Adjusting train routing in case of planned infrastructure maintenance

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MSc Thesis

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Preface

While making a final tour through the Netherlands by train before my student subscription for free public transport expires, one of the last tasks remaining to finish this thesis is writing this preface. I find travelling by train both very relaxing and interesting at the same time, and it is an appropriate finish of this master thesis project while I benefit once more from the privilege of exploring the Dutch railway network one more time for free. I have found working on this project both very rewarding and challenging. It takes a lot of dedication to work on such a large project independently. I very much enjoyed how the model improved along the process, seeing how all parts of it came together in the end, and I look forward to see how it could be put to practice.

I would like to thank the following people who have helped me in several ways completing this master thesis project:

Friends and Family for putting up with all my complaining on inconsistent data, errors in scripts that I wrote and going through large files of data manually. Also they have helped me get my mind off work and relax. Sander van Aken for introducing me to the topic, making the first contact with my daily supervisor and for making me familiar with the model he has developed. Nadjla Ghaemi for playing a big part in providing data regarding all possible itineraries, helping me find reasons for errors in the data and also solving several initial mistakes.

All the members of my thesis committee: Prof. Hoogendoorn for supervising the committee and providing feedback. Dr. Goverde for his very concise and helpful comments, and Prof. Witteveen on interesting new insights I wouldn't have gotten elsewhere. Swen van den Berg for helping me find all relevant data from NS and showing me the planning process within NS. Nikola Bešinović for doing all blocking time calculations, but mostly for his daily supervision, his helpful feedback and comments, both on the content as well as on the process. It would have been impossible to complete the project and I enjoyed working with you very much.

P. Looij
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Executive summary

In the busy railway network of the Netherlands, it is becoming more and more important to create good timetables to accommodate the large and growing demand. Increasing use of infrastructure also leads to more maintenance needed to be performed on the network. Due to multiple possessions of open-track and station sections, a timetable often becomes infeasible to operate. Therefore, an adjusted timetable is needed to satisfy passenger demand as much as possible while also coping with the possessed infrastructure. Currently, the creation and implementation of an alternative hour pattern, and adjusting rolling stock circulation and crew schedules accordingly, takes around 40 planners at the Nederlandse Spoorwegen (NS) a full week. A macroscopic model can be used to solve this problem for the complete Dutch network, but several issues, like possessions inside station areas, platform capacity and feasibility of the timetable on a microscopic level need to be solved. Therefore a route plan must be adjusted for each station area, taking infrastructure possessions into account while also keeping passenger dissatisfaction to a minimum.

In this thesis, a mathematical model is developed to solve the Train Routing Adjustment Problem (TRAP). The aim of the model is to generate feasible and robust train route plans while minimising passenger dissatisfaction for a given list of possessions in the station area, possible alternative train routes, rolling stock types and an original timetable used during periods without possessions. In addition, the model may use an adjusted timetable from a macroscopic model, which already considered large infrastructure possessions in the network, and a list of passenger transfers at the station so the model can ensure walking distances for passengers are feasible for the available transfer time.

We define a train itinerary as a set of consecutive resources (e.g., block section, a switch, or a weld) that are used by a given train. An itinerary with an assigned blocking time stairway that is computed using blocking time theory is called a route. A feasible route plan means that no conflicts exist at track detection section level, and a robust route plan means that the timetable can also withstand small delays and quickly recover from these.

In the preprocessing phase, we apply several procedures to set up the model for solving TRAP. First, all possible itineraries and their blocking times are generated between the entry or exit point of each train and all possible platforms of which at most one can be chosen in the model. Second, all possessed resources (platform, piece of track, switch) cannot be used for running trains, and therefore routes containing these resources are deleted so that only routes are used that contain available infrastructure. Third, rolling stock connections are created for both the defined fixed and free connections. A rolling stock connection is needed for each rolling stock that ends its service at the station. Fixed rolling stock connections imply that it is given as which service an incoming rolling stock will leave the station. These are ensured by starting the platform occupation of the departure immediately after the arrival time of the defined connection. Free rolling stock connections imply that the model is given freedom to find a rolling stock connection accordingly. This means that multiple rolling stock connections are possible, leading to several possible connecting departures for each itinerary of an incoming rolling stock with no connection defined. Fourth, we determine subsets of routes (cliques) that are in conflict, meaning that blocking times of two or more itineraries are overlapping.

The model also allows two types of shunting movements: to/from a shunting yard and directly between two station platforms. Shunting options are created for each arrival-departure pair without a specified rolling stock connection, which lie half of the period (within a given margin) apart. For these pairs a shunting movement is added multiple times, each time with a different departure time. Departing routes for the outgoing train are adjusted accordingly so that they connect to the shunting movements. Finally, in order to enforce more trains to operate, we consider choosing a shorter train formation and allowing a small time shift to train arrivals and departures. Shorter train formations are considered as an option when a platform is not long enough to accommodate the usual rolling stock length. Therefore being able to choose a shorter rolling stock length leads to more platforms to be considered for that train.

In the model, feasibility is maintained by choosing at most one route from each clique. If no conflict-free route exists for a train then such a train is cancelled. Furthermore, because of considering a periodic timetable, a cancellation of an arriving train line in a certain direction leads to the cancellation of a departing of the same train line in the opposite direction. In this way, the hourly pattern is kept balanced, and trains are prevented to end up all at one location. Additional constraints are formulated that ensure a rolling stock arriving at a certain platform or shunting yard also departs from that same platform or shunting yard.

In order to minimize passenger dissatisfaction, an objective function is formulated which consists of minimizing the following penalties: cancelled trains, shorter trains, routes with a time shift, extra shunting movements, missed transfers, different platform as in the original timetable, the largest platform total occupation time, the use of non preferred routes. Weight factors are selected accordingly.

Robustness of a route plan is increased using an iterative heuristic approach. In each iteration, a minimum buffer time is evaluated and increased by adding a blocking time supplement to all routes, and the model for solving TRAP is rerun. This leads to more time available between routes to recover from small disturbances. The heuristic terminates when the objective function has increased more than a chosen threshold value. This approach generates a set of route plans with a different trade-off between efficiency, robustness and passenger satisfaction from which planners could choose the best one to implement in operations.

Furthermore small time shifts of arrivals and departures can be used to prevent train routes from being cancelled. After the model has run for the first time, two groups of routes are selected to apply time shifts both forward and backward in time. The first group consists of all routes of the cancelled trains, and the second group consists of all routes that have a small overlap in blocking time with one or more routes belonging to the cancelled trains. Using routes with a time shift then leads to the elimination of overlap in blocking time between cancelled trains and other trains, and therefore leads to more scheduled trains.

Finally, we propose four feedback measures for improving input to a macroscopic timetable adjustment model on a network level such as new headways between trains, giving information on cancelled trains, applying shorter train formations to (part of) a train line, and suggesting alternative passenger transfer times.

A case study has been performed on station Den Bosch in which several different scenarios are considered. First a route plan is found for the original timetable using the proposed model, then multiple different possessions are imposed on the model and corresponding route plans are found. The results show that feasible route plans are computed for all scenarios, with a limited number of cancelled trains, short computation times of always under four minutes, even in complex cases with many short turning options. Also, a case has been created that is equal to a planned case at NS. This case also results in a feasible route plan that is suitable for operations, while a few differences are spotted between the route plan created by planners at NS. Furthermore it is shown that the time shift module works and can eliminate conflicts when these arise from an adjusted timetable. Robustness of route plans can be significantly increased in a few iterations. Planners at NS are pleased to see that feasible route plans can be generated at this speed and the model has been positively evaluated.

A study is performed to assess which model choice combinations together affect the total number of routes, and therefore the calculation time. The model choices consist of finding unknown rolling stock connections or using predefined connections, applying shunting movements or not, and applying time shifts to all routes or none. Results show that more all three model choices increase the calculation time when applied, but that a combination between unknown rolling stock connections and applying time shifts leads to a very fast increase in computation time. Also timetable size is varied to see how this influences the calculation time, showing that calculation time does increase exponentially.

In conclusion, the proposed model brings a great benefit to planners since it reduces workload and gives possibility to investigate multiple solution options, and therefore to passengers, since they benefit from better adjusted timetables and route plans. Computation times for all case studies are below 3 minutes.

It is recommended to use the presented model for each large station area independently to find accurate, feasible and robust route plans. It is important to keep the total number of routes in the model under control so that calculation times do net get too large, by 1) limiting number of options for connecting rolling stocks, 2) applying shunting movements only when they are expected to be useful, 3) applying time shifts only for small blocking time overlaps when trains are cancelled and 4) possibly eliminating some very unlikely itineraries in large station areas. In addition, cooperation with a macroscopic timetable adjustment model leads to accurate adjusted timetables for a complete network.

Contents

1

Introduction

According to Lidén (2015), 'Railways can offer high capacity and relatively low environmental impact, but require that several technical systems like track, power distribution, safety, telecommunications and trains are tuned and operate well.' In the Netherlands demand for railway transport is growing (Hansen et al., 2012), but infrastructure maintenance is also increasing. especially daytime maintenance are planned to increase over the coming years (I&M, 2016). In a dense network with high frequency services like the Netherlands it is important to consider the planning of both passenger and freight trains during these maintenance activities.

The infrastructure of the Dutch railway network is managed and controlled by ProRail (Dutch railway infrastructure manager). The NS (Nederlandse Spoorwegen) is the railway undertaking that operates passenger trains on the main railway network, while on several other smaller lines a regional undertaking operates trains by means of a tendered process. The network comprises of 2900 km of line length (Van de Velde et al., 2011) and produces over 19 billion passenger kilometres per year (NS, 2016). According to Hansen et al. (2012) it is expected that the demand in passenger kilometres will grow by 20 to 40 % from 2012 until 2020, and also an increase in track maintenance and inspection can be expected. More and longer track possessions used for construction, maintenance, renewal or inspection make it increasingly difficult to provide a fitting transport service. Timetabling becomes more difficult because of the increase of infrastructure works. Narayanaswami and Rangaraj (2015) state that railway planning contains complex interdependencies and that human resolutions are inconsistent, scale inefficient and potentially infeasible. Therefore it is important to improve automatic models which can create or adjust railway timetables.

1.1. Current practice of timetable planning

In the Dutch railway network NS is responsible for designing the timetable in cooperation and under supervision of ProRail. Assuming a yearly timetable is already present with a basic hour pattern, this pattern is used for 18 times on a regular day with adjustments being made for peak hours, irregular international trains, freight paths or empty rolling stock transport. Also it is checked whether the timetable is feasible regarding rolling stock circulation and personnel schedules. Based on infrastructure possessions and possibly differences in demand, an adjusted hour pattern is constructed if the timetable has to be changed for at least several hours of a day. In this adjusted timetable train services are cancelled, rescheduled, rerouted or replaced by a bus service. This adjusted timetable is then again used for the corresponding hours of that day (Planting, 2016). The construction of the yearly timetable starts on a strategic level years before the execution of the timetable starts, and for which new infrastructure is taken into account. Timetable adjustments are planned on average 6 months before execution so this planning is more on a tactical level.

1.2. Infrastructure possession

A possession is defined as the non-availability of part of the rail network for full use by trains during a period reserved for the carrying out of works according to Europe (2014). Examples are the (partial) closure of a station area, and the (partial) closure of open track. Possessions considered in this paper are longer than several hours so it makes sense to design a specific hourly timetable for that instance. The timing of the possessions is decided by ProRail. Possessions of more than 6 hours are calleds GIO's (Grote infrastructuur onttrekkingen). These possessions are used to construct alternative timetables in advance by about 40 planners at NS. They construct adjusted timetables, new rolling stock circulation and different crew schedules (Van Aken et al., 2017a).

A possession means that a piece of infrastructure can not be used for train operations, since maintenance has to be performed. Possessions can be considered for a large number of construction or maintenance activities.(Lidén and Joborn, 2016) describe several categories of railway maintenance: preventive and corrective tasks. Corrective maintenance is used when a fault in the infrastructure is detected. Preventive maintenance is applied when a fault in the structure has not yet been detected. Preventive maintenance can be done condition-based which means the maintenance takes place based on measurements and inspections, or predetermined which uses fixed intervals. Inspections and measurements can be done from a driving train which means the possession time of the infrastructure is equal to one time slot, or from besides the track. In that case the possession time is short in the order of about one hour.

Examples of maintenance tasks of the track are tamping (improving the compactness of ballast by the use of vibration) (Taoyong et al., 2012) , grinding (reprofiling of the railhead), joints repairing or switch replacement. Furthermore maintenance can be done on catenary wire in the form of inspection or replacement. Possessions can be on open track, station platforms, shunting yards or specific switches, and can vary from small inspections to large construction works for several days.

The planning of infrastructure possessions is done by ProRail in cooperation with the engineering companies that execute the construction or maintenance. A model for the planning of infrastructure possessions is described in (Lidén and Joborn, 2017), where it is assumed that possessions are given a certain size time window before a time slot is found to accommodate each time window. Both at the supply side of infrastructure, i.e., the maintenance planning, and the demand side, i.e., the timetabling of passenger trains the procedure could be improved or assisted with the use of mathematical models. In current practice in the Netherlands, the routing through stations is still done manually when the timetable is adjusted due to maintenance activities. A lot of time could be saved by building a microscopic model that adjusts routes in station areas based on the input given from a macroscopic model.

There are several ways to deal with infrastructure possessions and train operations. Cancelling services on a closed track is the easiest way of dealing with the possession in terms of planning, but limits the income of the operator and provides bad service for passengers. Other more passenger friendly approaches are to partially cancel services e.g., half the frequency of express and/or local trains, replacing a train service with bus transport, reroute the service over a different railway line or reroute the service over a different station track, depending on the size and complexity of the possession. When services are partially cancelled, rerouting in the station area is often necessary as well to provide short turning possibilities at the corresponding station. This thesis focuses on the last mentioned approach on dealing with infrastructure possessions: adjusting the routing of trains during possessions at a railway station.

1.3. Previous work on timetable adjustment during maintenance

The thesis is part of Project AUP (Alternatieve Uur Patronen) of the NS. In this project the objective is to find a more efficient and concise way of rescheduling timetables in case of planned maintenance by means of automation. A project regarding rescheduling has already been done giving promising results. This thesis is meant to be complementary to the previous project.

First it is important to describe the difference between the already made macroscopic model, and the presented microscopic routing model. The macroscopic model describes stations as nodes, and tracks by linking arcs and is useful to generate a timetable for the entire network. A representation of a macroscopic and microscopic network model can be seen in Figure 1.1. A microscopic model works on a more detailed scale, and includes speed limits, gradients, curves and signalling system (Bešinović et al., 2016) A microscopic model computes blocking time occupation using blocking time theory. This theory describes that blocking time of one train consists of the time it takes to ride through the occupied block plus the reserved block in front of it plus the train length added by several fixed values like sight and reaction time, setup time and release time. A description of the blocking time calculation can be seen in Figure 3.6. This model can therefore accurately calculate running and headway times which leads to a more accurate conflict detection.

Recently work has been concentrated on the macroscopic model as described in (Van Aken et al., 2017a). This model cancels, short turns and delays trains as little as possible during possessed track sections and closed platforms, and was called the Train Timetabling Adjustment Problem (TTAP). However the model does not take headway times and routes through stations fully into account, and only considers the number of platforms available instead of knowing which platforms are available. In a macroscopic timetable a

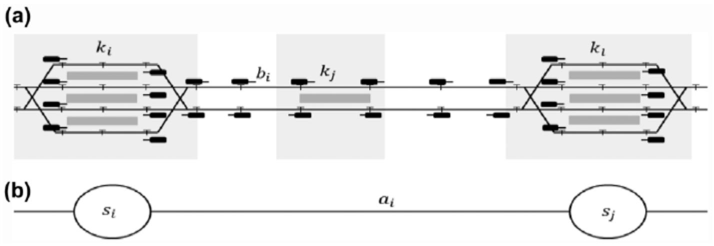

Figure 1.1: Representation of a microscopic network (a) and macroscopic network (b). (Bešinović et al., 2013).

fixed headway time is assumed, while a new route choice can influence the headway time. This leads to unreliable results because the new headway time is not considered in the TTAP, and no conflict free train path is guaranteed on microscopic level. Therefore a more accurate microscopic model is needed to change the routes in station areas, called the Train Routing Adjustment Problem (TRAP). A station area can be defined as all tracks, switches, signals and platforms in and around the stations. The station areas are marked in grey in Figure 1.1 in the microscopic network.

In order to adjust routes compared to the original timetable and check feasibility, a new route plan is created that is as much similar to the used route plan. A route plan is the set of routes used by trains to drive through the station area. Because the model adjust routes it is called the Train Routing Adjustment Problem model, or TRAP model.

1.4. Problem statement

Timetable adjustments on microscopic level during planned maintenance are now done manually, leading to inconsistent and suboptimal solutions.

1.4.1. Research objective

The main goal of this research is to develop a routing model that can adjust the alternative hour pattern on a microscopic level in the case of planned infrastructure possessions in a station area to shorten the lead time of the planning process and to make it conflict-free and efficient. Shortening the process can also lead to deciding to create AUPs as well for smaller possessions, since doing manual adjustments to the regular timetable can be omitted.

1.4.2. Research questions

The main research question is formulated as follows: *How to adjust route plans in station areas that provide the least changes in the original timetable and minimize the passenger dissatisfaction?* Furthermore there are several sub questions that are to be answered in order to fulfil the research objective:

- How can a mathematical microscopic model help to adjust the railway timetable during scheduled maintenance?
- What practical constraints are to be developed in order to make the model applicable to real life instances?
- How to set the cooperation between macroscopic timetabling and microscopic routing?

1.4.3. Scientific and social relevance

Only a little research has been done on microscopic timetabling, and no research exists on adjustment problems on microscopic level. Therefore there is scientific relevance. Both NS and passengers can benefit from this research. The process of adjusting an hourly timetable at NS can be made much shorter and more accurate and several different options can therefore be evaluated. Passengers can get a better service with less cancelled trains and more convenient transfers.

1.5. Scope of the study

The model presented in this thesis is to be applied to station areas. Conflict free and efficient routes through station areas are designed in this model, meaning that no train will run into a red signal, and the best route is chosen according to a set of objectives. Later when this microscopic model is coupled to the macroscopic model an overall conflict free adjusted timetable can be generated. For this thesis, the macroscopic model is only used as an input in the microscopic model. The TRAP model takes the list of events from the adjusted timetable found in the macroscopic model and tries to find a route for each train according to an objective function and several constraints. Besides only routing trains from an adjusted timetable, the microscopic model can also be used to route trains when maintenance activities are planned in the station area. These possessions can be of (a set of) smaller track section somewhere in the station, several platform tracks, switches or fixed switches.

Furthermore freight trains can easily be implemented in the model. However, in the case study these are not taken into account since the timetable gave multiple overlapping events for the same freight path. Process times used for events taking place at the station, like minimum dwelling times, minimum turn around times and transfer times are used from NS and ProRail. Splitting and combining multiple rolling stock units at the station is not taken into account, but it is expected that this extension does not cause any new issues when implemented.

Multiple objectives are taken into account when designing the model. These are number of scheduled trains, train length, passenger transfers, using the same platform as in the original timetable and choosing fast and preferred routes. Rolling stock couplings at turn around stations are found when necessary. Furthermore shunting movements between two platforms or shunting movements to/from a shunting yard are added by the model if needed. A iterative heuristic is formulated to retime trains to prevent cancellations and to increase robustness by optimising the minimum buffer time.

In the project AUP, there is a suggested framework in which the microscopic model uses input from the macroscopic model after which an optimisation process is performed. The outcome of this optimisation is then uses as input in the macroscopic model, until the iterations have converged to a feasible solution. Other suggested processes are an interaction module with a planner, using a database with previous timetables, working with alternatives of the timetable and using the model to plan maintenance possessions. This is not a part of this thesis. We focus on creating the microscopic model, and to give suggestions on how the feedback loop to the macroscopic model could work.

1.6. Thesis outline

The rest of the thesis consists of a literature review in Chapter 2 in which routing, timetable adjustment problems and bi-level railway scheduling are elaborated on. Chapter 3 describes the basic model for adjusting a route plan and gives definitions, an overview of the pre-processing where constraints are created and an explanation of the objective function, and Chapter 4 explains several extensions included in the model to overcome practical issues and increase the quality of the route plan. Chapter 5 describes several case studies made with the introduced model, and Chapter 6 elaborates on how this routing model can fit into a framework together with a macroscopic timetable adjustment model. Finally, Chapter 7 gives a conclusion by answering the research questions, suggestions for future work to extend and improve the model and recommendations to implement the model in practice.

2

Literature review

In this chapter a review is made on several topics related to the posed research questions in the previous chapter. First an overview of routing models for timetabling is given since the proposed model produces a route plan as an output, then a summary of recent work in train timetable adjustment problems is given since an original timetable is already given from which adjustments need to be minimized, and finally several papers on bi-level scheduling of train timetables is summarized because this routing model should be able to feedback information to the macroscopic TTAP model.

2.1. Routing

Routing problems can occur on three different planning levels, as described in Velasquez et al. (2005): Strategic, tactical or operational. The strategic problem covers planning problems of years ahead, usually concerning demand or infrastructure changes, the tactical planning level covers the generation of feasible route plans, and the operational planning level covers the real time solving of disturbances in the generated timetable. According to Lidén (2015) more than half of all research papers regarding train routing problems describe tactical level problems.

Over the years several approaches have been used to create routing models for railway timetabling. One way of modelling conflicts between routes is to model every route of each train as a node, and insert an arc between routes that conflict. This is called a conflict graph and can be solved using a node packing approach (Zwaneveld et al. 1996). In this independent set problem the goal is to find the largest set of nodes without having two chosen nodes linked together. In Zwaneveld et al. (2001) the model is extended to include shunting movements and platform and route preferences using a weighted node packing problem. However, only the decision to shunt is taken into account. The actual shunting movement is not implemented in the timetable. This may lead to decisions to shunt while it is not possible due to other conflicting trains. Using three hierarchical objectives (maximizing number of planned trains, minimizing shunting movements, minimizing number of switches) a route plan is constructed. With the use of a condition rule, detour routes are cancelled out of the route possibilities so that straight routes dominate the route plan. This is done with a node dominance algorithm. The model and algorithm have been implemented in the decision support system of the STATIONS module of the timetable planner at NS. In this thesis all shunting movements are also be explicitly modelled to ensure this shunting movement can be executed.

The disadvantage of the node packing model is that the graph gets very big when either the network or density of trains gets large and then is very hard to solve. Another disadvantage is that it is not clear where exactly in the infrastructure network the conflicts arises because there is only information visible by means of an arc whether or not there is a conflict (Fuchsberger and Lüthi, 2007). Both issues can be solved by introducing a resource tree conflict graph , or RTCG (Caimi et al., 2011a) This graph is constructed for each train separately in the following manner: The starting point is a double vertex graph, or colon graph that contains the topological network. In this graph every node is duplicated so that according to the rule that every path in the graph should follow the "node-node-link-node-node-link" relation only feasible paths are found. To build the RTCG we start from scratch by adding a node on which the route starts (i.e. the incoming portal). After that the path is followed in the double vertex graph to the next node that is then added to the RTCG. If a possibility arises to choose two directions while still being able to reach the assigned destination, two edges from the previous constructed node in the RTCG lead to each one new node corresponding to the two direction possibilities. If a node is just passed in the network topology, then it is also added to the RTCG. This leads to a tree for each train that has to be modelled, with each leaf of the tree representing a different routing possibility. An example of the RTCG of two trains can be seen in Figure 2.1.

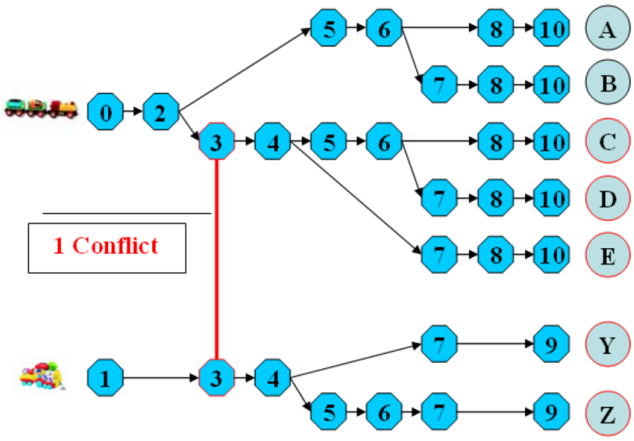

Figure 2.1: An example of a resource constraint conflict graph for two trains (Fuchsberger and Lüthi, 2007).

Each Letter corresponds to a different routing possibility in the network for each train. Now conflicts can be added to the RTCG by adding undirected arcs at the point where the routes conflict. An example of one modelled conflict can be seen in figure 2.1 where a conflict is present at node 3 because both trains use this node. This model is solved as a space-time integer multi-commodity flow. The model can be extended to incorporate time shifts in the timetabling process by duplicating the RTCG for each train with a different starting time. Later (Caimi et al., 2011b) extended the model of Fuchsberger, so that it is also applicable for multiple event times per route, and that the model optimizes for robustness by extending each blocking time by the highest value possible.

The advantage of such a model is that it is very clear at which point in the route the conflict arises, and that the number of conflicts are reduced because of the way routes are merged together at the beginning. This is also a downside since this means that the blocking times at these merged points should be equal for all routes following from that point. In the paper this was possible because the entry time in the station area for a train was given. However in the Netherlands it is important to have fixed arrival and departure times at the platforms instead of at the entry points at the station. Another disadvantage is that no small time shifts can be applied to the routes since this also does not comply to the principle of equal blocking times following a node in the model. In the model that is presented the arrival and departure times are given at the platforms. This means that the passing times at the entry of the station areas can vary, depending on the length and speed restrictions of the route that is chosen. Therefore it is chosen to use the node packing approach since it is easier to incorporate available data and has more flexibility to handle running time differences.

(Caimi et al., 2005) introduces two algorithms to find the routing of trains through a station for a given timetable. The first heuristic algorithm finds a feasible solution using an independent set approach comparable to Lusby et al. (2011), and the second algorithm increases the time slot of a chosen route using a local search optimization so that the timetable becomes more delay-tolerant. The computation time for the delay-tolerant is a lot more time consuming since the problem has a higher complexity, but the delay tolerance can be improved considerably. A set packing model is also presented by Velasquez et al. (2005) for the TRP in three planning phases. The solution is derived using column generation and constraint branching. The solution can also deal with delayed trains and make it therefore useful for operational planning.

