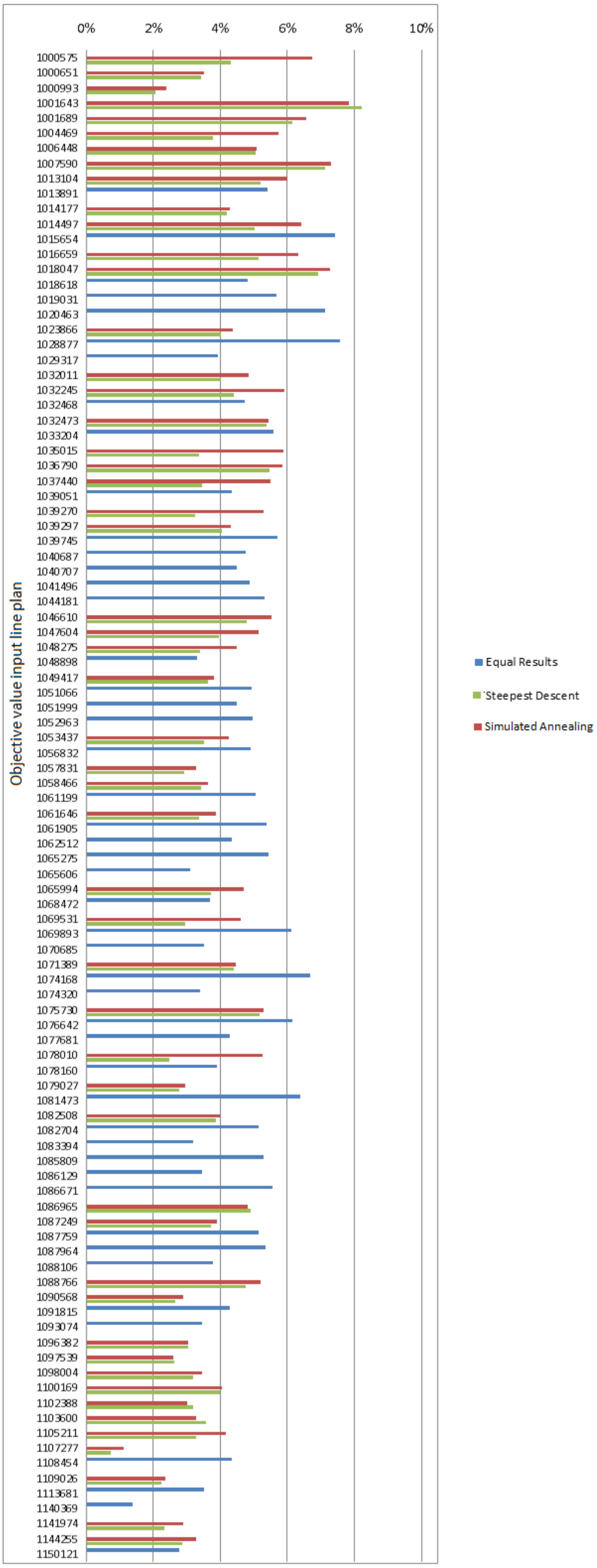

Figure C.3: Steepest Descent vs Simulated Annealing under loose NAP settings

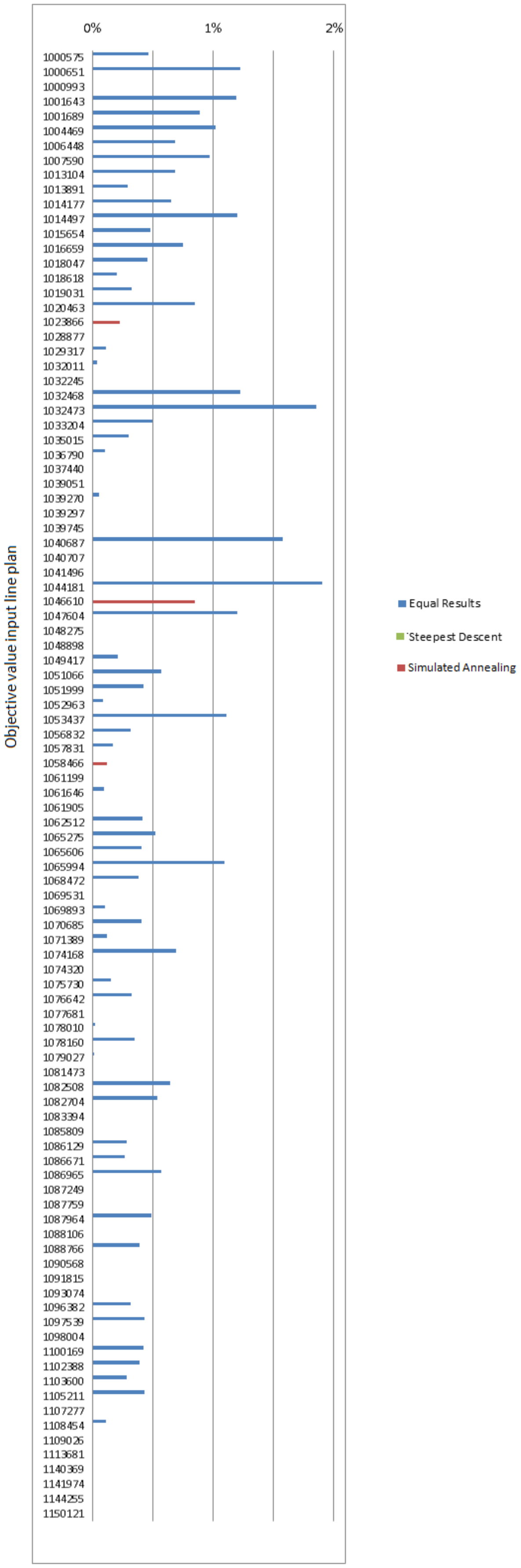

FIGURE C.4: Steepest Descent vs Simulated Annealing under strict NAP settings