Sels et al. (2016) propose an automated platforming and routing of trains in that has been implemented in the tool of the Belgian railway infrastructure manager. They describe the four main planning stages as lineplanning, timetabling, rolling stock assignment and crew scheduling. A fictive platform is used for trains that turned out to be infeasible. This makes a report on which trains to cancel very easy. The method was also used by Caprara et al. (2011). The tool is called Leopard, and also shows when there is little time between two planned dependent routes. The model itself is explained in Sels et al. (2014), this paper describes the application and use of the model in Belgium.

Samà et al. (2017) describe a Train Routing Selection Problem that creates a subset of all available routes to solve the a real time railway traffic management problem in a faster way. When the timetable is comparable to the original timetable, selecting a subset of routes could lead to faster results of equal quality as when considering all routes. When a lot of short turning is applied, other routes that are often not used in the original timetable can be used as well, making this approach less suitable.

Burggraeve and Vansteenwegen (2017) present an integrated routing and timetabling model to increase robustness in complex station areas. This is done by first finding an optimal route plan for each train that minimizes shared infrastructure with other trains, i.e., as much equal spreading of all trains over the available infrastructure. Then a timetable is computed that maximizes the minimum buffer time at each infrastructure point. Finding a route plan first is only possible when rolling stock connections are given beforehand. The TRAP model finds optimal rolling stock connections to minimize platform usage and passenger discomfort, or uses predefined rolling stock connections if desired.

2.2. Train timetable adjustment problems

The most often used methodology to reschedule is (mixed) integer linear programming, although different approaches like artificial neural networks (Dündar and Şahin, 2013) are also considered. Albrecht et al. (2013) describe a model that reschedules a single track rail network with multiple passing points at the same time as the given maintenance windows. This is done by using problem space search metaheuristic. This heuristic searches through multiple decisions in different orders by delaying random trains. For a periodic schedule as in the Netherlands this might not be applicable. The optimisation uses the objective of minimizing the total delay or minimizing the maximum train delay. However other passenger indicators like transfer time and waiting time, which is an important factor in the Dutch periodic timetable, are not taken into account in this model due to many single tracks in the network, and no alternative ways to arrive at a destination.

Van Aken et al. (2017b) adjust the timetable for the complete Dutch network using network aggregation and the model described in Van Aken et al. (2017a). Differences between results from the model and planning at NS are described extensively in Van Aken (2016). They suggest a framework in which the macroscopic and microscopic models, the planner and historic data cooperate to get the desired results. Suggestions and shortcomings in this macroscopic model are taken into account with the building of the microscopic model, since most differences between the models results and the planners' lie within the need for a microscopic model. The other differences occur because of the possibility of 'flexible short turning', which means that not all trains line services on the same open track also short turn on the same station but because of limited station capacity it is decided to short turn a station earlier. In the report it is suggested to: insert rolling stock couplings, create flexible short turning possibilities per line service, cancelling one or more stops of a line service if these stations cannot be reached due to a possession and to change routing in the case of partial open track closures or platform closures to calculate more accurate headway times. In the TRAP model rolling stock connections are created when needed, and routings are adjusted when short turning must be applied due to open track closures. Furthermore it is possible to cancel stops of smaller stations in a larger station area when multiple stations are present.

Vansteenwegen et al. (2016) describe a model that reroutes, retimes and if necessary cancels trains in a station area and double track. Because of that given order of changes in the timetable and the feedback coming from a robustness calculation and weighted travel time, the passenger discomfort is minimized. However the model does not take fixed block signal systems into account. The model is evaluated using a simulation and comparing methods where the allowed changes in retiming are varied. Only trains are retimed that have a conflict with the scheduled maintenance possession, and therefore ignoring arised conflicts that can occur due to short turning.

Instead of having infrastructure possessions as a given input of the scheduling problem, Lidén and Joborn (2017) describe a model in which trains and open track maintenance possessions are scheduled simultaneously for a small network in Sweden. The difference with the Dutch case is that the considered timetable is a-periodical and that the number of trains on each track is much lower so that there is already more time available to retime trains. For a less dense timetable in the night that is used in the Netherlands such a model could prove to provide better rail services by scheduling night time possessions and trains at the same time.

Brucker et al. (2002) describe a model that computes a timetable for a double track corridor on which partially only a single track is available due to maintenance possessions. Trains are delayed such that as many trains as possible can still run using the single track using a single machine job scheduling formulation. Both cancellation and delay are minimized, but no effects with respect to the larger network or transfers are taken into account. This model is mainly useful when one specific bottleneck originates due to maintenance possessions. In the TRAP model, multiple routes are available making a single machine formulation unusable.

2.3. Bi- level timetabling

Research has been done on macroscopic and microscopic timetabling, where the focus is mainly on the macroscopic level. For example (Lidén, 2015) states that several aspects of the railway system complicate the maintenance and operation, e.g., exclusive activities, interdependency between infrastructure and trains, and safety, and all sub-systems should function properly in order to provide a decent service. (Lidén and Joborn, 2017) describe an optimization model for integrated planning of railway traffic and network maintenance. Railway traffic is modelled at a macroscopic level, and networks are not heavily used and demand a non-periodic timetable as in Sweden. The working of bi-level timetabling is explained in Caimi et al. (2011b), and describes the use of flexible PESP (periodic event scheduling problem) for so-called compensation zones (links between stations), and a microscopic model for first only condensation zones (station areas) and after that also in the compensation zones.

Bešinović et al. (2016) describe a two level approach to design a timetable. A clear distinction is made between the microscopic and macroscopic level, and both levels are used for different purposes. First running times are computed on a microscopic level and these are converted to minimum headway times which are used to compute the macroscopic timetable. This timetable is then again checked on a microscopic level on feasibility and capacity norms. If at least one of the evaluations is not positive, the headways are adjusted so the macroscopic timetable can be calculated again. This can either be by increasing headway times because of a conflict, or running times can be made more similar between different types of trains. This loop continues until a feasible and stable timetable has been found. Furthermore, the macroscopic timetable is also adjusted by an integrated delay propagation model using Monte Carlo simulations to improve the delay recovery.

Bešinović et al. (2017) describe an automated railway traffic planning methodology based on microscopic models. With the use of network transformations it is possible to switch consistently between micro and macroscopic networks. The microscopic model is used to compute running times and headways and assess the timetable feasibility and stability for both each train separately as in the entire network. In order for both network levels to cooperate, an algorithm is introduced to convert a macroscopic network into microscopic.

Goverde et al. (2016) propose a three-level frame work to construct a timetable. This is an extension on the proposed two-level framework in which energy efficiency is taken into account. Using a mesoscopic model the buffer times on an open track can be optimised such that energy efficient driving can be applied as much as possible. However this extra level is only applied when the first two used levels have provided a feasible and stable timetable.

Caimi et al. (2011b) develop a bi level approach for scheduling trains using a micro and macro approach and condensation and compensation zones. In the compensation zones (or station areas) a routing model in the form of a RTCG is used to model the routes and conflicts, while the compensation zones (or open track) is modelled using a PESP formulation. This set up is similar to the way this thesis fits into an already existing macroscopic model for solving TTAP because it also uses PESP formulation.

Dewilde et al. (2013) describe an approach that increases the total buffer time between trains by adjusting routes, platforms, event times and order of trains. This maximizes the spread of trains in time and space, which is beneficial for the robustness of the timetable. Also here, rolling stock connections are assumed to be fixed.

2.4. Conclusion

No literature exists on creating route adjusted route plans in case of maintenance possessions. This thesis defines a mixed integer programming model for solving TRAP that minimizes passenger dissatisfaction and keeps the adjusted route plan as similar as possible to the original route plan. Rolling stock connections can be either predefined, or found by the model. Furthermore this thesis contributes by presenting 3 extensions in order to make the model suitable for real life applications. In particular, it includes 1) a method to use shunting movements where necessary and to model them explicitly in the route plan, 2) using both sides of a divided platform by the same train, 3) scheduling shorter trains where necessary. Next to this, 2 extensions are presented that are part of a heuristic to increase the quality of the route plan. These consist of 1) imposing small time shifts to the scheduled arrival or departure times in order to eliminate conflicts and 2) increasing the robustness of the route plan.

3

Model description

This document describes how a microscopic routing model for a station area could work. The main approach is to define all possible routes, and then by applying constraints the most optimal set of routes is chosen according to a multi-objective function. First it is necessary to define some terms and variables, then the inputs of the model are described, followed by a description of the pre-processing, show how the TRAP is solved using the objective function. The chapter is concluded with the outputs of the model.

3.1. Definitions

First several definitions should be given of inputs, outputs and variables of the model. A list of variables and parameters that are used and elaborated on below and in Chapter 4, can be found in Table 3.1.

Symbol	Meaning
z	Train z
Z	Set of trains
Z_i	Set of incoming trains
Z_o	Set of outgoing trains
Z_α	Set of trains moving in (chosen) direction α
Z_β	Set of trains moving in (chosen) direction β
Z_n	Set of trains from the same series n
w_z	Type of train service: (INT, IC, SP, CG, IC direct) of train z
n_z	Series or line number of train z
h	Platform h
H	Set of platforms h
T	Period length of the timetable
$t_{z,\text{dep}}$	Departure time of train z
$t_{z,\text{arr}}$	Arrival time of train z
j_z	Route j of train z
J_z	Set of all routes of train z
S_z	Set of all shunting routes of train z
q_z	Dummy route used for cancellation of train z
Q	Set of all dummy routes
J_i	Set of all incoming routes
J_o	Set of all outgoing routes
J_h	Set of all routes that use platform h
J_w	Set of all routes using the same train type w
J_n	Set of all routes of the same series or line number n
J_l	Set of all routes that use a train l carriages shorter than specified
J_y	Set of all routes that use a different platform than specified in the original timetable
J_t	Set of all routes that are shifted in time by time t

List of symbols continued on next page

Symbol	Meaning
J_g	Set of all routes that use shunting track g
$J_{z\mathrm{s}}$	Set of all shunting routes of train z
$J_{s'}$	Set of all routes that have a begin time at the platform resource at arrival time of shunting route s
$J_{z'}$	Set of all routes that have a begin time at the platform resource at arrival time of train z
J_c	Set of all routes from a conflict clique
x_{zj}	Binary variable whether route j is used by train z
$x_{z\mathrm{q}}$	Binary variable whether dummy route q is used by train z
$x_{z\mathrm{s}}$	Binary variable whether shunting route s is used by train z
C_r	Family of conflict cliques of resource r
R	Set of resources
r	Resource
g	Shunting track g
G	Set of all shunting tracks g
bt_{rjz}	Blocking time of resource r by route j of train z
s_{rjz}	Start time of the blocking time of resource r by route j of train z
e_{rjz}	End time of the blocking time of resource r by route j of train z
f	Transfer constraint
F	Set of all transfer constraints
Δt_j	Size of time shift of route j
t_{max}	Size of the largest absolute time shift
t_θ	Granularity of the time shift
$t_{\theta\mathrm{s}}$	Granularity of the time a shunting route is applied
t_{smax}	Size of the latest possible time a shunting route starts after its preceding arrival
ϕ_{q}	Weight to penalize a cancelled train
ϕ_{l}	Weight to increase the penalty for a shorter train length
ϕ_{s}	Weight to penalize the use of a shunting route
ϕ_{f}	Weight to increase penalty for a missed transfer
ϕ_{t}	Weight to penalize choosing a route with a time shift
ϕ_{y}	Weight to penalize choosing a different platform as in the original timetable
ϕ_{d}	Weight to increase the penalty for choosing less preferred routes
ϕ_{e}	Weight to increase the penalty for choosing slower routes
ϕ_μ	Weight to increase the penalty to minimize the maximum platform occupation
π_f	Number of passengers that use transfer f
$\pi_{\mathrm{l}j}$	Difference in rolling stock length of route j of train between original timetable and route plan
$\pi_{\mathrm{e}zj}$	Penalty for choosing a slower route j of train z in seconds
$\pi_{\mathrm{d}j}$	Penalty for choosing a non preferred route j formulated as a rank
b_{jk}	Auxiliary variable to model transfer constraints from route j to route k
c_z	Rolling stock type of train z
L_z	Rolling stock length of train z in the original timetable
l_z	Rolling stock length of train z

A station area is defined as all tracks, switches, signals and platforms in and around the stations. The station areas are marked in grey in Figure 1.1 in the microscopic network. They are bounded by the entry and exit points that describe the entrance or leaving of a train to/from the station area. These points are located at a signals so that blocking time calculations can be made. Furthermore shunting areas are also modelled, but as one platform with a maximum capacity in terms of train length under the assumption that for hourly operations a shunting track is only used for one train at the same time.

We denote the set of trains by Z and typically denote a train by $z \in Z$. Each train contains the following information: Train type w_z (intercity, sprinter, international, ICdirect, freight, shunting), rolling stock type c_z (VIRM, ICM, DDAR, IRM, SGMm, SLT, DM90, ICR, DDZ) and length L_z (longest length of most often driven rolling stock type for that train in the original timetable), entry or exit track and preferred platform h. Trains that are arriving at the station are in the subset of Z_{i}, and departing trains are in the subset of Z_{o}. A train in the model is therefore always either arriving or departing, but it is possible to connect trains using rolling stock connections. These are used to couple arrivals and departures of through trains, and can also be used in the same manner for trains that end their service at the station. If no rolling stock connection is defined for a train, the model finds a connecting train. A rolling stock connection couples one arriving train and one departing train. Furthermore each train also has a direction. This direction does not mean the destination of a train, but purely from which side of the station the train is coming or going. Trains running in one direction are in the set Z_α, and trains running in the opposite direction are in the set Z_β. Because a periodic timetable is used, each train belongs to a certain line number or series n_z. This is a collection of trains with the same timetable points. Usually in the Dutch railway system, each series has a fixed frequency. The set of trains using the same line number is denoted as Z_n.

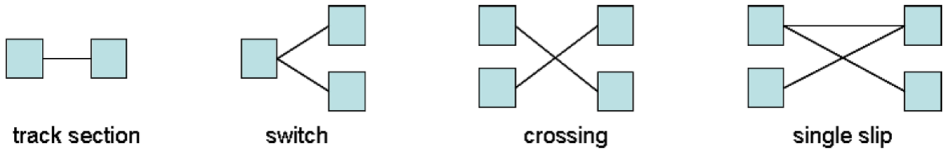

Figure 3.1: Resources that often occur in a station area (Fuchsberger and Lüthi, 2007).

A resource represents a subset of infrastructure elements that can be exclusively allocated to a single train at the given time (Fuchsberger and Lüthi, 2007). In practice, this is a track section, platform or an interlocking section such as switch, crossing, single or double slip. Track sections are divided by the block sections of the safety system. The set of resources is denoted by R, with a typical element $r \in R$. An itinerary of train z defines a set of consecutive resources that can be used by a train to traverse from an entry to a platform track in the station area or the other way around. When blocking times are added to the itinerary we call this a route. Different routes for a train could therefore implicate a different itinerary as well as slightly different blocking times. The set of routes of train z is denoted $J_z \subseteq J$. The starting and ending points of routes are an incoming point or outgoing point at the edge of the station area and an origin or destination point at a station track $h \in H$ for a train z. We define the set of all possible routes for a train z as J_z. Furthermore, the set of all train routes over all trains is denoted as J. Each train route uses resources for a limited time that can be computed using the blocking time theory (Hansen and Pachl, 2014).

A route plan consists of defined routes from the set of all possible routes for all scheduled trains including inbound and outbound routes and selected platforms within a station. A distinction can be made between the initial route plan, which is the route plan used in the regular timetable, and the alternative route plan, which is the route plan that is the output of the described model. The decision variable whether a single train route j of a train z is used in the route plan is denoted as x_{zj}, which is a binary variable equal to 1 if the route j of a train z is chosen. Timetables can be periodic and non-periodic. In a periodic timetable the same pattern of train operations is repeated every period T (Hansen and Pachl, 2014), while in a non-periodic timetable there is no repeated pattern for a continuing period. Note that in our approach it is not fundamental that the timetable is cyclic. However, the timetables in the Netherlands are planned as such, so we assume throughout this thesis that all route plans are also cyclic with a period T of one hour.

The process of parking rolling stock on a shunting area, together with several related processes such as routing rolling stock between the station area and the shunting area or between two platform in the same station area, short term maintenance, and inside and outside cleaning, is called shunting (Caprara et al., 2007). Shunting movements are necessary to start, end or keep operations going by removing rolling stock from a platform after an arrival, or moving it to the platform before a departure. Shunting movements to start operations are usually from a shunting yard to a platform, to start regular service, and shunting movements to end operations are usually from a platform track to a shunting yard because the regular service has ended. Because this model is used for periodic timetables, only shunting movements are considered that are applied every hour. These shunting movements are used to remove rolling stock from a platform track so that another train can arrive. Also we only consider adding shunting movements that are needed to short turn trains, and do not consider movements needed for cleaning or maintenance.

Shunting routes can be created by the model to make short turning possible where needed. When a train z is needed to be shunted away its route is denoted as s_z. Because shunting routes are consisting of a route away from the platform to a shunting track and then back to a platform, the shunting routes are divided in outgoing routes $s_z \in J_o$ and incoming shunting routes $s_z \in J_i$.

A timetable is defined as the listing of all event times for either arrival, departure or pass through, at certain timetabling points in the network including the used itineraries. In a macroscopic timetable these points are important infrastructure points in the network, e.g., stations, junctions, bridges or crossings in the network. In a microscopic timetable the pass through time at each signal, or the event time at a platform is to be calculated. Furthermore there is a difference between the original timetable, that is used in operation when no possessions are scheduled, and the adjusted timetable, that is modelled in this thesis on a microscopic level based on the already provided adjusted timetable on a macroscopic level.

3.2. Input of the model

In this part we describe needed inputs in order to set up the model for solving TRAP. The data can be divided into several categories: infrastructure, possessions, rolling stock data, alternative routes. These four data types are used to calculate blocking times. Furthermore, one or more timetables and a list of transfers is needed.

3.2.1. Infrastructure

First, detailed infrastructure data is needed where speed limit, gradient and curvature are given together with track length, platforms, switches and signals. This data is needed to calculate the running and blocking times of trains and after the optimization the data is used to visualize the output. Additionally, data is needed on shunting yards in order to ensure enough track length is available for new shunting movements. This data should consist of the length of train vehicles that are possible to be shunted to the yard described in either metres or carriages. Finally, the alternative routes for the station area should be available.

Furthermore, the border points of the station area should be defined. These are the entry and exit signals of the trains , and the starting or ending resources for each route. Trains have a certain speed at these points according to the blocking time calculation.

3.2.2. Possessions

The possession of resources is modelled as a use of the resources that are part of the possessed infrastructure. This means that for each possession in the station area the corresponding resource must be known, together with the time this resource is unavailable for operations. Every route containing that resource cannot be used and can be deleted from the set of possible routes. In this way time is saved when building constraints for the model because no infrastructure constraints can be generated for these routes since they have already been deleted. In conclusion, the list of possessed resources is used to delete possible routes so that an updated list of actual possible routes is generated.

Examples of these possessions are shown in Figure 3.2. On the far left a straight track is shown as possessed by highlighting it red. Next to that a platform track is possessed and a switch is not possible to be used. On the far right an open track possession is shown by possessing the borders of the station area. Any combination between possessions in the station area is possible to be modelled.

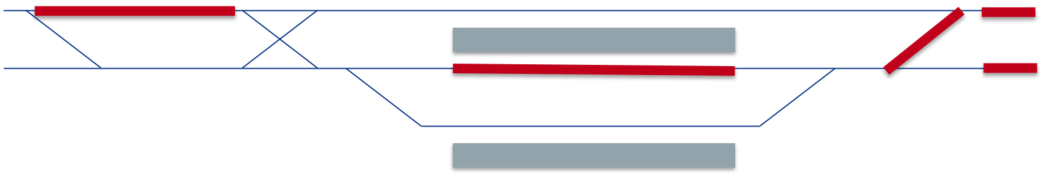

Figure 3.2: Example of possession types that are considered by the TRAP model. From left to right the figure shows a possession of a straight track, a platform possession, a possessed switch and an open track closure.

Besides having the possibility of one or more resources to be unavailable for operations due to maintenance or construction, it is also possible that a switch is fixed due to maintenance on the interlocking system or because other safety reasons at the station area. A fixed switch means that the switch does not give a choice in direction anymore, but is fixed in either the right or left position. This means that certain routes are not possible any more because they use the switch in the other position than the specified fixed position.

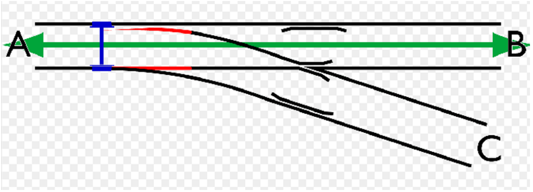

Figure 3.3: A switch fixed into the position of track A to B (or vice versa).

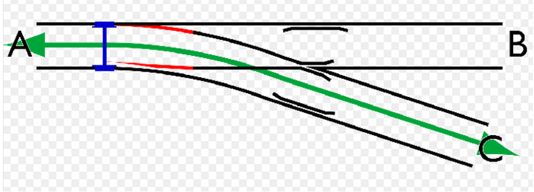

Figure 3.4: A switch fixed into the position of track A to C (or vice versa).

In order to be able to give a clear explanation on how to model fixed switches, it is important to describe how the switches are modelled in the infrastructure. A switch is modelled as the connection between three resources: one piece of straight track connected to two other resources. Unlike when one or more resources are possessed, a fixed switch means that all pieces of infrastructure are still available to use. However when a switch is fixed, it is not possible to use two of the three resources subsequently, since the fixing of the switch makes this combination impossible. Figure 3.3 shows a schematic image of a switch that is fixed to be only used from track A to B (or vice versa), and Figure 3.4 shows a schematic image of a switch that is fixed to be only used from track A to C (or vice versa). Therefore to model a fixed switch, the two resources are listed that are not possible to use subsequently due to the fixed switch. When all routes are listed, the model searches for routes using these two resources subsequently and deletes those routes. The order of the two considered resources is not important, since routes from both directions are not possible while the switch is fixed, as long as the two resources are listed consecutively. All routes are checked in the pre-processing, and deleted when the switch is used in the unavailable position.

In the model every possession is modelled for the entire period length T because of the periodic character of the timetable. It is possible to apply a possession of one or more resources for a certain part of period length T. This can be used in the case when an adjusted timetable is only needed for one period. The model can also be used in the case when a possession is longer than period length T, but does not start or end simultaneously with the beginning of the period. Then a transition hour can be made in which the possession is used for part of the period, after which the model is run again with the possession applied for the entire period.

3.2.3. Alternative routes

For each platform entry/exit track, a set of itineraries has to be listed. This list consists of all possible itineraries between the defined entry or exit track and all accessible platforms in the form of a list of the used resources. Also the preference of each itinerary should be given in the form of a ranking for every platform/entry track combination. Each route consists of the physical infrastructure a train uses combined with the blocking times at the infrastructure of the train. The different blocking times at the same itinerary is therefore defined as a different route in this thesis. Blocking times for all possible routes are calculated according to the description below.

3.2.4. Rolling stock

Rolling stock data is needed to compute blocking times. For each used rolling stock type in the timetable, data on the tractive effort should be available so that using the method described in the next subsection running times, and together with that, blocking times can be computed. The tractive effort consists of a linear and one or more hyperbolic parts as a function of the speed. This function depends on the rolling stock type and train length. The resistance of the train is modelled using a second order polynomial of speed. Difference between the tractive effort and the resistance force is the surplus tractive effort that can be used for acceleration as can be seen in Figure 3.5.

Besides data on the traction, it is also important to know the length of each rolling stock type, so that the model can check whether a platform is long enough to accommodate the train.

3.2.5. Blocking time calculation

Because of the microscopic way that trains are modelled to run through stations, it is important to know on a detailed level how each train run through the network and how the safety system responds to this. First, the running time is the time required to run over a given stretch of track, usually a block section based on the used speed profile and the rolling stock characteristics (braking and acceleration). The running times are

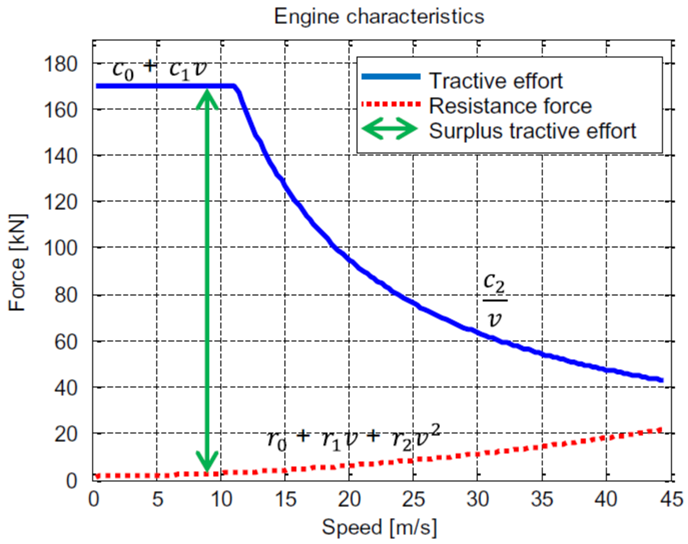

Figure 3.5: Tractive effort and resistance given as a function of the driving speed. The green arrow indicates the surplus of tractive effort that can be used for acceleration (Bešinović et al., 2013).

calculated based on Bešinović et al. (2017) using the dynamic Newtons motion equations. The procedure is to start by calculating the minimum running times, followed by inserting running time supplements. This can either be done by lowering the maximum operational speed or based on energy efficient train driving. In this thesis is chosen to use a lower maximum operational speed because this approach has a smaller computation time while still producing realistic running times.

The computation starts based on the microscopic infrastructure data, rolling stock type and length, the route, initial speed and end speed. When a train enters the station area it is assumed to have a certain initial speed. At platforms the speed is 0 if a stop is scheduled. The algorithm used assumes four driving behaviour phases: acceleration, cruising (keeping a fixed speed), coasting (turn of tractive power and let the vehicle roll out) and braking. Braking is initialised when a yellow aspect approach signal is passed until the desired speed has been reached. The operational running time is calculated by implementing running time supplements based on the given macroscopic timetable. The time supplements can be used by operating on a lower cruising speed or by applying coasting. A percentage of the maximum speed is used in order to decrease the minimum running time to the operational running time. In this thesis no coasting is applied for the calculation of the blocking times.

The blocking time of a resource is the time during which the resource is solely dedicated to a single train and cannot be used by any other. The main goal of using large enough blocking times is to prevent a train driver from approaching a yellow signal due to a train conflict. We denote bt_{rjz} as the blocking time of resource r in route j_z, this is defined with its starting and ending time, $bt_{rjz} = (s_{rjz}, e_{rjz})$. These blocking times are used later on for the conflict detection.

In the case of a three aspect signalling system, blocking time consists of a setup time to adjust signals and switches, sight and reaction time of a driver, approach, running and clearing time, corresponding to a train running from the approach signal to the block signal, traversing the block itself, and running out of the block until the train has completely left the block over its entire train length, and the release time. In formula this can be written as follows:

$$e_{rjz} - s_{rjz} = t_{\text{setup}} + t_{\text{sight}} + t_{\text{reaction}} + t_{\text{approach}} + t_{\text{block}} + t_{\text{clear}} + t_{\text{release}}. \tag{3.1}$$

A description of the blocking time calculation can be seen in Figure 3.6. For this purpose we use the timetabling models developed in Bešinović et al. (2017).

3.2.6. Timetable

Timetables are needed for two purposes: first as an input for the route plan, so the list of trains that is scheduled in the station. This timetable is called the input timetable in the rest of this thesis. Second, a timetable is needed to compare the adjusted route plan with, and to try to keep it as similar as possible. This timetable is

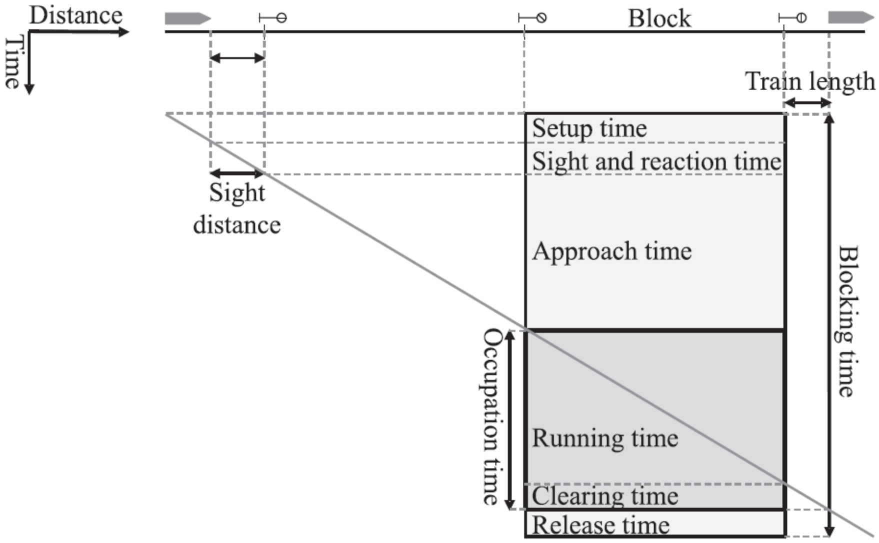

Figure 3.6: Blocking time calculation consisting of setup, sight and reaction, approach, running, clearing and release time (Goverde et al., 2016).

called the original timetable. Both needed timetables can be the same regular timetable that is used during a basic hour pattern when no infrastructure possessions occur, but the timetable used as input for the route plan can also be the output of a macroscopic model so that possibly other large possessions in the network are already taken into account.

A timetable should contain the entry track or exit track, event time, arriving and departing platform and train type and length for each train. Rolling stock characteristics are needed to calculate running and blocking times of the trains based on the rolling stock type and length stated in the timetable.

It must be noted that trains passing through the station have their activities also split up into an arrival and departure route. This means that while trains stopping at the station have a speed of zero at their arrival and departure, trains passing through the station have a speed higher than zero at their arrival and departure. Therefore through trains use two routes: an incoming and outgoing route, and starting/ending trains only use one of these two.

3.2.7. Transfers

A list of transfers is to be used to ensure that relevant transfers are still possible after platform assignment. A transfer is defined as a connection for passengers from an arriving train to another departing train at the station. The list of transfers therefore consists of an arriving train, a departing train, time between these trains and number of passengers that use this connection for each hour. This list of transfers should be based on the timetable adjustments made in the macroscopic timetable adjustment instead of the original timetable since the adjustments can cause transfers to be irrelevant. This happens for instance when connecting trains are cancelled due to an open track closure. Furthermore a list is available with minimum transfer times in case arrival and/or departure times of the trains have been adjusted. Checking with this list ensures that transfers are feasible for passengers.

3.3. Decision variables

For each train listed in the input timetable, the possible set of routes is listed. Using the timetable the calculated blocking times can be shifted accordingly so that the event time listed in the timetable corresponds with either the arrival or departure time of the blocking time. The created list of routes is based on the edge of the station area for each train z from the input timetable and the routing possibilities. A check is made whether the length of the platform of a route is sufficient for the train length specified in the original timetable. This results in a list of all possible routes for all trains from the input timetable. Each route is a decision variable x_{zj}, indicating whether route j of train z is used in the route plan or not.

Also, for each train a dummy route is created that simulates the cancellation of a train. This dummy route has no resources listed, and therefore cancelled trains never conflict with other trains. This method is similar to Sels et al. (2016), although they use a dummy platform. Because this model is a route allocation model, it makes more sense to use a dummy route. This approach gives a clear view which trains cannot be scheduled since they are now aligned at the same dummy route. The decision variable indicating a cancellation is called x_{zq}, indicating whether dummy route q of train z is used in the route plan or not.

3.4. Constraints

Before the optimization model runs, several constraints need to be defined. This section describes the constraints for cancellation, rolling stock constraints, conflict detection and constraints for conflicting routes.

3.4.1. Cancellation

For each train, we want exactly one route to be chosen, or to be cancelled, i.e., the dummy route to be chosen. This can be formulated in the equation below:

$$\sum_{j \in J_z} x_{zj} + x_{zq} = 1, \quad \forall z \in Z, \tag{3.2}$$

where J_z are all possible routes of train z, x_{zj} the decision variable for all routes j of train z, and x_{zq} is the dummy variable of train z.

Furthermore it is important in a periodic timetable to ensure that the number of ingoing trains in one direction is equal to the number of outgoing trains in the opposite direction. This is ensured by stating that a cancellation of an inbound train from a certain direction results in a cancellation of an outbound train in the same direction. Both of these trains have to be part of the same line number. Two equations result from this, since the direction for in and outgoing trains can change:

$$\sum_{z \in Z_\text{i} \cap Z_n \cap Z_\alpha} x_{zq} - \sum_{z \in Z_\text{o} \cap Z_n \cap Z_\beta} x_{zq} = 0, \tag{3.3}$$

$$\sum_{z \in Z_\text{i} \cap Z_n \cap Z_\beta} x_{zq} - \sum_{z \in Z_\text{o} \cap Z_n \cap Z_\alpha} x_{zq} = 0, \tag{3.4}$$

in which $Z_\text{i} \cap Z_n \cap Z_\alpha$ in Equation (3.3) is the set of all inbound trains of a certain series n in the direction α, and $Z_\text{o} \cap Z_n \cap Z_\beta$ is the set of all outbound trains from that same series in the direction β. In Equation (3.4) sets indicating the direction of the trains have been switched, in order to define the same balancing of trains arriving and departing on the other side of the station.

3.4.2. Rolling stock connections

In the macroscopic model described in the introduction, several tactics are used to reschedule trains: Retiming, short turning and (partial) cancellation. Short turning trains means that a train ends its service at a station because it cannot drive further to its destination according to the original timetable, and then starts a new service from there. Besides short turning, it is also possible that a train ends its service at the station in the original timetable. In that case it is specified in a list of rolling stock connections what the next train service is of the rolling stock that arrived at the station in the periodic timetable. In the model changes to this list are allowed since it gives a lot more opportunities to short turn and to influence the platform occupation. Especially in the case when the platform capacity is close to the needed capacity or when trains have been retimed by a macroscopic model, changes in the rolling stock circulation can result in less cancellations.

Every incoming route at the station needs to be connected to an outgoing route by using a rolling stock connection. This is necessary so that a different incoming and outgoing route for the same through train (with a possible stop at the station) can be chosen. This means that incoming and outgoing routes of through trains also need to be connected by a defined rolling stock connection. The coupling is necessary in order to prevent that more and more trains end up in the station, and that an incoming route does not arrive at a certain platform, while its outgoing route departs from a different platform. Rolling stock connections for each train can thus be considered given, or unknown, so that a rolling stock connection is found by the model. Below is described how incoming and outgoing routes are connected to each other so that choosing a certain route directly means choosing a certain rolling stock connection.

It has to be ensured the platform is occupied from the arriving time of the incoming train until the departure time of the same rolling stock. This is necessary to accurately model the occupation of platforms.

For through trains that have a predefined connection between the arriving and departing routes this is simple to achieve: all departing routes begin occupying the resource of the platform track from the moment the arriving train has arrived which is at $t_{z,\text{arr}}$. For trains with an unknown rolling stock connection it is more complicated, because there are more possibilities to connect these routes together. Since the platform occupation has to be modelled explicitly to check for infrastructure constraints, all outgoing routes are duplicated by the same number of possible incoming routes, in which the occupation of the platform track of the departing train begins at the arrival time of the incoming train to which it is connected. The method for this is shown in Algorithm 1. This algorithm connects all outgoing routes with an unknown rolling stock connection to all incoming trains with an unknown rolling stock connection. This means that the same outgoing route for a train is multiplied by the number of incoming trains without a rolling stock connection. The only difference between these outgoing routes is the begin time of the platform occupation, since this begin time depends on the arrival time of the incoming train that the outgoing train connects to. This begin time is equal to the arrival time of the incoming train plus one second, so that no overlap in blocking times occur but the trains do connect directly. When a model is used with a smaller granularity than one second, this smaller value must be added to the arrival time.

Algorithm 1 Creating outgoing trains

```
Input: List of incoming and outgoing routes for each train
Output: List of all possible routes with correct platform occupation between each arrival and departure
for all incoming routes of trains $z$ without a defined rolling stock connection do
    for all outgoing routes of trains $a$ without a defined rolling stock connection do
        if Platform of route $j_z$= platform of route $j_a$ then
            Copy route of outgoing train $a$ to $a'$
            Add constraint to connect the routes of trains $z$ and $a$
            $s_{rja} = t_{z,\text{arr}} + 1$
        end if
    end for
end for
```

An example of this procedure is shown in Figure 3.7. In two figures of a fictive example showing the same platform, three trains are departing: trains A, B and C, and two trains are arriving: trains Y and Z. On the left side it is shown with arrows at what time the blocking time of the platform track resource of the outgoing route must begin if the outgoing trains are connected to incoming train Z. On the right side it is shown time the blocking time of the platform track resource of the outgoing route must begin if the outgoing trains are connected to incoming train Y. This means that for example routes A_z and A_y are exactly the same using the same resources and the same blocking times, except for the blocking time at the platform resource. Now in the rolling stock connection, it has to be ensured that for arriving route Z one outgoing route (a_z, b_z or c_z) must be chosen. For incoming route Y one outgoing route (a_y, b_y or c_y) must be chosen. Of course, as previously defined in the basic model, only one route of each train A, B, C, Y and Z can be chosen. Furthermore it is possible the incoming trains have more than one route option available to the same platform. This does however not influence the outgoing routes because the arrival time of all these incoming routes is the same. Outgoing trains A, B and C can also have multiple route options. This means that all of these route options must be duplicated in order to change the platform resource begin time to the desired value.

Mathematically, rolling stock connections can be summarized as follows:

$$\sum_{j\in J_z\cap J_\text{i}\cap J_h\cap J_w} x_{zj} - \sum_{k\in J_y\cap J_\text{o}\cap J_h\cap J_w\cap J_{z'}} x_{yk} = 0, \quad \forall h\in H, \forall z, y\in Z, \tag{3.5}$$

and therefore taking into account that each connecting train departs from the same platform h and is of the same train type w. Furthermore the departing route must be connected to the arrival time of the incoming train z which is stated by $j \in \cap J_{z'}$. This set of routes contains all departing routes that start the blocking time of the first resource directly after the arrival time of the arriving train z.

This means, as stated in Equation (3.5), that all arriving routes from a certain train z, at a certain platform h must be equal to the sum of all departing routes at the same platform, with the platform occupation linked to the arrival time of train z. This is needed to ensure that the platform is occupied the entire time a train is dwelling. When rolling stock connections are fixed, this means only connections between predefined line

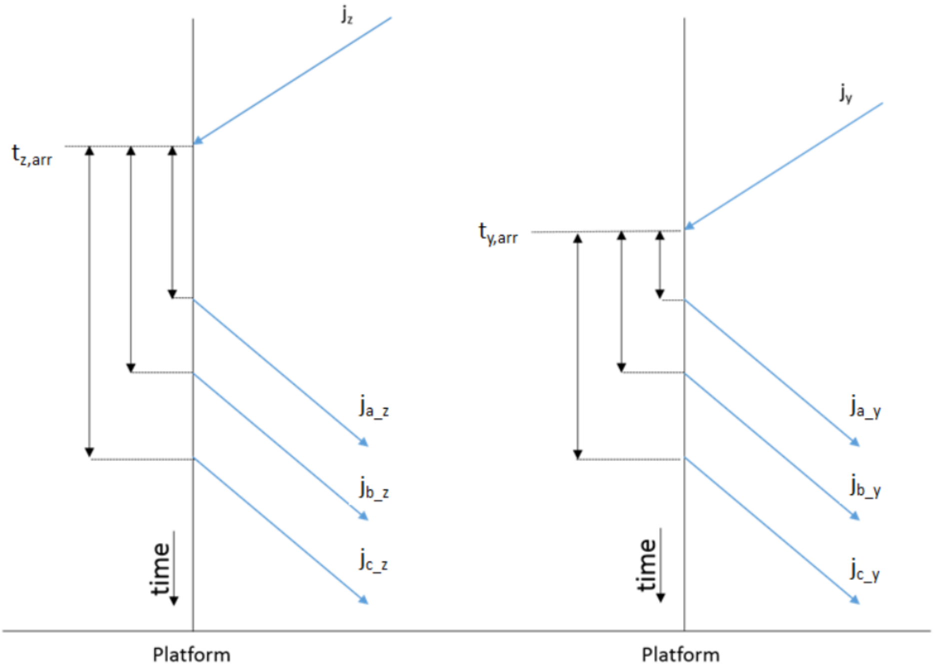

Figure 3.7: Visualisation of rolling stock connections. On the right side outgoing routes A,B and C connect to incoming train Z, and on the left side routes A,B and C connect to incoming train Y.

numbers are made. This leads to only routes from the same line number in the equation. When rolling stock connections are considered flexible, routes from multiple line numbers are in the same equation, meaning that a rolling stock can arrive at the station for a certain line service, and depart the station (in the same or opposite direction) as another line service.

Through services, either with or without stop are always defined as fixed connection. When short turning must be applied because one side of the station is closed, all connections are chosen to be free so that rolling stock connections for short turning can be found. Note that both regimes can be used next to each other: Fixed connections for through trains, and flexible connections for trains ending its service or short turning trains. Defining whether these connections are fixed or free is now done manually by planners and can influence results greatly, but in later work this could be automated.

3.4.3. Conflict detection

In the timetable a conflict only has to be modelled if the resource is being used by more than one train at the same time. Therefore a time component is introduced. With the running times and the blocking times for every route as an input, calculated as previously described, it is possible to check for each resource whether routes overlap.

In Figure 3.8 the blocking times of one resource are shown for all possible routes of a fictive example. Each horizontal line indicates the blocking time of a route, so of two horizontal lines overlap in time, they conflict.

Since a resource can only accommodate one train at a single time, none of these routes can overlap in a feasible route plan. Therefore a conflict is generated for every two routes that have an overlapping blocking time at a resource. To reduce the preprocessing time of the model, the conflicts are modelled as cliques: a group of routes from which a maximum of one can be chosen at the same time because all routes have an overlap with each other at a certain time. An example of conflict cliques can be seen in Figure 3.9. This constraint imposes that from all conflicting routes only one of them can be chosen:

$$\sum_{(z,j)\in J_c} x_{zj} \leq 1, \quad \forall J_c \in C_r, \quad \forall r \in R. \tag{3.6}$$

Equation (3.6) states that the sum of all routes in one conflict clique of resource r cannot be larger than 1, in which J_c denotes the set of train routes in one conflict clique, and C_r the family of conflict cliques at one resource.

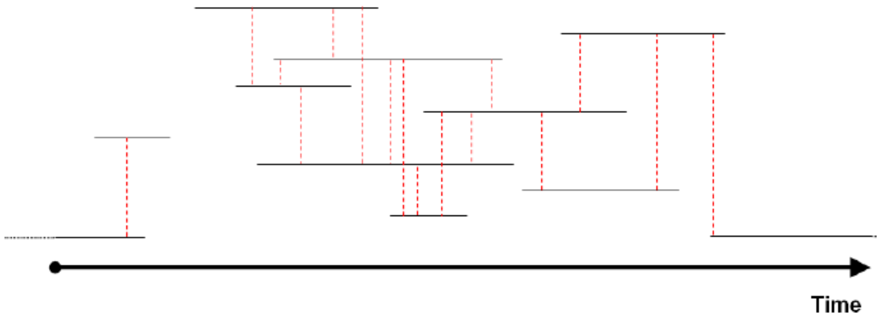

Figure 3.8: Blocking times of a certain resource given as a function of time including all conflict pairs in red dotted lines (Fuchsberger and Lüthi, 2007).

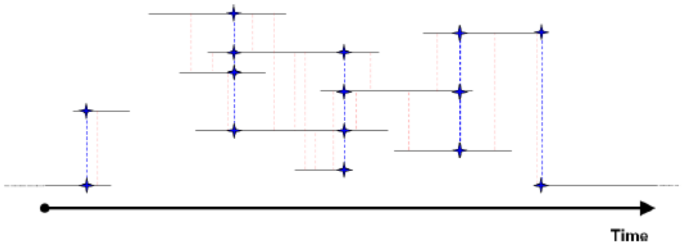

Figure 3.9: Blocking times of a certain resource given as a function of time including all conflict cliques in blue dotted lines (Fuchsberger and Lüthi, 2007).

Algorithm 2 describes the procedure for creating conflict cliques. This approach is suitable for a periodic timetable since it takes situations into account where the blocking time of a resource starts just before the end of a period but ends just after the beginning of the period. This is done by adding an extra starting time at 0 for routes that have a starting time later than the end time. In a non-periodic timetable this part of the construction of the list of routes in resource R could be omitted. List L contains times that can be either begin or end times of all routes that use a certain resource R, sorted from lowest to highest time. Shortlist M is used to compare the investigated subset of routes with the already present conflict cliques. The algorithm is very similar to Caimi et al. (2011a), although they also eliminate certain cliques so that only *maximum cliques* are left.

Table 3.2 shows how the data in list L is structured for each resource. Every route has at least two entries: one for the start time of the blocking time, and the second for the end time of the blocking time. If the start time is larger than the end time, a third entry is added to the list with begin time 0. The table lists the route name, the time, and whether it is a begin and end time. The route name consists of the series name, followed by the platform it arrives to or departs from, followed by its route preference and whether it is an arriving or departing route. Departure routes for which a rolling stock connection has not been given as an input also

Table 3.2: Fictive example of (part of) list L with all starting and ending times of all routes at one resource. This example shows that the routes of train 13600 and 4400 overlap because the blocking time of train 4400 begins before that of 13600 ends

Routename	Time	Begin/end
13600_4A_-1_A	760	Begin
4400_3A_1_V_9600_3A_-1	850	Begin
3601_6B_2_A	853	Begin
13600_4A_-1_A	870	End
3601_6B_2_A	900	End
4400_3A_1_V_9600_3A_-1	990	End

Algorithm 2 Creating conflict cliques

```
Input: List $L$ of starting and ending times of the blocking times sorted from low to high at resource $R$
Output: List of conflict cliques of routes that overlap in blocking time at resource $R$
for all Time and corresponding route listed in list $L$ do
    if Time is starting time then
        Add route to shortlist $M$
    else if Time is end time then
        if All routes from shortlist $M$ are in an earlier formed clique at resource $R$ then
            Delete route from shortlist $M$
        else
            Add current shortlist $M$ to cliques
            Delete route from shortlist $M$
        end if
    end if
end for
```

contain the preceding arriving route to which it connects in the name. This can be seen for train 4400 in Table 3.2.

Together with this example list of blocking times, a conflict clique can be made. First the three routes are added to shortlist M, because the first three entries are starting times. The fourth entry is an end time. Since the tree routes in the shortlist are not all in one of the formed cliques, because no conflict clique has yet been formed, the three routes form a conflict clique. Then route "13600_4A_-1_A" is deleted from shortlist M. The fifth entry of list L is also an end time. Now the two routes in shortlist M are both part of the already formed conflict clique, so no new clique is formed and route "3601_6B_2_A" is deleted from shortlist M. The same goes for the last entry of the blocking time list. This method has proven to create conflicts in a fast way for all resources with many blocking time overlaps.

3.5. Objective function

When a solution the Equations (3.2), (3.3), (3.4), (3.7)and (3.6) is found, a feasible routing plan is found for the adjusted timetable because no conflicts exist between the routes and different trains. However, in the case of multiple possible solutions it could be possible to find the best routing plan based on an objective function. This function and how these items are modelled are illustrated in this section. Although large possessions cause passenger discomfort in terms of either delayed or cancelled trains or longer transfer times, the goal is to minimize the discomfort as much as possible. This can be done by routing as many trains as possible that are scheduled by the macroscopic timetable, keeping as many as possible transfers in the schedule and implementing preferred routes to avoid longer than necessary travel times and avoiding lateral acceleration as much as possible by using preferred routes, i.e., not more switches than necessary. Furthermore the model considers optimal train short turnings when rolling stock connections are considered free. The importance of each objective is given in the following order with the first being the most important and the last being the least important: number of scheduled trains, transfers, train length, time shifts, platform assignment, platform occupation and preferred routes. More details about weight values of these objectives can be found in Chapter 5.

Penalties are introduced for each objective that is not fulfilled (completely) for each train here below. The value of the penalty is based on the given importance of the objective. The total objective is to minimize the sum of all the penalties in the station area. Each term is respectively elaborated on here below.

3.5.1. Number of trains

The most important objective is to route all trains that are scheduled in the macroscopic adjusted timetable. The penalty for a train using the dummy route should for that reason be the highest of all other penalties because running a train is considered more preferable over other objectives. Whenever the dummy route is used, the penalty is applied. In ILP formulation this looks like this:

$$\min \sum_{z \in Z} x_{zq} \cdot \phi_q, \quad \forall z, \tag{3.7}$$

where q is the dummy route node, z the relevant train, and x_{zq} stands for the binary variable of choosing route q of train z. This constraint should be checked for all trains from Z. Weight ϕ_q is a fixed value and imposed when route x_{zq} is chosen.

3.5.2. Transfers

A transfer is a passenger connection at a station from one train to another. This means that the arrival of a certain train z_{i} must be within a certain time and platform range of the departure of train z_{o}. In other words, passengers must have enough time to transfer from one train to another given a certain platform distance. When more station tracks are needed to cross to get from one train to another, more transfer time is needed. In the Netherlands these transfer times are specified for passengers depending on the distance between the station tracks (ProRail, 2016). Since this model (hardly) changes the arrival and departure times of trains, it is only possible to achieve feasible transfers by assigning platforms. The time component should be considered by a macroscopic model, so that all transfers in the network can be ensured at the same time.

In the original timetable a list of transfers is given. This list consists of an arriving train and a departing train, both with their corresponding event times and platform numbers. If due to any reason a platform has to be changed in the routing plan because for example one or more platforms at a station are closed, the distance between the two platforms cannot be larger than a certain value based on the transfer time. To model this without considering the walking routes of passengers at stations we only look at platform distance in terms of track number. This numbering can be different than the regular numbering used because of the given set of rules, but this is not a necessity.

In the preprocessing phase all arrival departure combinations are found that have insufficient time available to cover the walking distance according to the given set of rules for all given transfers. Other possibilities are to generate constraints in the preprocessing phase that find arrival departure combinations that simply have a larger difference in platform tracks than in the original timetable i.e., the walking distance for passengers can not become larger.

It is chosen to build flexible constraints between all platform combinations that are further from each other than the original transfer by imposing a penalty that is minimized in the objective function. Therefore a penalty is imposed when two routes are chosen by the model that result in a missed transfer. This penalty is a function of the number of people missing that transfer, meaning that the penalty for a missed transfer is equal to the number of passengers using that transfer multiplied by a weight factor. The objective function regarding transfers is:

$$\min \sum_{f=(j,k)\in F} x_{zj} \cdot x_{yk} \cdot \pi_f \cdot \phi_f, \tag{3.8}$$

for every given transfer constraint f. This transfer constraint lists a pair of routes that has a too large platform distance to satisfy the available transfer time. In other words: for each transfer between two trains, all route pairs belonging to those trains are found that use a platform too far apart from each other given their transfer time. The complete list of all these pairs is defined as F. Parameter ϕ_f describes how many passengers miss their transfer when the distance between two platforms is too large, and π_f is a weight factor to adjust the priority compared to other objectives in the model. In this way for each transfer a penalty is imposed if both the arrival of one train and the departure of another train are not within the accepted distance. Because this objective function is not linear, it is rewritten in the following form using an auxiliary continuous variable b_{jk} similar to Vansteenwegen et al. (2016):

$$\min \sum_{f=(j,k)\in F} b_{jk}, \tag{3.9}$$

$$s.t. (x_{zj} + x_{yk} - 1) \cdot \pi_f \cdot \phi_f \leq b_{jk} \text{ where } x_{zj} \text{ has a transfer conflict with } x_{yk}, j \neq k, z \neq y, \tag{3.10}$$

$$b_{jk} \geq 0, \tag{3.11}$$

for every given transfer f. A conflict in this case indicates that the distance between the two platforms used in the routes is too large given the available transfer time. This means that the list of transfers should be available before the optimisation so that the constraints can be generated from this in the pre-processing. In this model it is chosen to use the flexible constraints, since the frequency of trains in the Dutch network is high, and multiple transfers are often given for each station. However for some more rural stations it could be good to apply fixed constraints to ensure a transfer for passengers.

3.5.3. Platform assignment

The model gives the possibility to assign platforms when choosing routes. This choice should be made based on certain factors mentioned above like conflicts with other trains, transfers, and platform occupation. Besides these objectives, passenger comfort can be increased by trying to schedule trains as much as possible at the same platforms as in the original timetable so that passengers do not experience any nuisance and can use the platform they are used to. The model approach therefore is to allow all possible platforms, but to penalize all platforms for a train that are different from the one specified in the original timetable. This is a fixed value for every platform other than the specified one in the original timetable, because the main goal of this penalty is to prevent passengers as much as possible to have to check which platform to go to. Hence it does not matter whether the platform has changed a little i.e., only one or two tracks, or a lot i.e., many tracks a way. Therefore the objective function is formulated as follows:

$$\min \sum_{z \in Z} \sum_{j \in J_{\mathrm{y}} \cap J_z} x_{zj} \cdot \phi_{\mathrm{y}}, \tag{3.12}$$

for all j that are in the subset $J_{\mathrm{y}} \cap J_z$ of routes that do not use the original platform specified for that train. The weight ϕ_{y} influences the results greatly, partly depending on the chosen values for other penalties. A discussion on this can be found in Chapter 7.

In case of an open track possession, the macroscopic timetable model might assign a train to short turn at the station instead of continuing its service as originally planned. When this happens either the arrival or the departure can not occur at the same platform as in the original timetable, unless these events usually also happen on the same platform which is a very rare case. Even then, short turning at one of the two platforms (one for arrival and one for departure) stated in the original timetable is preferred over all other platforms, since choosing one of the two leads to only penalizing either the arrival or departure of the short turning train. Therefore when short turning, either the platform of the arriving or the departure train specified in the original timetable has a preference over other platforms in the station.

3.5.4. Platform occupation

Platform occupation is the total time allocated to trains stopping at a certain platform. This objective improves the robustness of the route plan by balancing trains over platforms more evenly if possible. Because the penalty of this objective is lower than the objectives mentioned above, it does not have a negative influence on passengers. The way this can be evaluated is to sum up the occupation time for each platform separately and then to minimize the maximum value of these. In this way the occupation times are balanced out more evenly if possible:

$$\min \max_{h} \sum_{z \in Z} \sum_{j \in J_h} x_{zj} \cdot ((t_{z,\mathrm{dep}} - t_{z,\mathrm{arr}}) \mod T) \cdot \phi_{\mu}, \tag{3.13}$$

considered for every platform h of all platforms H. The time a platform is used by each train is denoted as $((t_{z,\mathrm{dep}} - t_{z,\mathrm{arr}}) \mod T)$, being the departure time minus the arrival time. Because the model considers a periodic timetable, the modular value of this time must be calculated with modulo T. Since $((t_{z,\mathrm{dep}} - t_{z,\mathrm{arr}}) \mod T)$ is equal to a fixed value based on the timetable of train z, the model is still linear. A weight factor ϕ_{μ} is used to influence the importance of this penalty compared to other objectives.

3.5.5. Preferred routes

Both from a passenger perspective i.e., to minimize lateral acceleration because of running through switches and running time minimization, and from an infrastructure and rolling stock perspective i.e. to reduce the wear on switches and wheelsets, it is advantageous to reduce the number of switches used per hour if possible. Each route contains information on the running time duration and its preference. The preference of a route is defined by the infrastructure manager in which the highest ranked route is most preferred. In the model the fastest possible route is chosen. Because quite often different routes have the same running time duration, the rank of the route preference defined by the infrastructure manager is added to the penalty. In this way there is still a difference between routes with the same duration. Minimizing the penalties for using slower or non preferred routes is formulated as follows:

$$\min \sum_{z \in Z} \sum_{j \in J_z} x_{zj} \cdot (\pi_{\mathrm{e}zj} \cdot \phi_{\mathrm{e}} + \pi_{\mathrm{d}j} \cdot \phi_{\mathrm{d}}), \tag{3.14}$$

in which $\pi_{\mathrm{e}zj}$ is the penalty based on the running time of route j, and $\pi_{\mathrm{d}j}$ is the penalty regarding the preference of the route. The penalty $\pi_{\mathrm{e}zj}$ of route j is the running time of that route subtracted by the fastest possible running time of that train between that platform and entry/exit track. By this method the fastest route has the lowest penalty so that chosen routes are as fast as possible, and therefore increasing the robustness and shortening passenger travel time. Weight ϕ_{e} is used to influence the importance of choosing the fastest routes.

Besides the penalty for slower routes, also the route preference as defined by the infrastructure manager is taken into account. The route that is given as the most preferred route has no penalty, any other route with a lower preference receives an additional penalty based on the rank that is given to the route. Penalty $\pi_{\mathrm{d}j}$ is defined as the number of routes between the same platform and entry/exit point as route j that have a higher preference than route j. Weight factor ϕ_{d} is used to influence the importance of choosing the the most preferred routes. In this way both the running time and the preference stated by the infrastructure manager is taken into account. Both penalties are relatively low because all other constraints are considered more important. This means that being able to drive a preferred route is only considered important if it does not affect trains in a negative way.

3.5.6. Basic model

The complete objective function is equal to the sum of all previously described goal functions, which include penalties for choosing routes with/that cause: cancellation, missed transfers, different platform choice as in original timetable, unevenly balanced platform occupation and route preference. The complete function is therefore formulated as follows:

$$\begin{aligned} \min \sum_{z\in Z} & x_{zq}\cdot\phi_q + \\ & \sum_{(j,k)\in F} b_{jk} + \\ & \sum_{z\in Z}\sum_{j\in J_y\cap J_z} x_{zj}\cdot\phi_{\mathrm{y}} + \\ & \sum_{z\in Z}\sum_{j\in J_z} x_{zj}\cdot(\pi_{\mathrm{e}zj}\cdot\phi_{\mathrm{e}} + \pi_{\mathrm{d}j}\cdot\phi_{\mathrm{d}}) + \\ & \max_h \sum_{z\in Z}\sum_{j\in J_h} x_{zj}\cdot((t_{z,\mathrm{dep}} - t_{z,\mathrm{arr}}) \mod T)\cdot\phi_\mu \end{aligned} \tag{3.15}$$

such that:

$$\sum_{j\in J_z} x_{zj} + x_{zq} = 1, \qquad \forall z\in Z \tag{3.16}$$

$$\sum_{z\in Z_{\mathrm{i}}\cap Z_n\cap Z_\alpha} x_{zq} - \sum_{z\in Z_{\mathrm{o}}\cap Z_n\cap Z_\beta} x_{zq} = 0, \tag{3.17}$$

$$\sum_{z\in Z_{\mathrm{i}}\cap Z_n\cap Z_\beta} x_{zq} - \sum_{z\in Z_{\mathrm{o}}\cap Z_n\cap Z_\alpha} x_{zq} = 0, \tag{3.18}$$

$$\sum_{(z,j)\in J_c} x_{zj} \leq 1, \qquad \forall J_c\in C_r, \forall r\in R \tag{3.19}$$

$$\sum_{j\in J_z\cap J_{\mathrm{i}}\cap J_w\cap J_h} x_{zj} - \sum_{k\in J_y\cap J_{\mathrm{o}}\cap J_{z'}\cap J_w\cap J_h} x_{yk} = 0, \qquad \forall z,y\in Z \tag{3.20}$$

$$(x_{zj} + x_{yk} - 1)\cdot\pi_f\cdot\phi_f \leq b_{jk} \text{ where } x_{zj} \text{ has a transfer conflict with } x_{yk}, \qquad j,k\in F, j\neq k, z\neq y \tag{3.21}$$

$$b_{jk} \geq 0, \qquad j,k\in F \tag{3.22}$$

$$x_{zj}, \in \{0,1\} \qquad j \in J_z \cup q, z \in Z \quad (3.23)$$

The first objective is minimizing the number of cancelled trains or minimize choosing route q_z and the second objective is minimizing the penalty for eliminating transfer possibilities. The third part of the summation penalizes the choice of a platform different from the original timetable. The fifth objective is to minimize the largest platform occupation time and the last summation is to minimize the penalties regarding the running time of the routes and their preference. Equation (3.16) states that one route for each arrival or departure can be chosen, or needs to be cancelled. Equations (3.17) and (3.18) ensure that the number of trains in each direction is equal, and Equation (3.19) ensures only one route from each conflict clique is chosen. Equation (3.20) ensures rolling stock connections, and Equations (3.21) and (3.22) define transfers. Finally, Equation (3.23) defines that the decision variables can only consist of boolean values.

3.6. Model outputs

The main output of the model is the list with optimal routes for each train, divided into cancelled trains and scheduled trains with their alternative route plan specified by listing all resources of the station area that the trains use and their blocking times. Also, a list is created with all buffer times between the routes. Furthermore a platform occupation diagram is generated so that results can be visually observed and checked. The diagram shows when chosen routes or platforms differ from the original timetable. Also possible a number of buffer times between successive trains can be shown in the diagram. Furthermore, some of the output data from this model is intended to be used as input for the next iterative step in the macroscopic model. An introduction to this can be found in Chapter 6.

4

Model extensions

In this chapter several extensions are described to add more flexibility to find the most preferable route plan, or to improve the route plan by modelling real-life situations found in practice. First two extensions to the model are proposed that deal with the length of train vehicles, the third extension provides increased short turning possibilities, the fourth extension provides some flexibility in the event times of the input timetable, and the final extension increases the quality of the route plan by extending buffer times where possible.

First, an extension provides the possibility to use both parts of a divided platform for a train at the same time. This gives the possibility to accommodate longer trains than only one part of the platform. Second, an extension is presented to let the model decide to use shorter trains than specified in the timetable if the platform limits rolling stock length. Third, an extension is presented that adds shunting movements to the model so that it is ensured that these shunting movements, when needed, do not conflict with other trains in the station area. Forth, an extension is presented that applies small time shifts to the events of the adjusted timetable to decrease conflicts and prevent trains from being cancelled. Fifth, an iterative process is described to increase the buffer time of the route plan and therefore the robustness. The chapter concludes with presenting the complete mathematical formulation of the model including the mentioned extensions. All proposed extensions are used in the case studies explained in Chapter 5.

4.1. Divided platform

The first option to cope with the length of the trains is to provide the possibility to use both parts, or phases, of the divided platform for the same train simultaneously. Not all, but mostly large stations in the Netherlands consist of platforms that are divided into an A and B part. Some of these platform parts are not long enough to handle longer trains, therefore such a train may need to occupy both parts of the platform simultaneously. When trains are short enough, it is possible to handle two different trains on both parts of the platform at the same time without causing a conflict. This is possible because of a separate incoming track to both phases and a signal placed in between the two parts of the platform. In this extension new routes are created that can use both sides of the platform at the same time, so that there are more options to assign a platform to longer trains.

In Figures 4.1 and 4.2 a schematic design of a divided platform is given. Figure 4.1 shows the basic situation where a short train waits at platform 5B, while platform 5A is empty and could possibly be used for another train. Figure 4.2 shows the situation where a longer train occupies the entire platform 5.

By default trains are all scheduled by the model to stop at one part of the platform if a stop is scheduled. However for longer trains it might be necessary to occupy both parts of the divided platform at the same time, because one part of the platform is not long enough for the train. Not all arriving routes make the use of both parts of the divided platform possible, since it is not guaranteed that all routes use both parts of the same platform. Therefore several conditions have to be met in order for a route to be used as a route with a divided platform. First the route must end at a the part of the platform furthest away from the origin of the route. In Figure 4.2 this means that for trains arriving from the left side of the image a route to platform 5B or 6B are a candidate. The second condition is that the route also runs over the first part of the same platform track. In the example this means that a route arriving at platform 5B must also use the resource of platform 5A. This is necessary because the long train must be positioned over the whole length of platform 5, and not over platform 6A or a possible middle track between the platform tracks. After the route is considered suitable to be used for a divided platform, some blocking times have to be adjusted in order to ensure that both platform parts are occupied by the same train. This means that the end time of the blocking time of the first platform part is extended until the end time of the furthest part of the platform.

After the arrival route using both parts of a platform has been created, one or more departure routes need to be found. The departing platform side must be equal to the location of the front of the train. If the direction of the train remains the same, the departing platform is equal to the arriving platform. Alternatively, if the direction changes due to short turning or shunting, the departing platform is the other part of the platform, since that has become the front of the train. At the arriving route, the resource of the other platform part has to be added to the resource list. The begin and end time are equal to those of the blocking time of the departing platform part. This is an overestimation, since the rear part of the platform will already have been released earlier. However since this sectional release time is not known by the blocking time calculation, it is chosen to use a slightly larger time that is known through route locking.

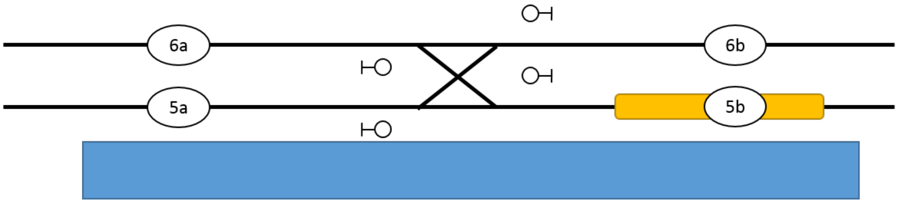

Figure 4.1: Schematical design of a divided platform with a short train waiting at the B-part of the platform.

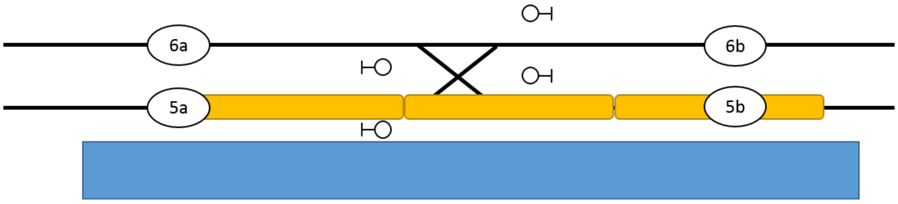

Figure 4.2: Schematic design of a divided platform with a long train waiting at the both parts of the platform.

It must be noted that in practice there are one or two other resources between the two divided platforms. These resources indicate the switches used to pass or overtake trains at one part of the platform. The end times of the blocking times are also set to the arrival time of the train, and the resources are added to the resource list of a departing route in order to ensure accurate conflict detection. Using both parts of a platform at the same time is not penalized directly in the model since it does not lead to higher operational costs or lower passenger satisfaction, but can be affected by the objective function that minimizes occupation time of the most used platform. Since using two platform parts for the same train at once increases the total use of all platforms, the occupation time of the most used platform can therefore also be higher. Depending on the weights used for penalties, this will influence other choices or not. An explanation of the weights used in this thesis can be found in Chapter 5.

When divided platform use is combined with unknown rolling stock connections, it is useful to create routes for trains that do not need to use a divided platform due to their shorter rolling stock length. This is because a train arriving at a divided platform can only short turn to a train departing at a divided platform. Depending on the timetable, it could lead to very few rolling stock connection possibilities if no extra departing routes with a divided platform are created. Therefore arriving and departing routes with a divided platform are added for all trains that do not have a rolling stock connection specified. This is done in the same way as for trains with long rolling stock, except now a long train length is not a requirement anymore to create these routes.

Rules indicating the minimum transfer time depending on the arriving and departing platform can be affected depending on which part of the divided platform is used. The rules in the model are not adjusted for trains using both parts of a divided platform since it can affect the transfer time both positively as negatively. Also it will depend on where passengers are located in the train how long they will actually take to transfer.

4.2. Shorter train

The second extension to cope with longer trains is to choose to use shorter trains than specified. When long trains are used in the original timetable, it is possible they cannot be used in the adjusted timetable due to the fact that one or more (divided) platforms are inaccessible, not available because of a possession, or other trains need to use (part of) the platform as well. It can be argued that using a shorter train is preferred over cancelling the train completely, which justifies this extension. In this case an option is added to use a shorter rolling stock length than specified in the original timetable for that train so that it is possible to use only use one part of a divided platform or to simply use another shorter platform.

It is assumed that there are no changes in passenger flows due to cancellations of trains, and therefore all train lengths are scheduled according to the original timetable. The penalty that is imposed if a shorter train is chosen is as a fixed value:

$$\min \sum_{z \in Z} \sum_{j \in J_l} x_{zj} \cdot \pi_{1j} \cdot \phi_{\mathrm{l}}, \tag{4.1}$$

in which $j \in J_l \subseteq J_z$ represents a route from the subset of all routes with rolling stock length shorter compared to the train length that is specified in the original timetable. Furthermore,

$$\pi_{1j} = L_z - l_z, \tag{4.2}$$

meaning that π_{1j} is the difference in carriages between the train in the original timetable and the chosen length in the model, and ϕ_{l} is the weight to increase the importance of using the specified train length. The penalty value should be quite high, since this decision also affects all other station areas that are served by the shorter train. These stations will also suffer from a lower passenger capacity.

4.3. Shunting movements

The third extension provides more routing possibilities for short turning trains. A shunting movement is an empty train ride inside a station area that is necessary because the rolling stock is needed at a different location than where it arrived. The use of shunting movements can have two benefits. The first is to reduce the occupation time of a certain platform that may be needed for another train. The second reason is to increase the short turning possibilities. Due to the station layout it is not always possible to short turn between the incoming and outgoing tracks, or only a limited number of routing options is available. Thus, adding shunting movements can lead to more and better options to reduce the number of conflicts with other trains.

Shunting movements can be divided into two categories: Those from a platform to another platform and therefore consisting of one movement, or those from a platform to a shunting yard/track, and then back to the same or another platform and therefore consisting of two movements. The latter combination of two movements is also called a saw movement (Van Den Broek and Kroon, 2007). This section describes how these two types of shunting routes are found and implemented in the model.

In order to include the actual shunting movements in the station area, it is necessary to generate all possible shunting movements so that they can be chosen in the model when needed. This means that for each platform - shunting yard combination a train has to be generated with possible routes in both directions. These generated routes are used to calculate the blocking times in preprocessing. Later these shunting movements can be chosen to be used if the turnaround time of a train is large enough. Whether or not a shunting route is chosen by the model is denoted by variable x_{zs}.

In the case of having one shunting movement i.e., from one platform to another platform, the incoming route must be connected to the shunting movement after which the shunting movement must be connected to the outgoing route. This can be achieved by expanding the constraints that were set up for the rolling stock connections:

$$\sum_{j \in J_z \cap J_w \cap J_{\mathrm{i}} \cap J_h} x_{zj} - \sum_{k \in J_z \cap J_w \cap J_{\mathrm{o}} \cap J_{z'} \cap J_h} x_{yk} - \sum_{s \in J_s \cap J_w \cap J\mathrm{o} \cap J_{z'} \cap J_h} x_{zs} = 0, \quad \forall z, y \in Z, \forall h \in H, \tag{4.3}$$

$$\sum_{s \in J_s \cap J_w \cap J_{\mathrm{i}} \cap J_{z'} \cap J_h} x_{zs} - \sum_{j \in J_z \cap J_w \cap J_{\mathrm{o}} \cap J_{s'} \cap J_h} x_{zj} = 0, \quad \forall z \in Z, \forall h \in H. \tag{4.4}$$

Equation (4.3) states that all chosen arriving routes from a certain train z, at a certain platform h must be equal to the sum of all chosen departing routes and the outgoing shunting routes at the same platform. The platform occupation of these departing trains must be linked to the arrival time of train z, for all trains z, at all platforms h. Equation (4.4) states that all chosen shunting routes arriving at a certain platform h must be equal to the sum of all chosen departing routes at the same platform with the platform occupation linked to the arrival time of the shunting route. By stating that the routes must all be from the same set J_w, indicating their train type is equal, these equation also hold as rolling stock connections. This means that also the shunting routes contain the train type to which they connect, so that it is ensured that the outgoing train is of the same train type as the incoming train. Set $J_{s'}$ indicates all routes connecting to incoming shunting routes s. It must be noted that when there is only one shunting movement i.e., from one platform to another platform, these shunting routes are both in the set J_i as in the set J_o because the shunting route departs from one platform, but arrives at another one.

When two shunting movements are executed before the outgoing train departs from the station, the constraint look slightly different because it is described that trains entering the shunting track need to leave that track as well:

$$\sum_{j \in J_z \cap J_w \cap J_\mathrm{i} \cap J_h} x_{zj} - \sum_{k \in J_z \cap J_w \cap J_\mathrm{o} \cap J_{z'} \cap J_h} x_{yk} - \sum_{s \in J_s \cap J_w \cap J\mathrm{o} \cap J_{z'} \cap J_h} x_{zs} = 0, \quad \forall z, y \in Z, \forall h \in H, \tag{4.5}$$

$$\sum_{s \in J_s \cap J_w \cap J_\mathrm{i} \cap J_g} x_{zs} - \sum_{s \in J_s \cap J_w \cap J_\mathrm{o} \cap J_{s'} \cap J_g} x_{zs} = 0, \quad \forall z \in Z, \forall g \in G, \tag{4.6}$$

$$\sum_{s \in J_s \cap J_w \cap J_\mathrm{i} \cap J_{s'} \cap J_h} x_{zs} + \sum_{s \in J_s \cap J_w \cap J_\mathrm{i} \cap J_{z'} \cap J_h} x_{zs} - \sum_{j \in J_z \cap J_w \cap J_\mathrm{o} \cap J_{s'} \cap J_h} x_{zj} = 0, \quad \forall z \in Z, \forall h \in H. \tag{4.7}$$

Equation (4.5) describes that an incoming route must be connected to an outgoing route to either out of the station area or by shunting the rolling stock away from the platform. Equation (4.6) ensures that the rolling stock arriving at shunting track g also departs again from this track. Finally, Equation (4.7) describes that an outgoing route must either be connected to a shunting route coming from another platform, or to a shunting route coming from a shunting track.

Timing of the shunting movement is a complex matter, since the timing affects the constraints. However ensuring a flexibility in the timing of these trains can generate much better solutions. The way this is modelled is to generate a shunting movement every θ seconds within a certain time range $t_{\theta \mathrm{max}}$, and find the conflicts with other trains for each shunting movement. This method results in a lot more total routes to be considered by the model, also because each outgoing train from a certain platform has to be connected to all shunting routes arriving at that same platform. If a shunting movement has 10 different event times, this results in 10 different routes for each outgoing train on that same platform.

In order to reduce the total number of routes, it is chosen to only insert shunting movements after an incoming route if it satisfies certain conditions: First, there is no connecting outgoing route specified in the rolling stock connections of the timetable. Second, there should be an outgoing train in the opposite direction departing within a certain time interval from arrival time of the incoming train, i.e., the departing train must depart slightly before or slightly after the arriving train. The second condition ensures there is enough time available to shunt trains away. Also if the arrival and departure time are almost the same when short turning, the platforms of the arriving and departing train can not be the same due to overlapping blocking times. This would lead to alternating platform use, or adding a platform to platform shunting route. If a set of two trains satisfy both conditions, shunting movements are added in between them.

The capacity of the shunting track can be considered by assuming that a maximum of one train is allowed on the shunting track at the same time. In that case the shunting track is modelled in the same manner as platform capacity is ensured: by modelling the occupancy of the train throughout the entire time that the train is occupying the platform track. If a shunting track is very long, the possibility arises that multiple trains could be positioned there at the same time. In that case the capacity can be checked by taking the length of the trains into account combined with using a capacity model as in Van Aken (2016) using a last in first out approach.

Since actually using shunting movements in the hourly operation is not very preferable due to more complex operations, higher personnel costs and higher vehicle kilometres, a fixed penalty is introduced for the use of each shunting movement. This means that the process of shunting from one platform directly to another platform is less penalized than performing a saw movement. Since there are often not many route options to shunt, the running times are often approximately equal. Therefore a fixed penalty for each used shunting route is used:

$$\min \sum_{s \in J_s} x_{zs} \cdot \phi_\mathrm{s}, \tag{4.8}$$

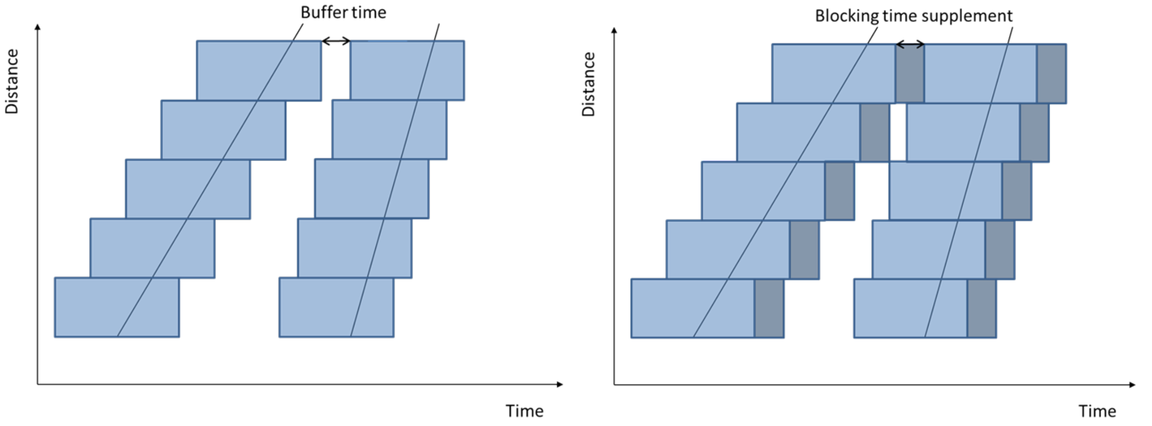

Figure 4.3: Graphical representation the smallest buffer time between two trains (left), and the blocking time supplement that is added in order to improve robustness (right).

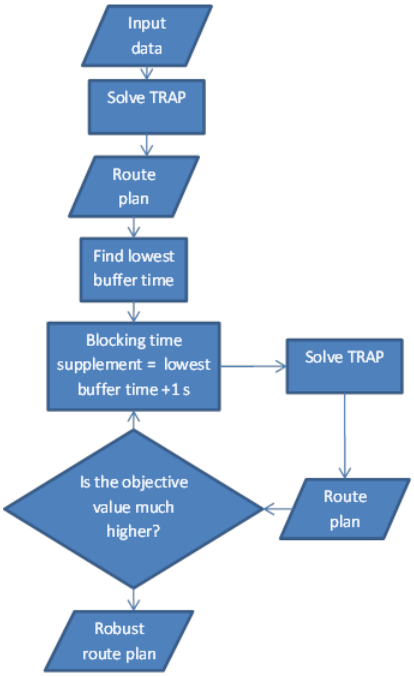

Figure 4.4: Flowchart diagram of heuristic process of increasing the buffer time of the route plan.

in which ϕ_s is the fixed penalty for using a shunting route. When multiple route options between a shunting track and a platform exist, an extension could be to add a penalty for choosing routes that are not most preferred.

4.4. Buffer time

Initial testing of the model showed that the found route plan was feasible, but buffer times where small, meaning that trains should keep to the schedule as much as possible to prevent conflicts.

According to Kroon et al. (2008), a train timetable is considered robust if it can absorb small disturbances in real-time operations. The time difference between the ending blocking time of the first train, and the begin of the blocking time of the second train is called the buffer time. Initial testing of the model showed that the found route plan was feasible, but buffer times where small, meaning that trains should keep to the schedule as much as possible to prevent conflicts.

In order to increase the buffer time between trains within the model for solving TRAP, a blocking time supplement is added to all blocking times, meaning that the end time is postponed to a later time. Figure 4.3 shows the blocking time diagram of two trains and depicts a buffer time and a blocking time supplement. When referring to the buffer time, we refer to the actual time available between the blocking times of trains, without taking the blocking time supplement into account, i.e., the time a preceding train can be delayed without influencing the following train. Note that the blocking time supplement is only added to found routes that are spread more evenly in time. For the proposed model, the blocking time supplement is an input parameter, while buffer time is a measure evaluated a posteriori.

In order to increase the robustness, an iterative heuristic approach is proposed that increases the robustness while only increasing the objective value slightly. A summary of this process can be seen in Figure 4.4. First an initial chosen blocking time supplement is added to the resources of each route, so that the conflict finding algorithm takes this supplement into account. It must be noted that the last resource i.e., that of the arriving platform, of each arriving route does not need a supplement because an outgoing route starts occupying that platform immediately after the arrival. After a solution has been found using the initial blocking time supplement, the smallest buffer time between two trains is found in the route plan. The found buffer time is at least larger than the chosen blocking time supplement. In the next iteration step, the blocking time supplement is updated to the value of the smallest buffer time increased by 1 second. This is the lowest blocking time supplement that leads to different results, because any value lower than the lowest found buffer time also fits into the current route plan.

After a solution has been found with the increased buffer time, the objective value of the new solution is compared with the old solution. If the objective value has increased a lot, then the previous solution is chosen as the definitive solution. If the objective value has increased not more than a chosen threshold, then the process starts again by finding the lowest buffer time between two trains, increasing the blocking time supplement up to the found lowest buffer time plus one second, and finding a solution for the new problem. This is possible because choosing a route that is less preferable for a certain train can lead to a larger buffer time between two trains or even make the two trains independent of each other. If a too small threshold value is chosen, only different routes can be chosen to increase the robustness while if the value would be somewhat increased, also platform changes can be applied and transfers made impossible. In the results the values of the buffer time at each iteration step can be seen, so that other solutions are easy to retrieve and the best route plan can be manually selected after analysing the obtained trade-off balancing efficiency and robustness of solutions.

A practical issue that needs to be solved is to prevent blocking times from taking up the complete period T when adding the blocking time supplement. This happens at platform resources where trains wait a long time for their rolling stock connection. If the end time at the platform resource therefore exceeds the begin time when adding the blocking time supplement, this route is deleted because it can not be used together with the desired buffer time.

4.5. Time shifts

Trains may be cancelled because not enough infrastructure is available to satisfy the exact event time from a given timetable. The routing model cancels these trains because all their possible routes have at least one conflict with the other used routes. A train z is chosen to be cancelled because it leads to the lowest objective value. This can either be the result of the cancellation leading the the highest number of other trains being able to be routed, or because other objectives regarding platform allocation, transfers and route preference are lower for the trains that can still be scheduled.

In order to prevent trains from being cancelled, an extension is proposed so a small retiming of arrival and departure events is possible. In this way it is checked whether more flexibility in the model leads to more scheduled trains and a lower objective function. These small changes in arrival and/or departure time only have effect if at least one feasible route is found for the previously cancelled train because of the time shifts.

A time shift of route j is represented by Δt_j. This time shift is applied in steps of t_θ both forward and backward, until a maximum absolute value of $t_{\max}$. The time shifts are applied to all routes of the cancelled trains, and all other routes that have a overlap smaller than $t_{\max}$. Both the size of the time shift Δt_j, granularity t_θ and $t_{\max}$ must be defined beforehand. For simplicity, it is chosen to use only one time shift step in this model, so $t_\theta = t_{\max}$, but it is possible to use multiple shifts as well. Because the small overlaps in blocking time can be at both the beginning and the ending of the blocking time, the time shifts are made both forward and backward. Shifting a route in time therefore essentially means that the route is duplicated, and blocking times of this duplicated route are shifted a certain time both forward and backward. So every considered route leads to a total of 3 routes. Some notation is required to describe the procedure of finding small overlaps. Parameter b_{rjz} indicates the end time at resource r of route j of train z, while e_{rjz} represents the end time of the same blocking time. Furthermore, b_{rkc} represents the begin time at resource r of route k of cancelled train c, and e_{rkc} indicates the corresponding end time.

If there are cancelled trains after the first optimisation has been performed, a list is generated that includes all routes that need to be shifted in time. This list firstly consists of all routes from the cancelled trains. Then the model searches for routes that overlap within the given time frame of $t_{\max}$ and adds these routes to the list as well. The routes from this list are then all shifted in time forward and backward.

Algorithm 3 Finding small overlaps

```
Input: List $L$ of starting and ending times of the blocking times sorted from low to high at resource $R$,
       and a list of all routes of cancelled trains
Output: List routes that have a small overlap with a route from a cancelled train at resource $R$
for all $bt_{rkc} \in L$ do
    for all $e_{rkc}$ do
        for all $b_{rjz} \in L$ do
            if $b_{rjz} \in (e_{rkc} - 2 \cdot t_{\max}, e_{rkc}]$ then
                Add route $j$ to shortlist $M$
            end if
            if $e_{rkc} <= 2 \cdot t_{\max} \wedge b_{rjz} > e_{rkc} - 2 \cdot t_{\max} + T$ then
                Add route $j$ to shortlist $M$
            end if
        end for
    end for
    for all $b_{rkc}$ do
        for all $e_{rjz} \in L$ do
            if $e_{rjz} \in (b_{rkc} + 2 \cdot t_{\max}, b_{rkc}]$ then
                Add route $j$ to shortlist $M$
            end if
            if $b_{rkc} >= T - 2 \cdot t_{\max} \wedge e_{rjz} > b_{rkc} + 2 \cdot t_{\max} - T$ then
                Add route $j$ to shortlist $M$
            end if
        end for
    end for
end for
for all Routes $j$ in $M$ do
    $\Delta t_j = t_\theta$
    while $\Delta t_j <= t_{\max}$ do
        Apply time shifts of $+\Delta t_j$ and $-\Delta t_j$
        $\Delta t_j = \Delta t_j + t_\theta$
    end while
end for
```

Along with Figures 4.5 and 4.6 the procedure is explained. First, the same list L with begin and end times at a resource is created as in Section 3.4.3. This list consists of all begin and end times at one resource with their corresponding route name and indication whether it is a begin or end time, sorted by time. Second, for each time in list L it is checked whether it is from a route of a cancelled train. If so, and the found time is a begin time, routes in the same list L are found that satisfy the following three conditions: First, the time must be an end time, or e_{rjz}. Second, e_{rjz} must be larger than b_{rkc}, meaning that these blocking times overlap. Third, e_{rjz} must be smaller than $b_{rkc} + 2 \cdot t_{\max}$, meaning that a time shift can eliminate the overlap in blocking times. The value of $t_{\max}$ is doubled, because both routes can be shifted in time with a maximum value of $t_{\max}$, meaning that all routes with an overlap smaller than $2 \cdot t_{\max}$ can be eliminated if both routes are shifted in time. If the found time of a route of a cancelled train is an end time, the conditions the are slightly different: First, the time must be a begin time, or b_{rjz}. Second, b_{rjz} must be smaller than e_{rkc}, meaning that these blocking times overlap. Third, b_{rjz} must be larger than $e_{rkc} + 2 \cdot t_{\max}$, meaning that a time shift can eliminate the overlap in blocking times.

Figures 4.5 and 4.6 show an example of two blocking times at a resource R. Horizontal lines describe the blocking times of route j_z and cancelled route k_c with both a begin and end time. The situation is shown in Figure 4.5 in which a begin time b_{rkc} is shown. This means that the end time of another route e_{rjz} has to lie between b_{rkc} and $b_{rkc} + 2 \cdot t_{\max}$ in order for it to be useful to apply time shifts for that route. Figure 4.6 shows the situation in which there is a end time e_{rkc}, meaning that the begin time of another route b_{rjz} has to lie between $e_{rkc} - 2 \cdot t_{\max}$ and e_{rkc} in order for it to be useful to apply time shifts for that route.

Because the model is periodic, it is possible that the time window of $2 \cdot t_{\max}$ overlaps with the value of T. These situations are shown in Figures 4.7 and 4.8. In Figure 4.7 b_{rkc} lies in between $T - 2 \cdot t_{\max}$ and T, meaning that b_{rjz} can also lie between 0 and $b_{rkc} + 2 \cdot t_{\max} - T$. Figure 4.8 shows the situation in which e_{rkc} lies between 0 and $2 \cdot t_{\max}$, meaning that e_{rjz} can also lie between $e_{rkc} - 2 \cdot t_{\max} + T$ and T. This is also taken into account in Algorithm 3.

The routes that are then found having a slight overlap with the cancelled routes are shifted in time. After this is done, the platform occupation has to be ensured between the arrival and departure time of a train. This means that all shifted departing routes need to keep their first blocking time to the original value so that it still connects the the arriving route i.e., for a departing route all beginning and end times of the blocking times are shifted, except for the beginning time of the first block. When an arriving route is shifted in time, all beginning and ending times of the blocking times are shifted. After this is done, the connecting routes to these arriving routes have to be found. These connecting routes then need to be duplicated so that they connect appropriately to the shifted arriving route, i.e., a new departing route is needed for each time shift applied to the connecting arriving route. This means that the begin time of the blocking time of the first platform resource of the departing route is moved by the same value as time shift Δt_j. To simplify the problem, routes using a shared platform are not considered when applying time shifts.

Shifting the times of certain routes means that the arrival and/or departure time of this train change. This

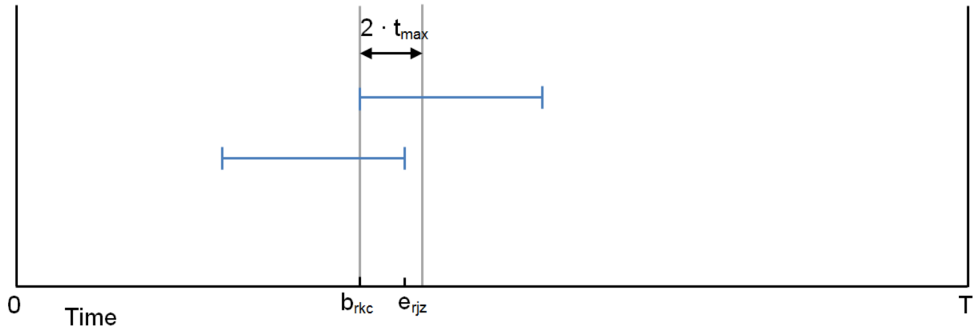

Figure 4.5: Graphical representation of the begin time of a cancelled train and the corresponding time window in which the end time of another route needs to lie in so that time shifts lead to a prevention of overlap of blocking times at a resource.

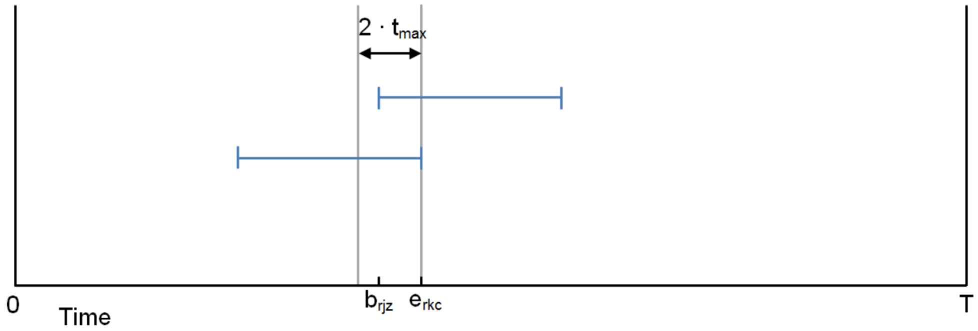

Figure 4.6: Graphical representation of the end time of a cancelled train and the corresponding time window in which the begin time of another route needs to lie in so that time shifts lead to a prevention of overlap of blocking times at a resource

Figure 4.7: Graphical representation of the begin time of a cancelled train being between 0 and $t_{\max}$, and the corresponding time window in which the end time of another route needs to lie in so that time shifts lead to a prevention of overlap of blocking times at a resource.

Figure 4.8: Graphical representation of the end time of a cancelled train being between 3599 $-t_{\max}$ and 3599, and the corresponding time window in which the begin time of another route needs to lie in so that time shifts lead to a prevention of overlap of blocking times at a resource

can lead to infeasible transfers for passengers, or not enough time available to satisfy given minimum dwell times for both short turning and through trains. When a transfer becomes impossible, the model takes this into account by imposing a penalty as explained in Section 3.5.2. When the dwell time for a train becomes too short because of a time shift, the route is not possible to use and therefore eliminated.

The dwell time for through trains is checked for all possibilities, since both the arriving and departing route can shift in time independently. This means the available dwell time in the timetable can be twice the time shift shorter than originally planned. If one or more combinations of arrival and departure time lead to an insufficient available dwell time according to the minimum given process times, these infeasible combinations are deleted.

In order to ensure the model only chooses time shifts when it is assumed to be valuable for the route plan and timetable, a penalty is added to the objective function. The number of seconds of the time shift is multiplied by a fixed penalty, so that the smallest time shift is chosen. This is described according to the following equation:

$$\min \sum_{j \in J_t} x_{zj} \cdot \left|\Delta t_j\right| \cdot \phi_{\mathrm{t}}, \tag{4.9}$$

where $\left|\Delta t_j\right|$ is the absolute value of the used time shift so that negative time shifts are not rewarded, and ϕ_{t} the fixed weight factor to influence the importance in the objective function.

Figure 4.9 shows the iterative process for applying a time shift if a cancellation is found, after which blocking time supplements are increased. This means that time shifts, that are applied for the considered trains to prevent cancellation, could also be used to increase the buffer time where necessary. This is however not the main intention of applying the time shifts and could therefore be improved in future work. To show the functionality of using time shifts, a case study has been made in which using a time shift prevents the cancellation of a train in Den Bosch. More details about this case study can be found in Chapter 5.

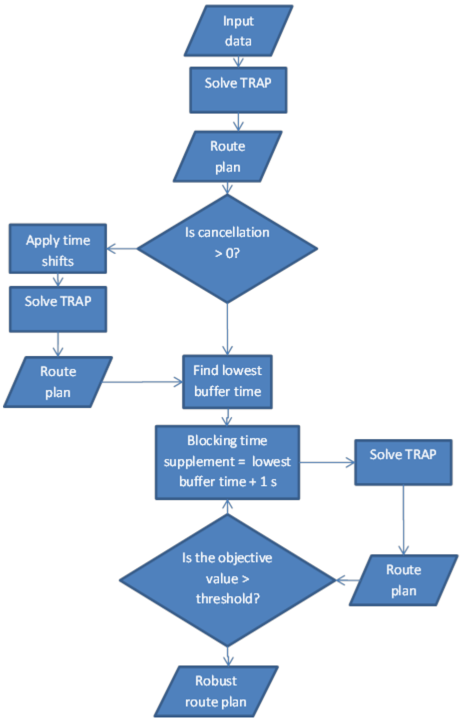

Figure 4.9: Flowchart of heuristic procedure of applying time shifts to routes in order to decrease the number of cancelled trains

4.6. Summarised model for solving TRAP

We introduced several constraints and objectives in the previous part. Below you can find a summary of all constraints and objectives with a short explanation. The constraints for the model are:

$$\begin{aligned}\min \sum_{z\in Z} & x_{zq}\cdot\phi_q + \\ & \sum_{z\in Z}\sum_{j\in J_l\cap J_z} x_{zj}\cdot\phi_{\mathrm{l}}\cdot\pi_{\mathrm{l}j}, \\ & \sum_{s\in J_s} x_{zs}\cdot\phi_{\mathrm{s}} + \\ & \sum_{(j,k)\in F} b_{jk} + \\ & \sum_{j\in J_t} x_{zj}\cdot\left|\Delta t_j\right|\cdot\phi_{\mathrm{t}} + \\ & \sum_{z\in Z}\sum_{j\in J_y\cap J_z} x_{zj}\cdot\phi_{\mathrm{y}} + \\ & \sum_{z\in Z}\sum_{j\in J_z} x_{zj}\cdot(\pi_{\mathrm{e}zj}\cdot\phi_{\mathrm{e}} + \pi_{\mathrm{d}j}\cdot\phi_{\mathrm{d}}) + \\ & \max_h \sum_{z\in Z}\sum_{j\in J_h} x_{zj}\cdot((t_{z,\mathrm{dep}} - t_{z,\mathrm{arr}}) \mod T)\cdot\phi_\mu,\end{aligned} \tag{4.10}$$

such that:

$$\sum_{j\in J_z} x_{zj} + x_{zq} = 1, \qquad \forall z\in Z, \tag{4.11}$$

$$\sum_{z\in Z_{\mathrm{i}}\cap Z_n\cap Z_\alpha} x_{zq} - \sum_{z\in Z_{\mathrm{o}}\cap Z_n\cap Z_\beta} x_{zq} = 0, \tag{4.12}$$

$$\sum_{z\in Z_{\mathrm{i}}\cap Z_n\cap Z_\beta} x_{zq} - \sum_{z\in Z_{\mathrm{o}}\cap Z_n\cap Z_\alpha} x_{zq} = 0, \tag{4.13}$$

$$\sum_{(z,j)\in J_c} x_{zj} \le 1, \qquad \forall J_c\in C_r, \forall r\in R \tag{4.14}$$

$$\sum_{j\in J_z\cap J_w\cap J_{\mathrm{i}}\cap J_h} x_{zj} - \sum_{k\in J_z\cap J_w\cap J_{\mathrm{o}}\cap J_{z'}\cap J_h} x_{yk} - \sum_{s\in J_s\cap J_w\cap J\mathrm{o}\cap J_{z'}\cap J_h} x_{zs} = 0, \qquad \forall z,y\in Z, \forall h\in H \tag{4.15}$$

$$\sum_{s\in J_s\cap J_w\cap J_{\mathrm{i}}\cap J_g} x_{zs} - \sum_{s\in J_s\cap J_w\cap J_{\mathrm{o}}\cap J_{s'}\cap J_g} x_{zs} = 0, \qquad \forall z\in Z, \forall g\in G \tag{4.16}$$

$$\sum_{s\in J_s\cap J_w\cap J_{\mathrm{i}}\cap J_{s'}\cap J_h} x_{zs} + \sum_{s\in J_s\cap J_w\cap J_{\mathrm{i}}\cap J_{z'}\cap J_h} x_{zs} - \sum_{j\in J_z\cap J_w\cap J_{\mathrm{o}}\cap J_{s'}\cap J_h} x_{zj} = 0, \qquad \forall z\in Z, \forall h\in H \tag{4.17}$$

$$(x_{zj} + x_{yk} - 1)\cdot\pi_f\cdot\phi_f \le b_{jk} \text{ where } x_{zj} \text{ has a transfer conflict with } x_{yk}, \qquad j,k\in F, j\neq k, z\neq y \tag{4.18}$$

$$b_{jk} \ge 0, \qquad j,k\in F \tag{4.19}$$

$$x_{zj}\in\{0,1\}, \qquad j\in J_z\cup q, z\in Z \tag{4.20}$$

$$x_{zs}\in\{0,1\}, \qquad s\in S_z, z\in Z \tag{4.21}$$

Equation (4.10) denotes the complete objective function, consisting of penalties for cancellation, missed transfers, shorter trains, applied time shifts, changed platforms, maximum platform occupation and non preferred routes. Equation(4.11) ensures that for every train only one route is chosen or the train is cancelled, and Equations (4.12) and (4.13) ensure that the number of trains in each direction remains the same. The cliques that are constructed to model the infrastructure constraints are noted in Equation (4.14), ensuring that every resource can only be used by one route at the same time. Equations (4.15), (4.16) and (4.17) provide rolling stock connections and if necessary shunting options, and equations (4.18) and (4.19) provide transfer constraints in two parts with equation (4.18) imposing a penalty when two routes that do not provide a given transfer are chosen and equation (4.19) ensuring this penalty can not be negative. Equations (4.20) and (4.21) ensure that variables x_{zj} and x_{zs} are binary.

As can be seen above the most important objective is to schedule as many trains as possible. The second objective is to keep as many transfers possible that are listed beforehand for passengers by changing the platform to a reachable distance for the given transfer time. Furthermore, the time shifts that are used are kept to the minimum. The other two objectives regarding platform assignment are to schedule as many trains as possible on the same platform as specified in the original timetable, and to balance the platform occupation time of each platform, ensuring that the platform occupation is not too high while another platform has available time. At the end of the priority list is route preference. For each possible route, the total running time is known and a rank defined by the infrastructure manager indicating the preference. The driving speed is aimed to be as high as possible, and there are as many as possible preferred routes chosen. These goals are considered less important because they have no influence on transfers, but they can improve the travel time of passengers and comfort. In Chapter 5 details on the weights used for the case study can be found.

5

Case studies

In this chapter a description of the case study is be given. The case study consists of several fictive scenarios in the station area of Den Bosch in the Netherlands for the 2016 timetable of NS. First a description of the station area and the regular services, timetable and transfers is given. Then several data sources that are used for the case study are listed. Afterwards multiple disruption scenarios are explained and the results are given and discussed. Experiments were run using an Intel core i5-6198DU (2.8 GHz) processor, 8 GB RAM and 3946 MB of virtual memory. The model is programmed in Matlab and solved using Gurobi optimisation solver.

5.1. Description

The station area of Den Bosch has been rebuilt completely in 2014 in order to detangle several routes of trains and to increase the driving speed of trains to improve the timetable (ProRail, 2013). A schematic layout of the station area of Den Bosch can be found in Figure 5.1. At the southern side there are three tracks, that later change into two sets of double track at the level crossing called "Vught Aansluiting" (Vga). One set leads to the direction of Tilburg, and the other leads to the direction of Eindhoven. At the northern side of the station there are two sets of double track located: One set to Utrecht with first timetable point being Hedel (Hdl), and one set to Nijmegen with the first timetable point being Den Bosch Oost (Hto). These two sets of double track include an overpass so that incoming and outgoing trains of both directions can run simultaneously without conflicts. There are 5 platform tracks available for passenger trains. All platform tracks are divided platforms consisting of an A and B part except for platform 1, which is not a divided platform. Cross platform transfers are possible between platform tracks 3 and 4, and platforms 6 and 7. Furthermore the station has 3 through tracks that can be used for freight trains or to access the divided platforms, these are tracks 2, 5 and 8. Furthermore there are several shunting tracks available in Den Bosch, however these can not be used for hourly operations due to the station layout.

Station Den Bosch is served by 3 intercity services and 4 local trains (also called sprinter trains). All passenger services stop at the station. An overview of the regular services in Den Bosch can be seen in Table 5.1. The sprinter trains all start/end at Den Bosch. During the regular timetable series 16000 connects to series 13600, and series 4400 connects to 9600. Both connections are applied in both directions. The timetable uses a period of one hour.

Series	Type	O/D	Frequency
800	IC	Utrecht - Eindhoven	2
3500	IC	Utrecht - Eindhoven	2
3600	IC	Tilburg - Nijmegen	2
16000	SP	Utrecht - Den Bosch	2
13600	SP	Tilburg - Den Bosch	2
4400	SP	Nijmegen - Den Bosch	2
9600	SP	Eindhoven - Den Bosch	2

Table 5.1: Overview of series that serve station Den Bosch in the 2016 NS timetable.

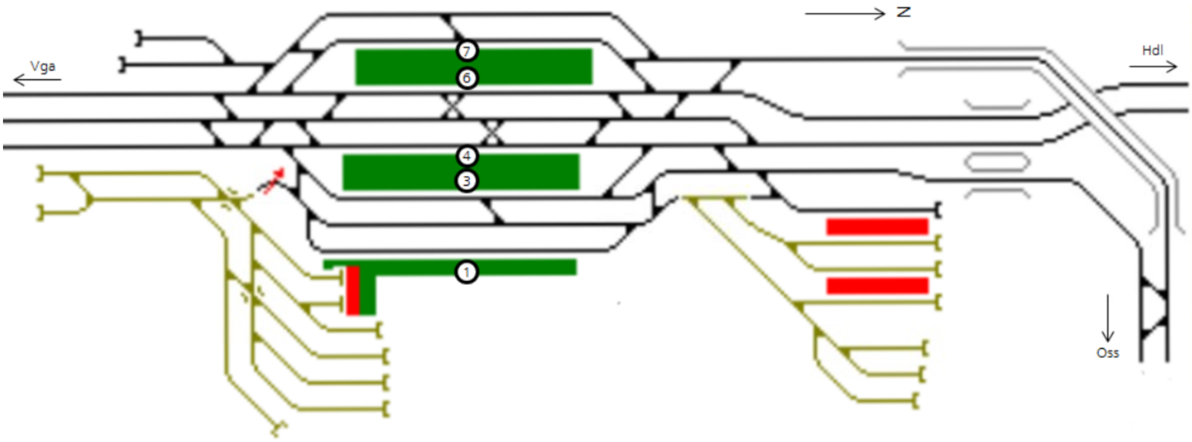

Figure 5.1: Schematic layout of the station area of Den Bosch.(Zeegers, 2017).

5.2. Data sources

Event times from the 2016 timetable used at regular hours are obtained from the InfraplanData, the timetable data source from NS. Freight trains are not considered, since multiple paths exist, making it hard to decide which path to take into account. However when a timetable exist for a freight train and blocking times are computed, the TRAP model can take them into account as well.

The adjusted timetable is generated from a macroscopic model if applicable. Furthermore a description of rules for transfers, dwell times and turning around times is used from NS. The blocking times are calculated using the blocking time calculation model as described in Bešinović et al. (2013) in combination with itineraries that are found by a conversion tool developed by TU Delft based on infrastructure data provided by ProRail. Slight adjustments to this data have been made, so that conflict detection can work based on the names of each resource. This means that it is checked that all resources of straight track that should have the same name do have the same name. Furthermore, at the intersection of crossing switches, which is a combination of four switches and an intersection point, a dummy resource is introduced. This is done because no resource exists at the intersection point, the location where crossing trains should have an overlapping blocking time. This procedure should be identified manually for each switch in the station area. The dummy resource has a length of zero so that blocking times of other resources stay correct, but does have blocking times of its own, equal to the resources used before and after the dummy resource so that conflicts at that point are detected.

Furthermore the timetable should also state whether a train should use a predefined rolling stock connection because the train continues its service, or the model should find a rolling stock connection. For the intercity trains rolling stock connections are defined because these trains do not end their service at Den Bosch. All sprinter trains do end their service, and therefore a rolling stock connection are found for them. When open track possessions lead to the necessity of short turning intercity trains, it has to be defined beforehand that a rolling stock connection must be found for the intercity trains since the given rolling stock connection does not hold.

When rolling stock changes direction, a certain time is needed in order to execute the necessary processes. Process times to change rolling stock direction is provided as a set of rules by NS in the ISIDOOR document. These rules specify that based on rolling stock type and train length a certain time is needed between the arrival and departure of the train. The train length is defined as the longest length of the most often used rolling stock type of that train service. For every rolling stock connection that changes directions it is checked whether sufficient time is available. If a rolling stock connection is made between two trains using different rolling stock types, the longest minimum process time of the two rolling stock types is used. This will always result in a feasible timetable, unregarded of which of the two rolling stock types is chosen.

Furthermore, due to the periodicity of the model, the arrival time cannot lie between the begin and end time of the platform occupation time of the departing train. This is also checked in the same module.

A same set of rules is applied for trains dwelling at a platform between their arrival and departure time. When no time shifts are applied, the dwelling time should be large enough because it should fulfil the timetable requirements applied in the macroscopic model. However when time shifts are used the dwelling times may

Arriving train	From	Departing train	To	Passengers
4401	Vga	803	Hdl	344
4403	Vga	801	Hdl	344

Table 5.2: List of transfers used in the model

Weight	Value
Cancellation	1000000
Train length	5000
Shunting	1000
Transfer	$100 \cdot \phi_f$
Time	$1000 \cdot \Delta t_j$
Platform	500
Route preference	10
Route speed	1
Platform occupation	1

Table 5.3: Overview of the weights used in the case studies.

change and can lead to too small values. Therefore the dwelling times are checked when rolling stock connections are defined in the routing model. Furthermore, the time shifts that are applied in the last scenario are made in one step forward and one step backward of 30 seconds.

The passenger transfers can be described in a list. This list consists of the arriving train and the departing train. Then depending on the transfer time an allowed distance between the platforms of both trains can be found. When not much time is available to transfer, the distance between the two platforms of the arriving and departing train can only be a certain value. These rules thus depend on the available time to transfer, the difference in platform track number and the side of the divided platform that is used if applicable. This platform distance is then used to optimize in the routing model. For the used timetable, no list of transfers was available. Therefore possible transfers were identified manually based on the arrival and departure times of all trains. This leads to a short list since almost all departure times do not have an arrival time of any train just before it, meaning that all platforms are reachable within the given transfer time. Only two arrivals and departures are found within this time range, which are listed in Table 5.2. The number of passengers is taken from the list of transfers of the 2017 timetable provided by NS. Since the found connection was not part of the list of transfers at NS, an often used value for transfers in similar cases was used.

The buffer time supplement that is added to the blocking times has a starting value of 30 seconds, after which it is increased in the iterations. This value is quite low, but in this case the first iterations do show situations in which routes have a strong dependency due to their small buffer time. This can give insight on how to improve the timetable. The stopping criterion is set in such a way that the cancellation of a train leads to the stopping of the iterations.

Shunting movements are applied for incoming and outgoing train pairs that fit the formulated criterion described in Chapter 4. A shunting movement is created every 3 minutes until 25 minutes after the arrival time of the arriving train. These values were chosen so that the number of routes do not grow very fast, while still getting a suitable number of possibilities to time the departure of the shunting movement. Possible shunting routes used in the model are derived based on manual identification of shunting operations in an hourly timetable in Den Bosch. These can be found in Appendix 7.3.

5.3. Scenarios

Seven scenarios are used in order to show the functions of the model. First it is shown the model also works for generating the route plan for the original timetable. The second scenario is the closure of the complete platform track 3. This means that the resources indicating the tracks of these platforms cannot be part of the considered routes. Routes using these resources are deleted. The same procedure is used for scenario three, but now also including the resources of platform tracks 4A and 4B. The fourth case consists of an open track closure between Den Bosch and Vught aansluiting (Vga), leading to cancellations of trains coming from and going to Tilburg and Eindhoven and therefore to short turning of trains from line numbers 4400, 3600, 800,

Parameter	Value
t_{max}	30 seconds
t_{θ}	30 seconds
$t_{\theta \text{s}}$	3 minutes
t_{smax}	25 minutes

Table 5.4: Overview of the parameter values used in the case studies.

3500 and 16000. The fifth case consists of the same open track closure, but now a switch near the platforms is fixed, making it impossible to run trains between station tracks 4B and 5A. The sixth scenario is also similar to the fourth case, but now the 800 series can run to/from Vga using single track usage. This scenario has also been planned by NS, and results of the model is compared to actual planning made by planners at NS. The last case consists of a manually adjusted timetable so that two trains conflict. Applying a time shift can solve that conflict so that a feasible route plan can be constructed.

1. Original timetable
2. Platforms 3A and 3B closed
3. Platforms 3A, 3B, 4A and 4B closed
4. Tracks to Vga closed
5. Tracks to Vga closed and a switch fixed
6. NS case
7. Adjusted timetable to demonstrate time shifts

Finally, the weights used for these experiments can be seen in Table 5.3, and the parameter values used for shunting movements and time shifts can be seen in Table 5.4. A cancellation is penalized the most, therefore imposing to look for all other possibilities before a train is cancelled. The weight of the penalty for missing a transfer ensures that on average, depending on how many passengers use a transfer, the penalty is higher than a penalty for time shift. The penalty for using a shorter train length than specified in the original timetable is set to 5000, and the penalty of using a different platform than specified in that timetable is 500. The weight factor for the platform occupation is set as 1, keeping in mind that the highest platform occupation is in the order of 2000 seconds for these case studies. The weight for the penalty of the route preference is set to 10, while the speed has a weight of one. This means that for every rank a route is less preferred, it should be 10 seconds faster in order to be valued equally. When applying these values speed is taken into account, but only slightly since some routes that scored very low on the preference rank were in fact the fastest routes.

The values of the weights proved to lead to favourable results. However, in different cases the values could be tweaked. This especially holds if the model would be used for stations other than Den Bosch. With different infrastructure, different number of trains and other transfer characteristics adjusted weight factors can be necessary.

5.4. Results

In this section the results of the seven scenarios are described. A platform occupation diagram is shown to display the routes, and a description of the found routes is given. First, the results are discussed in general together with a summary of all iterations and results from Table 5.4. After that each scenario will be discussed.

Scenario	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
originaltt	96	2510	1638	126.83	17.47	0	0	0	0	0
originaltt	114	2952	1638	100.70	16.20	0	0	2	0	0
originaltt	116	30602	1638	106.58	21.64	0	16	2	0	2
originaltt	118	4009288	1638	113.95	20.89	4	10	2	0	0
pf3closed	49	6509	1412	111.05	15.48	0	8	0	0	0
pf3closed	96	6684	1412	98.97	15.00	0	8	2	0	0
pf3closed	110	7006	1412	99.08	15.50	0	8	4	0	0
pf3closed	114	7169	1412	99.22	16.16	0	8	3	0	0
pf3closed	118	4013230	1412	100.97	17.50	4	16	2	0	0
pf3closedwp0	49	4344	1412	101.27	13.22	0	8	0	0	0
pf3closedwp0	96	4366	1412	86.36	14.20	0	8	0	0	0
pf3closedwp0	114	4406	1412	86.08	14.39	0	8	2	0	0
pf3closedwp0	118	4010444	1412	85.94	16.38	4	16	2	0	0
pf34closed	40	54788	782	76.33	6.81	0	24	2	0	4
pf34closed	43	54902	782	60.38	6.38	0	24	2	0	4
pf34closed	48	8014414	782	64.61	6.17	8	24	0	0	0
pf34closed	70	8014544	772	59.61	7.64	8	16	2	0	0
pf34closed	102	8036818	772	61.00	7.67	8	20	0	0	2
pf34closed	118	12015384	772	61.38	7.30	12	14	0	0	0
vgaclosed	82	20019612	2548	219.73	36.13	20	12	4	0	0
vgaclosed	84	20020871	2548	194.78	36.13	20	15	1	0	0
vgaclosed	177	20021672	2548	192.00	36.22	20	16	2	0	0
vgaclosed	192	20022178	2548	199.031	35.30	20	17	1	0	0
vgaclosed	194	20022687	2548	205.25	39.50	20	18	0	0	0
vgaclosed	197	20022713	2548	205.63	39.75	20	18	0	0	0
vgaclosed	212	20022826	2548	210.64	39.34	20	18	0	0	0
vgaclosed	225	20022860	2548	210.41	42.02	20	18	0	0	0
vgaclosed	260	22020156	2548	206.84	42.91	22	13	3	0	0
vgaclosedswitch	65	20023095	3222	229.73	67.42	20	18	1	0	0
vgaclosedswitch	84	20022049	3222	199.72	63.56	20	17	1	0	0
vgaclosedswitch	177	20022542	3222	200.77	64.63	20	18	0	0	0
vgaclosedswitch	195	20023231	3222	201.39	68.55	20	19	0	0	0
vgaclosedswitch	222	22021141	3222	201.28	71.69	22	15	2	0	0
NScase040616	41	16016402	2494	189.27	40.42	16	12	2	0	0

Continued on next page

Scenario	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
NScase040616	82	16016418	2494	171.34	41.95	16	12	2	0	0
NScase040616	136	16017272	2494	170.81	42.03	16	14	2	0	0
NScase040616	202	16018238	2494	171.61	42.13	16	16	2	0	0
NScase040616	212	16019258	2494	172.42	48.53	16	18	0	0	0
NScase040616	225	16019414	2494	169.97	46.97	16	18	0	0	0
NScase040616	256	16039250	2494	171.81	48.83	16	16	2	0	2
NScase040616	270	18018188	2494	171.28	47.56	18	16	0	0	0
NScase040616adj	82	12013242	1976	157.72	27.17	12	14	0	0	0
NScase040616adj	120	12015202	1976	141.92	27.12	12	14	0	0	0
NScase040616adj	123	12015238	1976	140.56	26.70	12	14	0	0	0
NScase040616adj	242	12015769	1976	141.98	26.95	12	15	0	0	0
NScase040616adj	255	12015789	1976	142.09	32.25	12	15	1	0	0
NScase040616adj	280	12017204	1976	140.53	32.69	12	18	0	0	0
NScase040616adj	297	12018180	1976	140.50	31.75	12	20	0	0	0
NScase040616adj	301	14015275	1976	146.05	32.58	14	18	1	0	0
timeshifts	97	2004044	1638	114.31	17.00	2	2	2	0	0
timeshifts	54	33235	4638	114.31	126.22	0	0	0	1	0
timeshifts	56	45999	4638	297.53	114.23	0	6	1	1	0
timeshifts	97	2004791	4638	278.47	110.00	2	2	3	0	0

Table 5.5: This table shows all iterations to obtain the results described in Chapter 5.

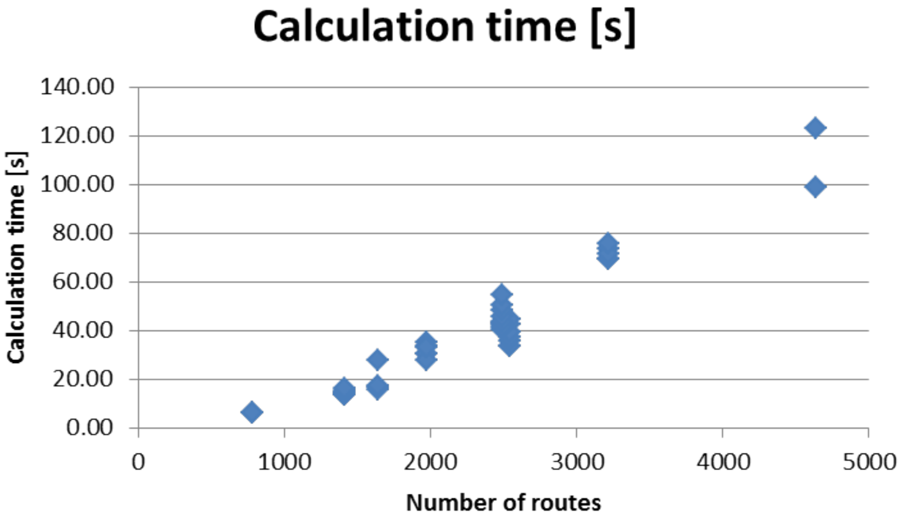

Figure 5.2: The number of routes versus the calculation time of the model for all case studies.

Table 5.4 shows the results of all iterations made for the scenarios described earlier in this chapter. The number of routes considered for each scenario has quite a large range. For generating a route plan for the original timetable, 1638 routes are considered. When a platform closes, less routes become feasible due to a possession, and when two platforms close, even less routes are considered. When short turning must be applied, because of an open track possession, more trains need to find a rolling stock connection. This means that more incoming routes are connected to outgoing routes and therefore much more routes are considered. A larger number of routes for scenarios where Vga is closed is because a shunting movement between incoming and outgoing trains of the 3600 series are considered. The objective value of the found original route plan is not equal to 0, since the largest total platform occupation time is added to the objective function (2136), and because the chosen routes are not always the fastest possible which also leads to some small penalties.

The computation time for all iterations is below 80 seconds, except for when time shifts are considered to eliminate cancellations. This leads to a computation time just over two minutes. This does make sense since applying time shifts also leads to the most routes. In Figure 5.2 the number of routes is plotted versus the calculation time. It is clear that the number of routes influences the calculation time. Section 5.5 describes a study assessing how several options in the model as well the timetable size affect the number of routes.

The number of iterations varies between 3 and 9, depending on the available feasible solutions and the timetable. When multiple solutions are possible due to less trains but the same number of available platforms, for example when the open tracks to Vught aansluiting are closed, a lot of freedom occurs for choosing routes. In other words, multiple platform options then exist for a train that do not conflict with other trains. In these cases multiple iterations are necessary to find the maximum lowest buffer time. For all cases in which the Vga side of the station is closed, a solution is found for quite a low buffer time, but after a number of iterations a route plan with a minimum buffer time of almost 200 seconds is found. Sometimes the increase in buffer time after one iteration is only a few seconds. This is mostly, but not always, the case when a different route is used while keeping the same platform choice. Often this leads to a change in location where two trains use a common resource, and therefore a small change in buffer time. When a larger increase occurs, this happens often, but not always, due to a platform allocation change. In this way it can be achieved two routes do not have any resources in common, making the routes independent and therefore eliminating that buffer time.

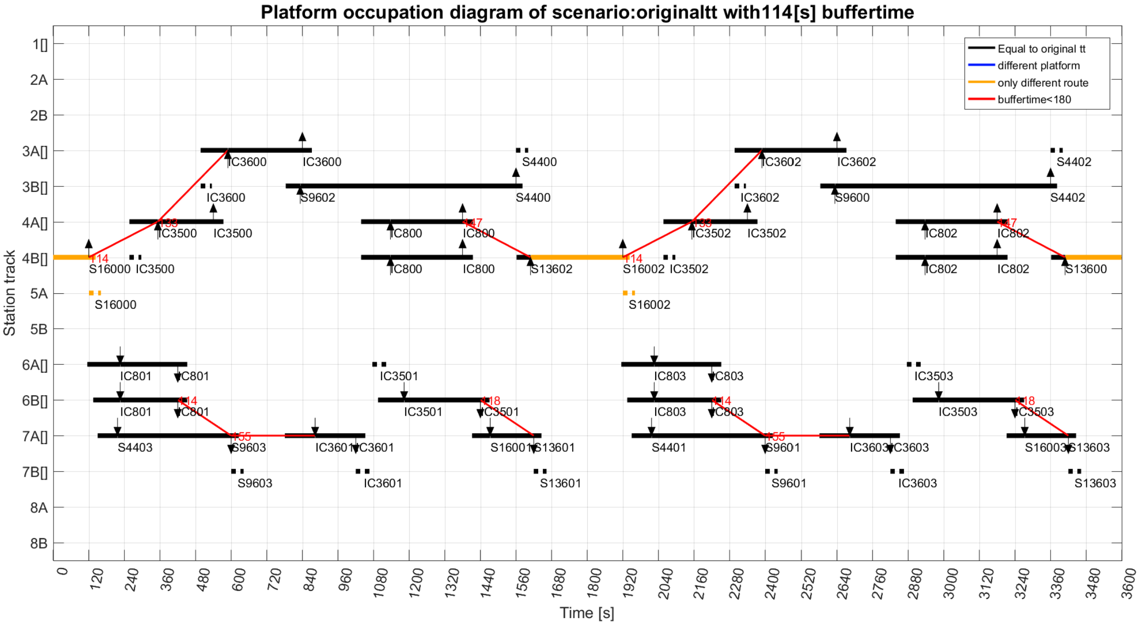

Figure 5.3: Platform occupation diagram of Den Bosch for the original timetable of the most robust route plan

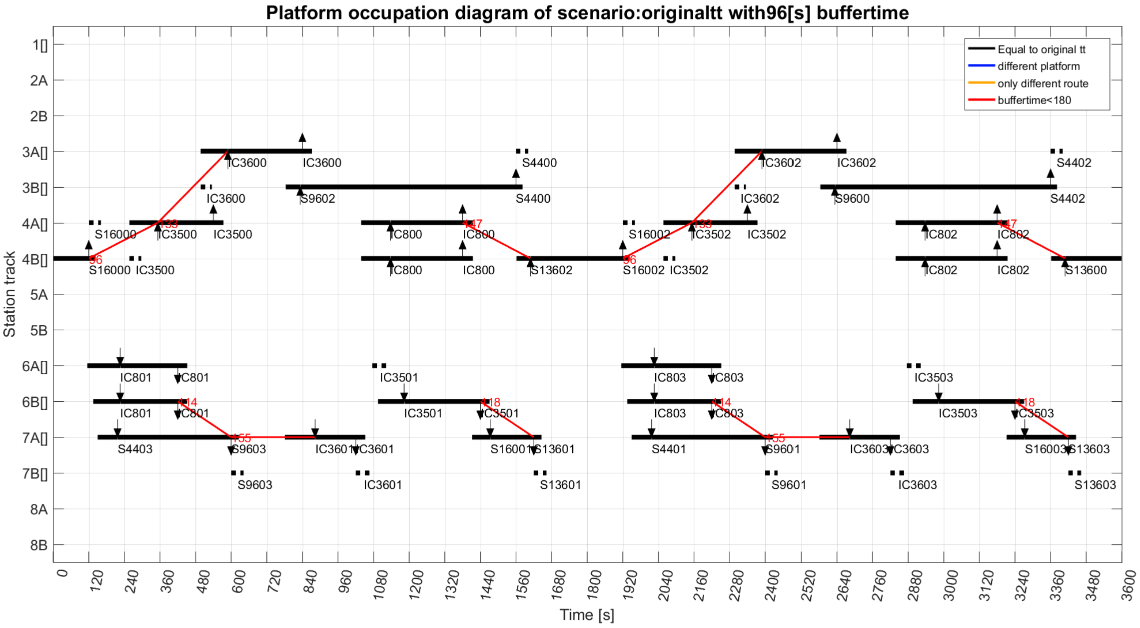

Figure 5.4: Platform occupation diagram of Den Bosch for the original timetable of the second most robust route plan. These results are used to compare other scenarios.

5.4.1. Scenario 1: Original timetable

To construct the route plan for the original timetable, the original timetable is used as an input, and no infrastructure possessions are considered. A total of 3 iterations are preformed. The first generated the same solution as of NS, while the second improved robustness. The third solution contained a cancelled two trains and is therefore disregarded. The first two iterations are described here below.

A platform utilization diagram of the route plan resulting from the first iteration is shown in Figure 5.3. On the horizontal axis time is displayed, and on the vertical axis the list of all station tracks is given, with a small

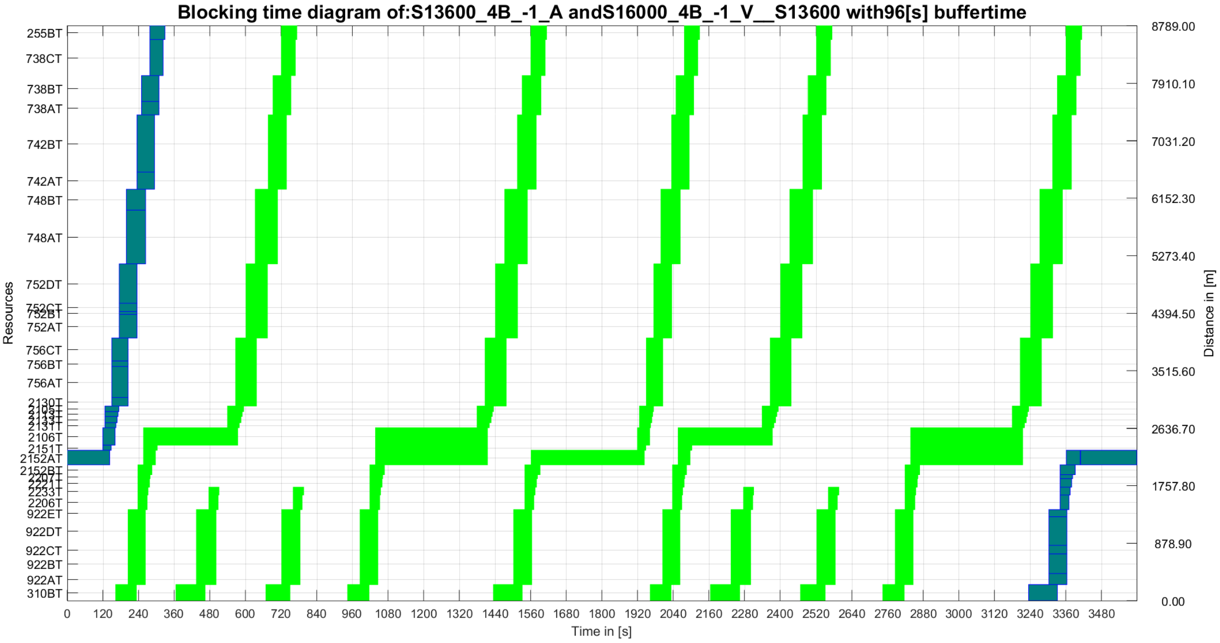

Figure 5.5: Blocking time diagram of arriving train 13600, continuing its service as the 16000 at Den Bosch station for the original timetable of the second most robust route plan. The blocking time stairway of the mentioned train is shown in blue, all blocking times of other trains using the same resources are shown in green.

square indicating the station tracks that serve a platform. The diagram shows the duration that platforms are used for each train, with arrows indicating the driving direction and the arrival or departure time. An arrow pointing towards a line indicates an arrival, and an arrow pointing away from a line indicates a departure. The direction of arrows correspond to the driving direction of trains: with an upward arrow being the northern direction (to Utrecht or Nijmegen) and an downward arrow being the southern direction (to Tilburg or Eindhoven). It can be observed that a platform is already occupied by a train before the arrival time of that train. This happens because the track section must be reserved before the train can enter the platform and besides that, arriving at the platform itself also takes some time. Solid lines indicate a stop of a train at that platform, while dashed lines indicate running activities of a train at that station track. Furthermore, colours indicate whether a chosen route is equal to the original timetable. A black line indicates that the platform and route preference is the same as in the original timetable. A yellow line indicates that the platform of the train is the same, but a different route has been chosen. Finally, a brown line indicates a different platform and therefore automatically a different route for the corresponding train compared to the original timetable. To show the dependency between trains, red lines and numbers are used to show the size of buffer times between two trains when their buffer time is below a certain chosen value. There is no fixed minimal value the buffer times should have in order to ensure a robust timetable, so a value of 180 seconds is chosen. This is however not an indication that the route plans are sufficiently robust.

The most robust route plan shown in Figure 5.3 uses track 5. The reason for this is that departing trains from the 13600 series have a larger buffer time with arriving trains of the 3500 series because the 13600 series does not use platform 4A, the arriving platform of the 3500. However, this is is not according to what is done in practice since track 5 is only used for freight trains. Therefore the previous iteration is taken as a base scenario to which all other route plans are compared that is shown in Figure 5.4. This route plan uses all routes used in the original timetable from NS.

A blocking time diagram of one of the two trains trains with the lowest buffer time is shown in Figure 5.5. This train is shown in blue, while all other trains using the same resources are shown in green. The diagram shows that no train path overlaps. Also it is clearly visible that resources close to platforms use sectional release points in order to decrease the blocking time. For each iteration done for the case studies, a blocking time diagram can be found in Appendix 7.3.

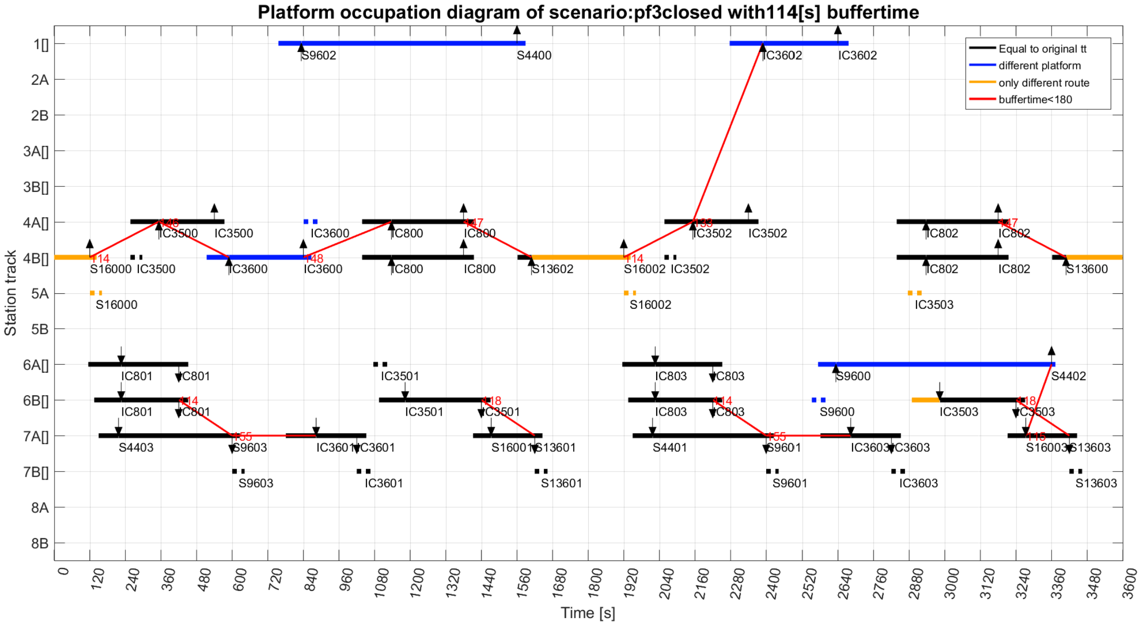

Figure 5.6: Platform occupation diagram of Den Bosch when platform tracks 3A and 3B are closed.

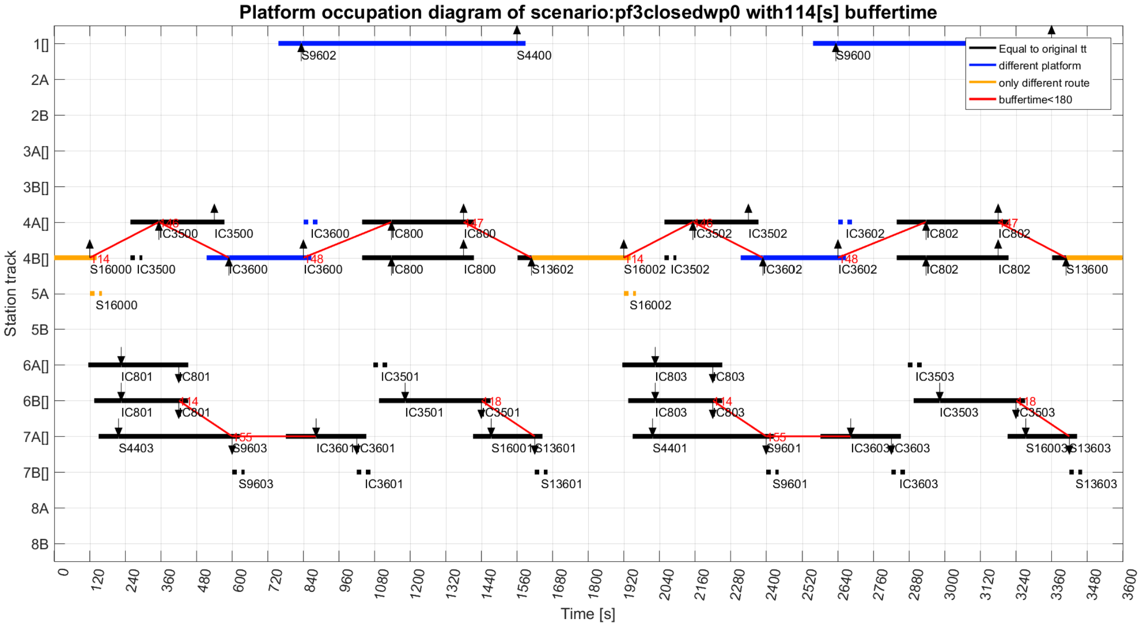

Figure 5.7: Platform occupation diagram of Den Bosch when platform tracks 3A and 3B are closed, with the objective of minimizing the largest platform occupation turned off in order to generate regular patterns.

5.4.2. Scenario 2: Platform 3 closed

A platform occupation diagram of the case can be seen in Figure 5.6. No trains are cancelled in this scenario, 8 routes use a different platform compared to the original timetable, and 3 trains only use a different route compared to the original timetable.

It can be seen that although the route plan is feasible and has the same buffer time, it is not as regular as might be expected. Regular route plans are easier to operate. Especially when the timetable is equal for both half hours, the same route plan could be expected. The reason of the irregular route plan lies in one of the

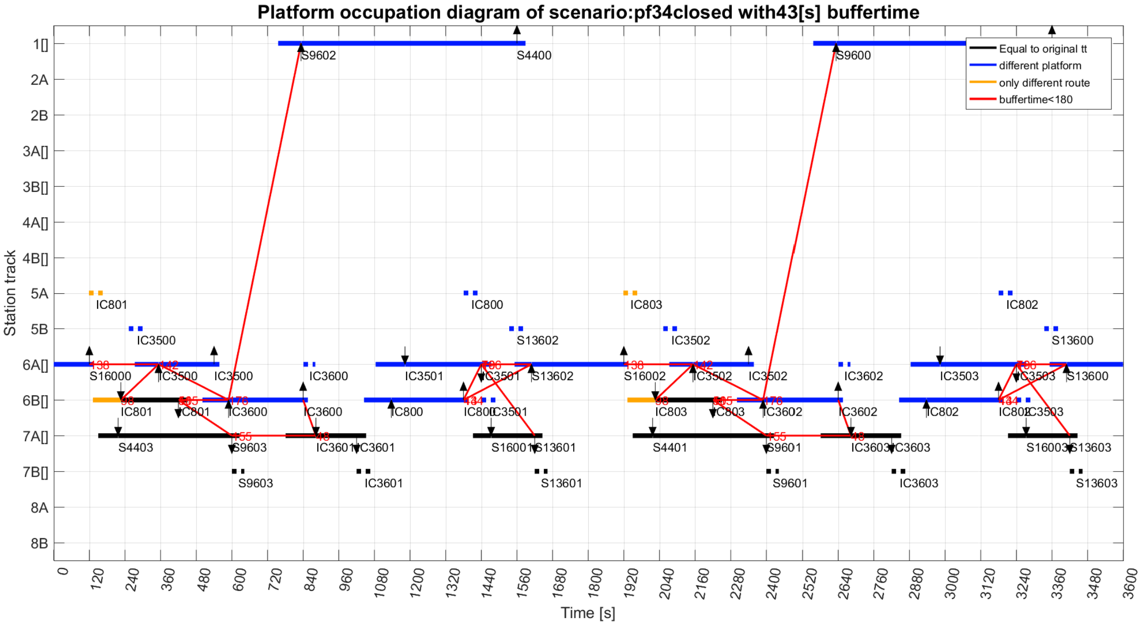

Figure 5.8: Platform occupation diagram of Den Bosch when platform tracks 3A, 3B, 4A and 4B are closed.

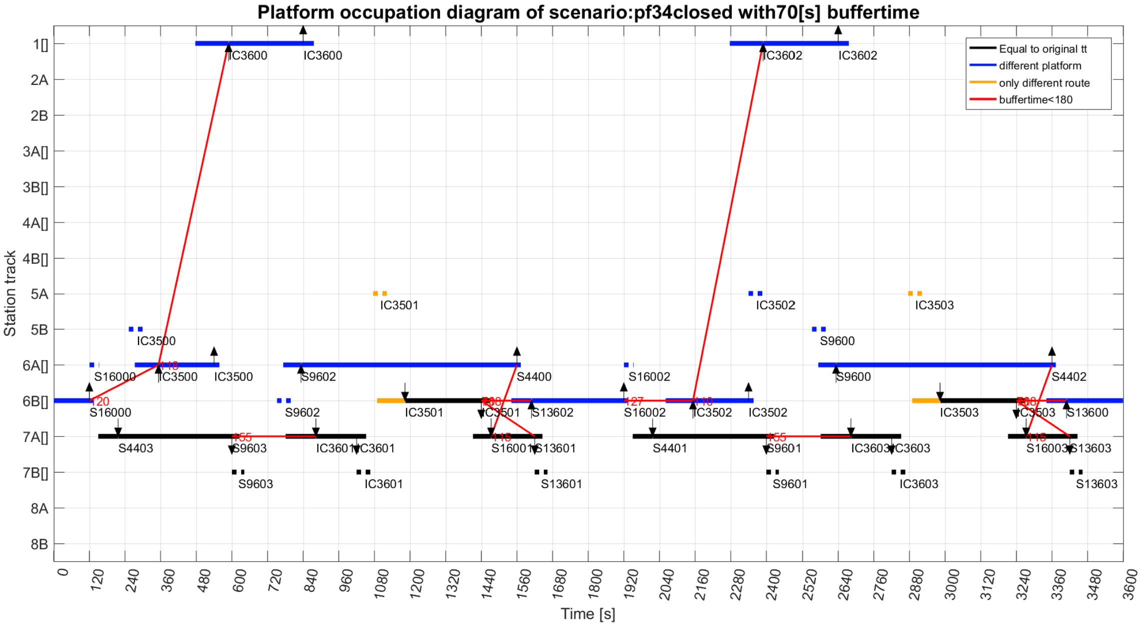

Figure 5.9: Platform occupation diagram of Den Bosch when platform tracks 3A, 3B, 4A and 4B are closed, now with increased buffer time. Series 800 is cancelled.

objectives of the model, namely minimizing the largest platform occupation. This leads to moving train 3602 away from platform 4B so that the platform occupation of 4B is lower. When not considering the objective of minimizing the maximum platform occupation, a regular route plan as shown in Figure 5.7 is generated. Whether regularity or robustness in the form of more balanced platform occupation is more important is a decision that could be different for each situation. Especially since in this case both route plans have the same minimum buffer time of 114 seconds.

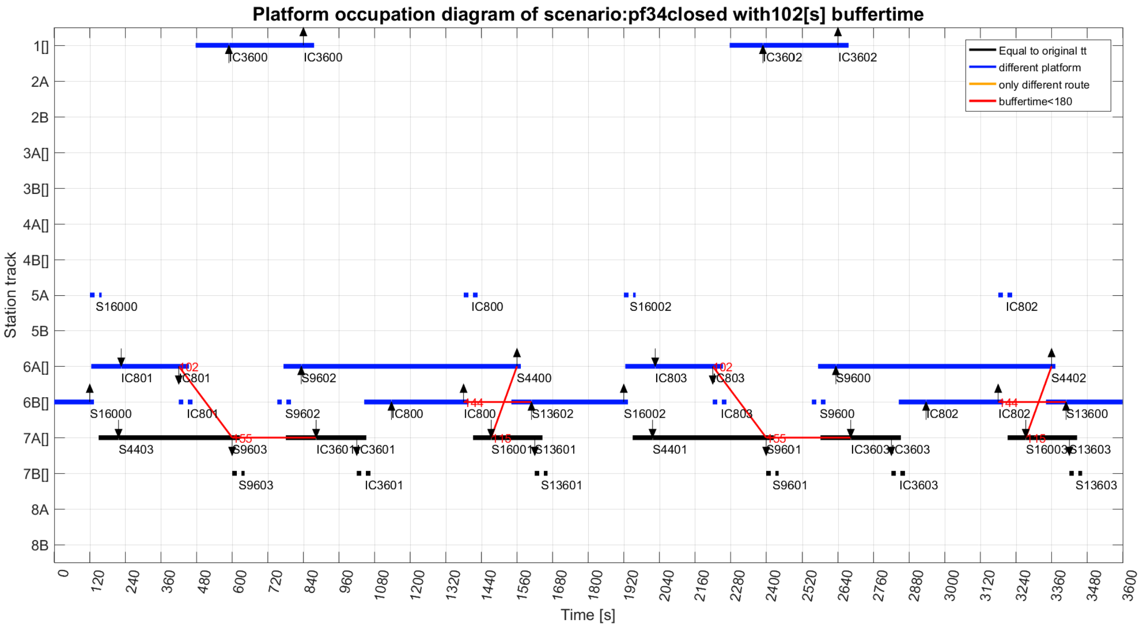

Figure 5.10: Platform occupation diagram of Den Bosch when platform tracks 3A, 3B, 4A and 4B are closed. Series 3500 is cancelled, and series 800 uses shorter trains in order to fit on platform 6B.

5.4.3. Scenario 3: Platform 3 and 4 closed

Closing platforms 3 and 4 leads to the cancellation of 4 inbound trains and 4 outbound trains, all from the 800 series which means this complete service is cancelled. All other trains are still possible to be scheduled according to the model. The platform occupation diagram with the results can be seen in Figure 5.8. 24 trains use a different platform compared to the original timetable, and 2 routes use a different route but the same platform as the original timetable.

Buffer times between several trains in the route plan are still quite small. This resulted since cancellations of multiple trains lead to the termination of the heuristic. Such small buffer times can be an indication that the route plan is not desirable, and the model is run again with now a larger starting blocking time supplement of 44 seconds. Two results of this optimisation are shown in Figures 5.9 and 5.10 (penultimate result).

Figure 5.9 shows that the 800 series is cancelled, and Figure 5.10 shows that the 3500 is cancelled while the 800 series uses a shorter train formation, leading to a larger buffer time. The final iteration cancels both the 800 and 3500 series, and therefore the heuristic procedure is terminated. A (human) planner assessing both the capacity and robustness of the route plan should decide what is more desirable to operate: a route plan with lower buffer time but more capacity, or a route plan with more buffer time, but less passenger capacity.

5.4.4. Scenario 4: Vga side closed

Because intercity trains need to short turn, it is used as an input that rolling stock connections must be found for these trains as well since now all three tracks to Vught Aansluiting are closed. This leads to more possible routes, because each outgoing route connecting to a different incoming route is a new route, and therefore longer preprocessing and computation time.

Results can be seen in Figure 5.11. All trains to and from Vught aansluiting are cancelled, and all trains to/from Utrecht and Den Bosch Oost can short turn at Den Bosch. The 800 series turns around on itself, and the 3500 connects to the 3600. This has large influence on rolling stock circulation, and should therefore be checked by planners whether this result is desirable. If not, specific rolling stock connections for turn around trains can be specified, or certain rolling stock connections can be excluded from the model.

5.4.5. Scenario 5: Vga side closed and fixed switch

This case is exactly the same as the previous one, except that a fixed switch prevents routes from using tracks 4B to 5A and vice versa. This route is used for both incoming trains of the 800 series as outgoing trains of the 800 series as is shown in figure 5.11. Figure 5.12 shows the result when the switch is fixed.

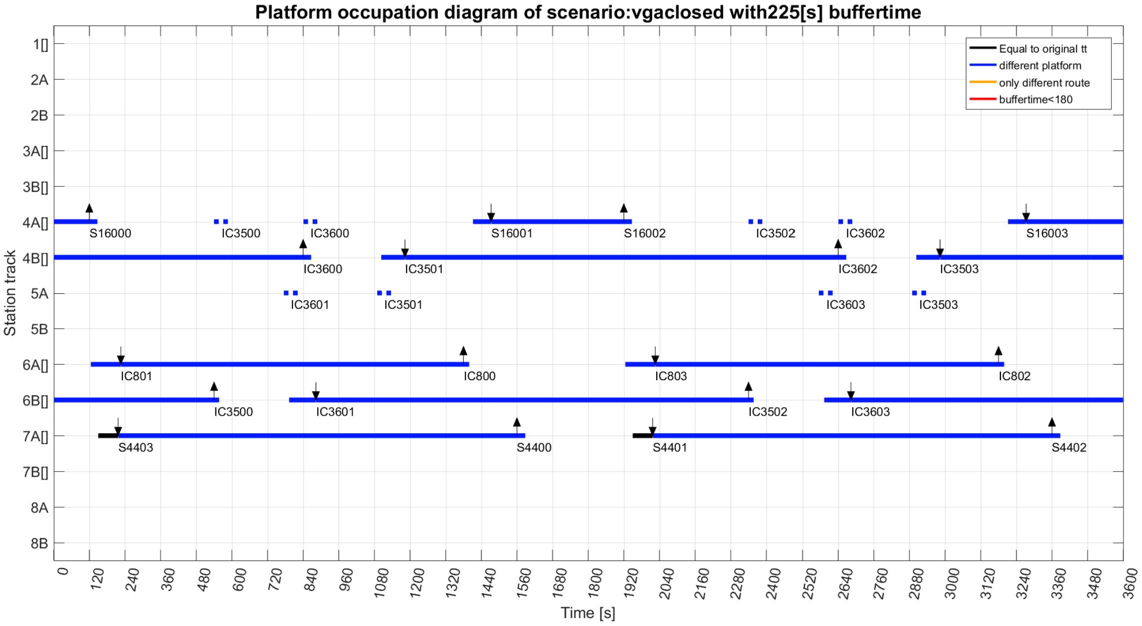

Figure 5.11: Platform occupation diagram of Den Bosch when all open tracks in the direction of Vught aansluiting are closed.

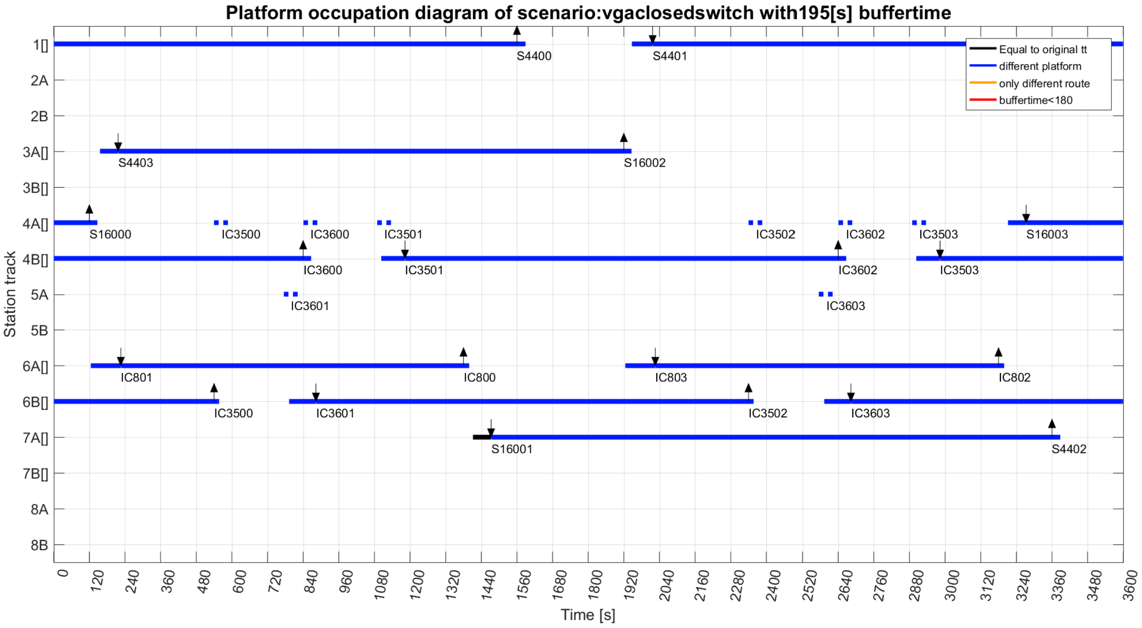

Figure 5.12: Platform occupation diagram of Den Bosch when all open tracks in the direction of Vught aansluiting are closed, and a fixed switch makes routes using both tracks 4B and 5A impossible.

Besides cancelling all trains to and from Vught aansluiting, now also a 3600 series to and from Den Bosch Oost is cancelled once an hour because of this fixed switch. Using a shunting movement from platform 4A to 4B it is possible to operate this train once an hour. Besides the fixed switch, the timing of the arrival and departure of the 3600 series also has an influence. Because these times are almost equal, it is impossible to turn around this series twice an hour on the same platform, because this causes conflicts. For this reason either multiple platforms must be used, or a shunting movement should be applied. The model chooses to use a shunting movement once an hour, and use all other platforms for other trains. An important note on this

Table 5.6: Overview of route plan of 04/06/16 as planned and operated by NS

Series	Event	Platform NS	Platform TRAP model	In/out track	Route choice	Time [s]	Rolling Stock	Time shifts
800	A	4B	3B	CH	-1	1137	VIRM10	0
800	D	4B	3B	CG	-1	1380	VIRM10	0
801	A	6A	4B	BG	1	480	VIRM10	0
801	D	6A	4B	CH	-1	1260	VIRM10	0
4401	A	3A	1	OL	-1	217	DDZ4	0
4400	D	3A	1	PL	-1	1560	DDZ4	0
3601	A	6B	6B	OL	-1	883	DDZ6	0
403600	D	6B	6B	BG	-1	43	DDZ6	0
403600	A	4A	4A	BG	-1	117	DDZ6	0
3600	D	4A	4A	PL	-1	840	DDZ6	0
16001	A	6A	6A	BG	-1	1473	SLT10	0
16000	D	6A	6A	CG	-1	120	SLT10	0

is that not all platforms can be used to short turn in Northern direction because of the infrastructure layout of the station. Scheduling the cancelled 3600 train for example on platform 6A would lead to the cancellation of 2 arrivals and departures of the 800 series, while only 1 arrival and departure of the 3600 series would replace it. Since this causes a higher objective function it is obvious that the model chose differently.

5.4.6. Scenario 6: NS case

The NS case dates 4th of June 2016. A regular hour pattern is used at daytime so that no irregular night trains are present. This case is also similar to the closing of the open tracks directed to Vught aansluiting.The only exception is that one of the tracks to Vught aansluiting is still available, and single track operations is possible for the 800 series. This leads to a longer stop of the 800 series in southern direction, because it has to wait for the arriving train from Vught aansluiting. These mentioned adjustments in the timetable are applied manually, and fixed rolling stock connections between the arrival and departure of the 800 series is also added, after which the model can find a route plan.

Figure 5.13 shows the platform occupation diagram of the route plan created by the model. It shows that shunting movements are used for the 3600 series from platform 4A to 6B, that the 3500 series short turns at platform 6A, and the 4400 series short turns at 7A. Furthermore the 800 series use platform 3B in northern direction, and 4B in southern direction. A large difference with the route plan made by NS is that in the route plan created by the TRAP model the 3500 series can still be operated. A possible reason why this series was cancelled by NS could be that a large part of Utrecht Centraal, a station also served by both 800 and 3500 series was possessed. Therefore the TRAP model was run again with the 3500 series cancelled beforehand. This leads to results shown in Figure 5.14.

In Figure 5.15 the platform occupation diagram as planned by NS is shown, and Table 5.6 shows a list of platforms of both the route plan generated by the model as planned by NS. Not all platforms that are allocated to trains by the model are equal to what is planned at NS. The objective function that would corresponds to the planning made by NS is equal to 12019106, while the model found a solution with a slightly lower value of 12018180. The objective function of the NS planning is therefore 0.0077 % higher, and the minimal buffer time that results from the NS planning is only 118 seconds while the route plan generated by the TRAP model has a minimum buffer time of 297 seconds. Therefore the route plan that is generated can be considered more robust than the planning made by NS.

Series 16000 and 3600 use the same platform in both route plans, although the departure time of the shunting movement series 403600 is slightly different: at NS this train departs at 0:29 and 0:59, while in the model this train departs at 0:31 and 0:58. Not exactly the symmetrical times are chosen in the model because the timing does not directly influence the objective function since no new conflicts arise. The departure times differ slightly with NS since a shunting movement is generated every 3 minutes in the model, out of which one was chosen, therefore it is possible this also leads to small differences. The departure times of the shunting movements do influence the the buffer time in the route plan. Instead of departing at 0:31 it would have been better in terms of robustness to depart at 0:28 since this increases the lowest buffer time for the

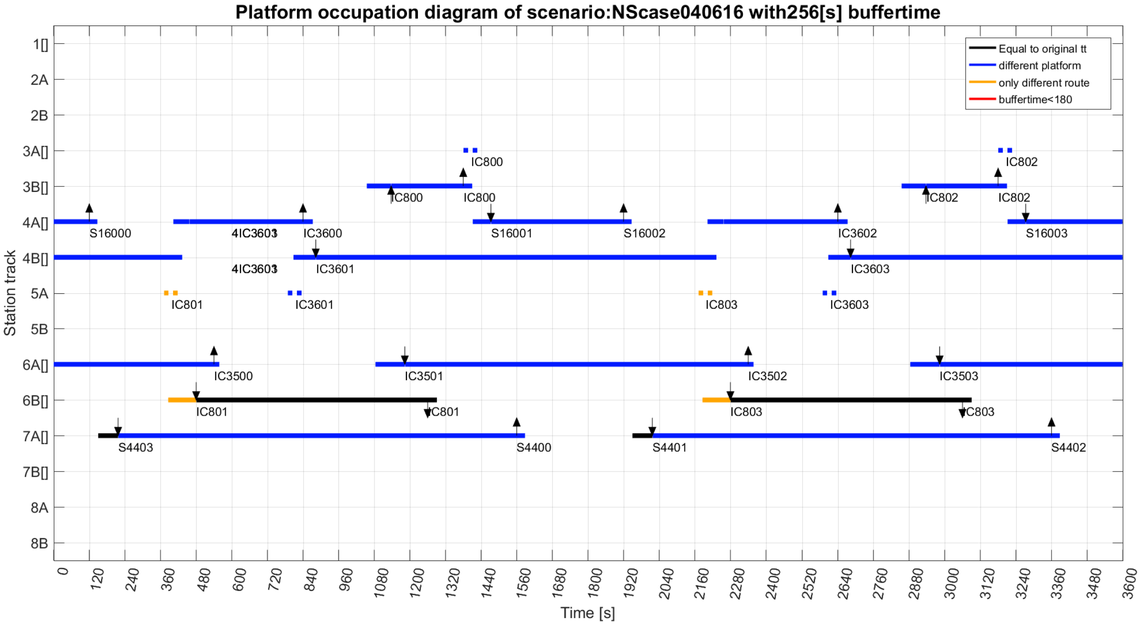

Figure 5.13: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

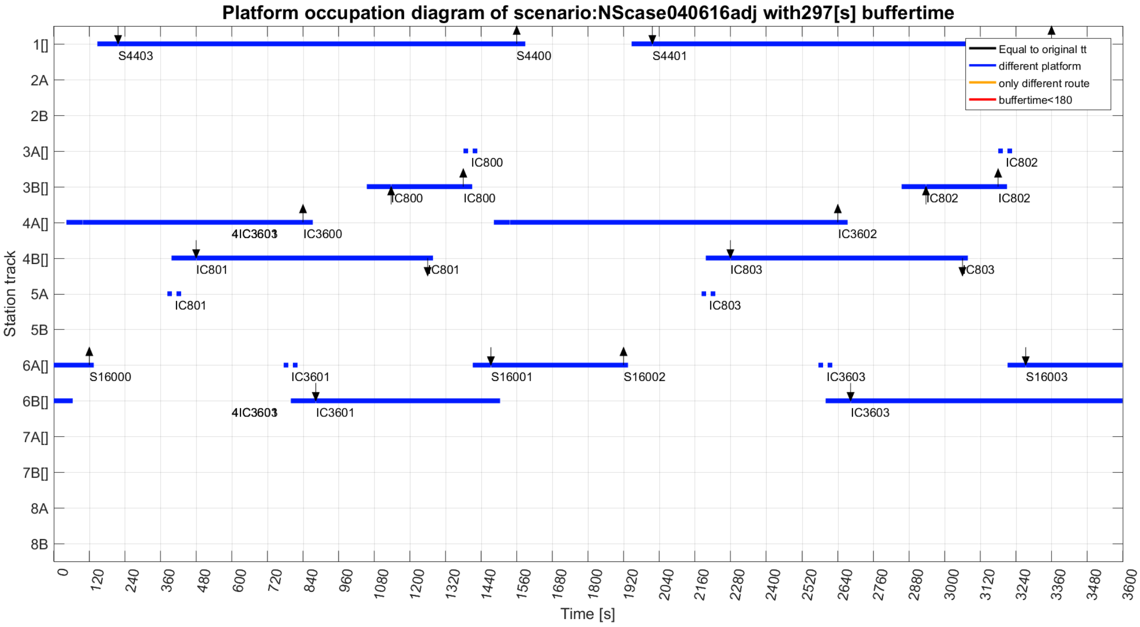

Figure 5.14: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Here the 3500 series is cancelled manually in order to improve the reference route plan used at NS.

shunting movement with 3 minutes. Future work could improve the timing of shunting movements in terms of robustness.

Because a more robust route plan was found by the TRAP model, several trains have a different platform allocated compared to the NS planning. Series 800 finally uses a different platform in the model in both directions. NS planned trains 801 and 803 in southern direction on platform 6A, which resulted in the smaller

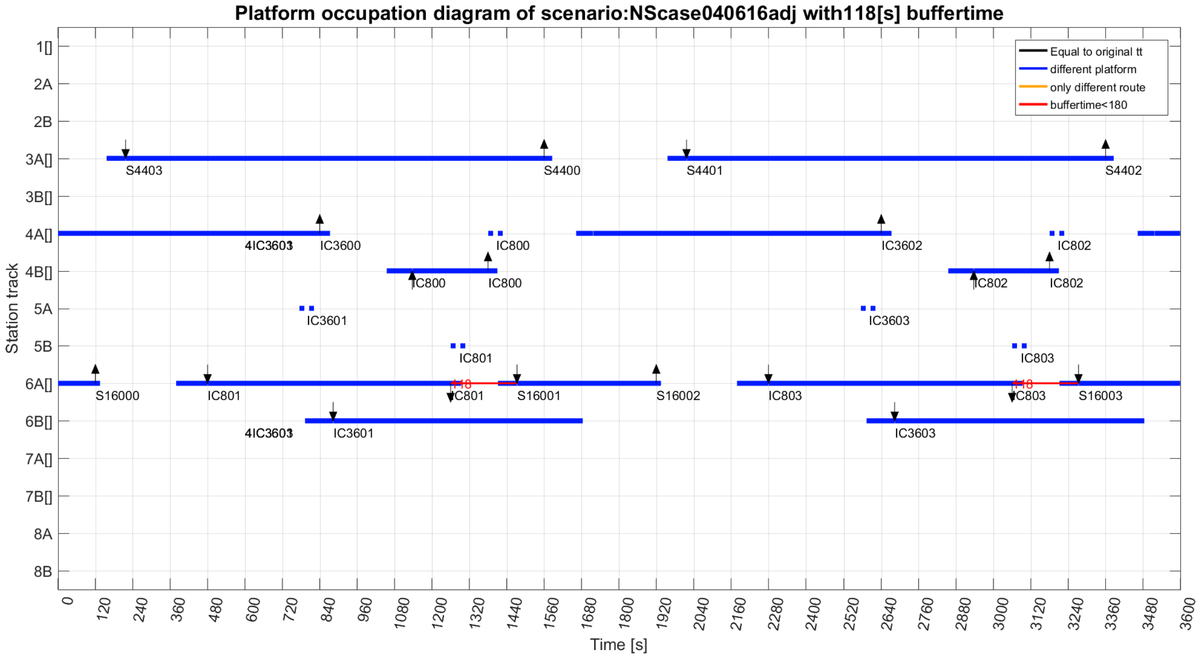

Figure 5.15: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught as has been planned by NS.

buffer time since the 16000 series arrives shortly after the departure of trains 801 and 803. By moving these trains to platform 4B, this low buffer time disappears. Because of this change, trains 800 and 802 in northern direction are moved to platform 3B, because platform 4 is occupied by the 800 series in the opposite direction. The 4400 short turns at platforms 1 in the model, instead of platform 3A as planned by NS. The reason for this is that series 800 uses platform 3B, and needs platform 3A in order to get to the necessary exit track. Although some differences between the route plans made by NS and the TRAP model are spotted, planners at NS confirm that the solution found by the TRAP model also satisfies all planning constraints that are applied. In other words, the solution found by the model is suitable for operations.

5.4.7. Scenario 7: Time shift

In this scenario a manually adjusted timetable is used as an input, so that two trains conflict regardless of the route that is chosen. Imposing a time shift for one of these trains can solve that conflict. This scenario is run with the time shift extension as explained in Chapter 4.

The original timetable is used as an input, except for a small change: The departure time of train 813 is delayed so that it just conflicts with train 9601. Since both trains use the same exit track, only a time shift can delete the conflict.

Figure 5.16 shows the route plan generated by the model for this timetable. An incoming and outgoing route of the 9600 series is cancelled, because the outgoing route conflicts with train 813. This means that the 4400 series needs to short turn at a platform. In the next iteration time shifts are applied. From the 2 cancelled trains, 132 routes were shifted in time. Furthermore there were another 451 routes that have a small overlap with one of the routes of the cancelled train, leading to a total number of 4638 routes. This number is so much higher because of rolling stock connections that need to be determined by the model. Results are shown in Figure 5.17. Now train 9601 is shifted 30 seconds forward, so that no overlap with train 813 exists. Since there was an overlap in blocking times for these two trains, and the total time shift is 60 seconds (one train forward, and one train backward), the buffer time between these trains is also lower than 60 seconds.

After the iteration with time shifts, it is possible to try to improve the robustness by extending the blocking times. Results for this are shown in Figure 5.18. Some changes in platform assignment occur, leading to a larger minimum buffer time. Also, train 813 now only uses platform 6B, which is too short to accommodate the regular train length of the 800 series. Therefore a shorter train is chosen. The next iteration leads to the cancellation of trains, which terminates the heuristic. If a larger buffer time is desired, two or more trains

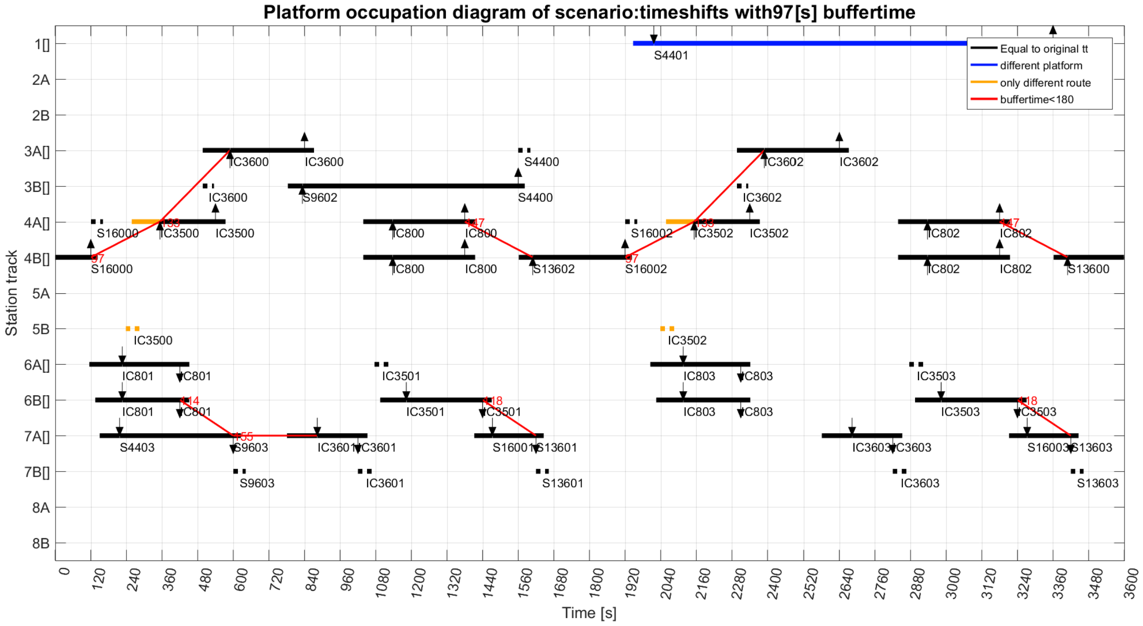

Figure 5.16: Platform occupation diagram of Den Bosch when such an input timetable is used that not all trains can be scheduled, leading to the cancellation of an incoming and outgoing train of the 9600 series.

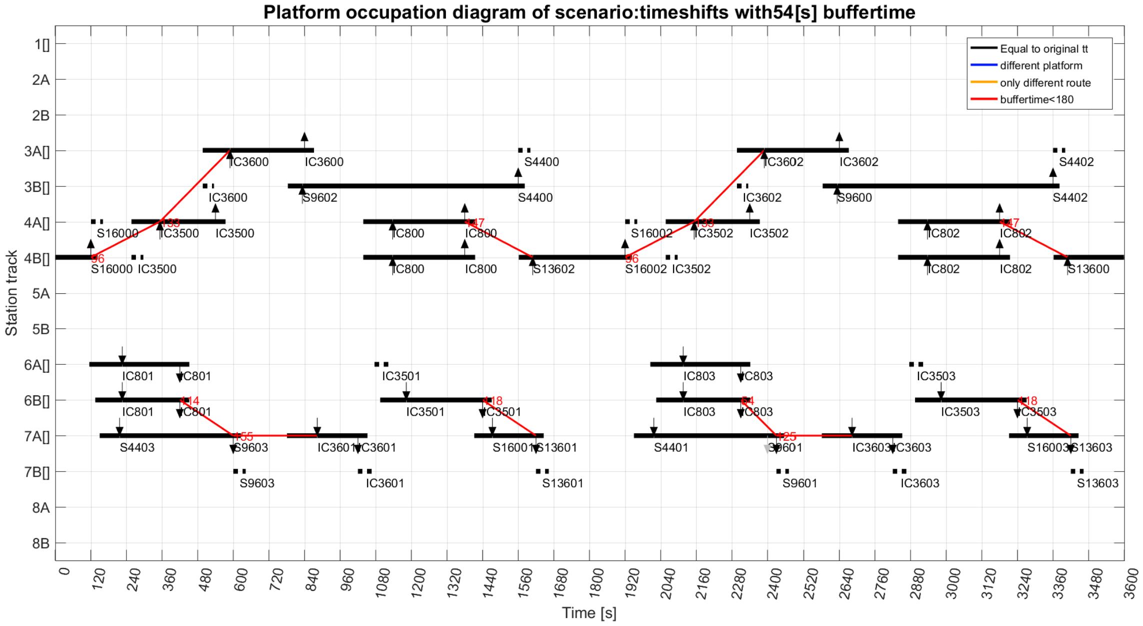

Figure 5.17: Platform occupation diagram of Den Bosch for the same timetable as in Figure 5.16 but when timeshifts are applied. Now all trains can be scheduled because train 9601 has been shifted 30 seconds forward, thereby eliminating the conflict with train 813.

need to be cancelled, or larger time shifts need to be applied. Chapter 7 gives recommendations on this.

Applying time shifts for all trains makes the problem too big to solve fast. It takes about two hours to pre-process and solve that problem while considering a total number of 11794 routes. Compared to the 4638 routes that results from using the heuristic this number is much higher. Therefore the heuristic approach presented in Chapter 4 performs much better with a calculation time of just over 2 minutes, while leading to the same results.

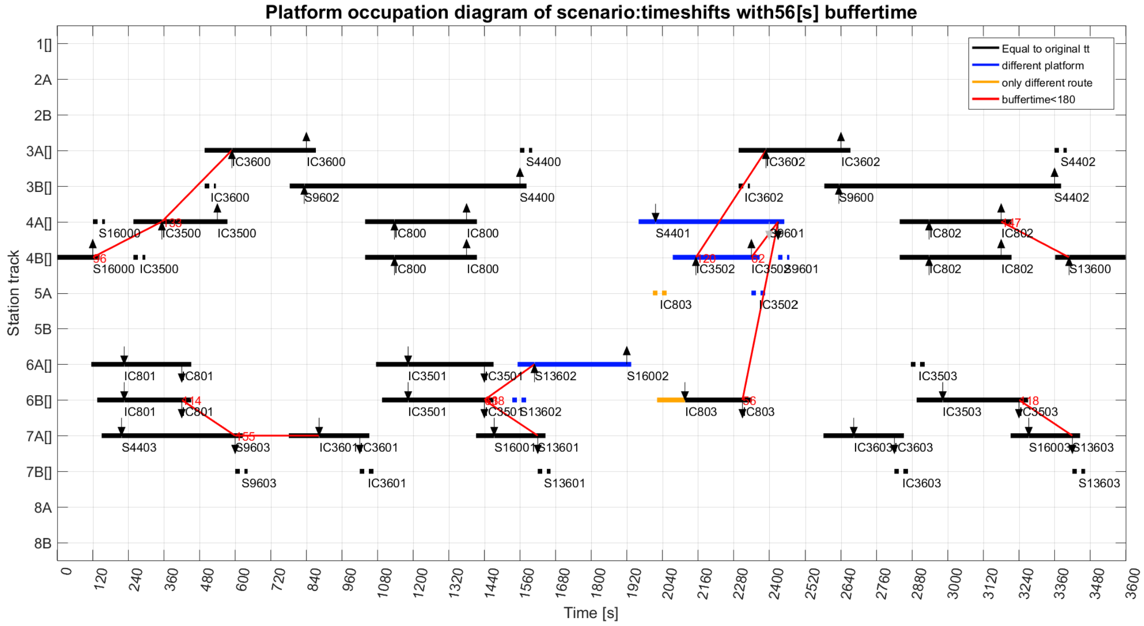

Figure 5.18: Platform occupation diagram of Den Bosch for the same timetable as in Figure 5.16 but when timeshifts are applied and robustness increased. This leads to several changes in platform allocation and the use of a shorter rolling stock for train 813.

5.5. Number of routes

The number of routes and constraints are the variables that influence the calculation time of our TRAP model. Several model choices may have a large influence on the number of routes: the number of trains for which no rolling stock connection is specified, the number of shunting movements to be investigated and whether time shifts are applied. Furthermore the number of trains in a timetable also influences the total number of available routes, and therefore the calculation time. This section shows how much the number of routes increase when each of these model choices are changed.

5.5.1. Approach

Route plans are created for multiple timetable sizes and for several model choice combinations. All route plans are created with platforms 3A and 3B being possessed. This possession is chosen to show the model works for possessed resources, while not that many routes are deleted due to the possession.

To achieve the desired timetable size, we start with the 2016 timetable of NS. This timetable consists of 40 different arrivals and departures. Every arrival and departure are coupled with another arrival and departure of the same train line in opposing directions. This leads to 10 groups of each 4 train routes that are eligible to be in the smaller timetable. From these 10 groups a certain number is randomly chosen, based on the desired timetable size.

For several fictive timetables the routes are generated that would be used to find a route plan in Den Bosch. The number of trains in each timetable varies from 12 until 28 trains. For each of these timetables the three model choices are varied: First, shunting movements are applied for all train pairs that satisfy the criterion defined in Section 4.3 or not at all. Second, time shifts are applied for all trains in the timetable, or not. Third, rolling stock connections are provided for all trains, indicated with a 1 in Tables 5.7 and 5.8, or determined by the model, indicated with a 0. The three choices are combined when possible, since shunting movements are only implemented for trains without a rolling stock connection specified. This leads to 6 different combinations of the three model choices that are assessed.

For each investigated timetable size, five timetables are created for which each of the 6 different choice combinations are run. It is chosen to create multiple timetables, and average the results since a larger variation between the number of routes for each timetable can be expected. Especially the number of shunting routes to be created depends a lot on both the defined criterion and the timetable.

Shunting movements	Time shifts	Rolling stock connections	Number of routes				
			12 trains	16 trains	20 trains	24 trains	28 trains
0	0	1	196	261	334	403	448
0	0	0	377	726	1014	1467	1708
0	1	1	1151	1554	1992	2414	2670
1	0	0	472	1143	1681	2510	2933
0	1	0	2592	5246	7424	10926	12787
1	1	0	2828	6276	9081	13519	15822

Table 5.7: Overview of number of routes depending on the number of trains in the timetable, and whether shunting movements are used, time shifts are applied, and rolling stock connections are specified.

Shunting movements	Time shifts	Rolling stock connections	Calculation time [s]				
			12 trains	16 trains	20 trains	24 trains	28 trains
0	0	1	2.54	2.98	4.76	4.31	6.80
0	0	0	3.68	8.32	12.16	15.45	23.93
0	1	1	12.97	17.29	26.88	32.59	43.88
1	0	0	5.21	17.63	27.42	52.68	70.28
0	1	0	39.28	152.29	266.93	570.98	736.35
1	1	0	46.09	212.16	516.45	1163.47	1455.30

Table 5.8: Overview of calculation time depending on the number of trains in the timetable, and whether shunting movements are used, time shifts are applied, and rolling stock connections are specified.

5.5.2. Results

In Figure 5.19 the number of routes that are considered are set out to the calculation time needed to solve the problem. Now the expected non-linear relation is clearly visible. Also, the case studies considered earlier in this chapter fit perfectly in the same graph, explaining why Figure 5.2 looks linear.

Figure 5.20 shows the number of routes for all six combinations of model choices for each chosen timetable size. It is clear that applying time shifts to all trains increases the problem a lot when this is combined with unknown rolling stock connections. When either one of these two is investigated, the computation time is always lower than 100 seconds, as can be seen in Figures 5.22 and 5.23. In order to show the differences in problem size between the other four combinations, a graph without the largest two combinations is shown in Figure 5.21. It is clear that not adding shunting movements, not applying time shifts and using predefined rolling stock connections for all trains leads to the smallest number of routes and therefore fastest computation times. Next, letting the model find rolling stock connections without adding shunting movements and timeshifts leads to just larger number of routes, followed by knowing rolling stock connections and applying

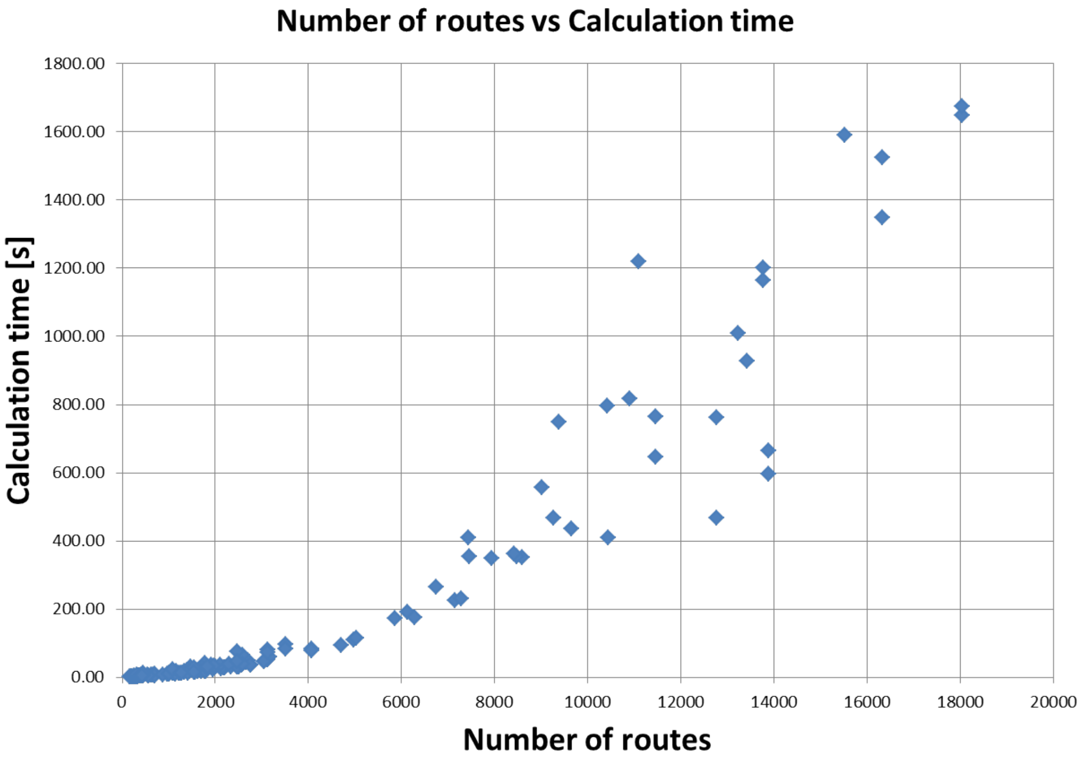

Figure 5.19: The number of routes versus the calculation time for all cases taken into account while assessing how the problem size increases.

time shifts while not adding shunting movements. It must be noted that for small timetables, adding shunting movements has almost no influence on the problem size, while for larger timetables, adding shunting movements can almost double the problem size. This is because in small timetables the criterion to add shunting movements is much less often met. In addition, changing the value of the selection criterion will also lead to a different number of shunting routes.

It can be concluded that finding rolling stock connections in general has a smaller influence than applying time shifts to all routes. When these two are combined together, the problem becomes very large, especially considering that the current investigated timetables can be considered quite small. Adding shunting movements to the set of routes does lead to higher computation times, mainly for larger timetables.

5.6. Conclusion

The case studies demonstrate that the model finds a feasible route plan that takes passenger transfers, platform assignment in the original timetable and route preference into account. The minimum buffer time is maximised in order to increase robustness, and shunting movements are applied where necessary.

However, results are not (always) equal to similar cases planned by NS. The main reason behind this lies in the chosen objectives, combined with the situation when route plans are completely different from the original timetable. The model only makes a distinction between using the same platform as the original timetable, or any other platform. In this situation the model gets no feedback which trains to schedule to which platform, since most of them need to use a completely different platform for both their arrival and departure. This leads to multiple available platforms that are all not chosen in the original timetable and are therefore equally penalized. This means only the route preference, consisting of a given preference and driving time, is left as an objective that can influence the platform decision.

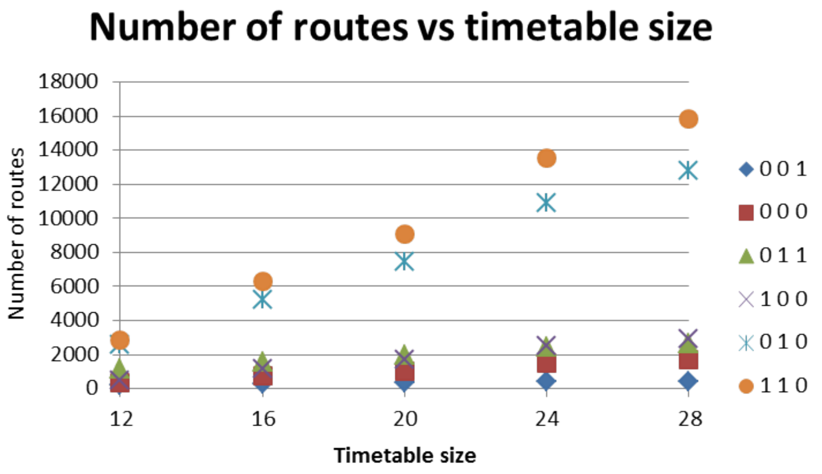

Figure 5.20: The number of routes for 5 different timetable sizes at each of the 6 model choice combinations.

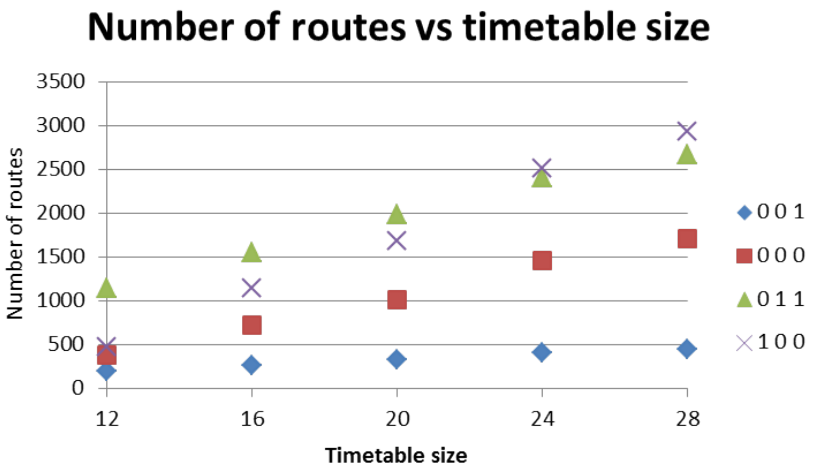

Figure 5.21: The number of routes for 5 different timetable sizes without the two highest model choice combinations.

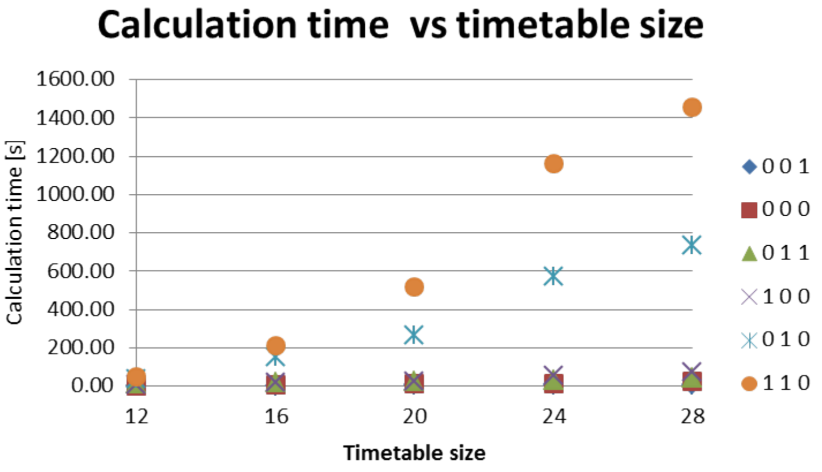

Figure 5.22: The calculation time for 5 different timetable sizes at each of the 6 model choice combinations.

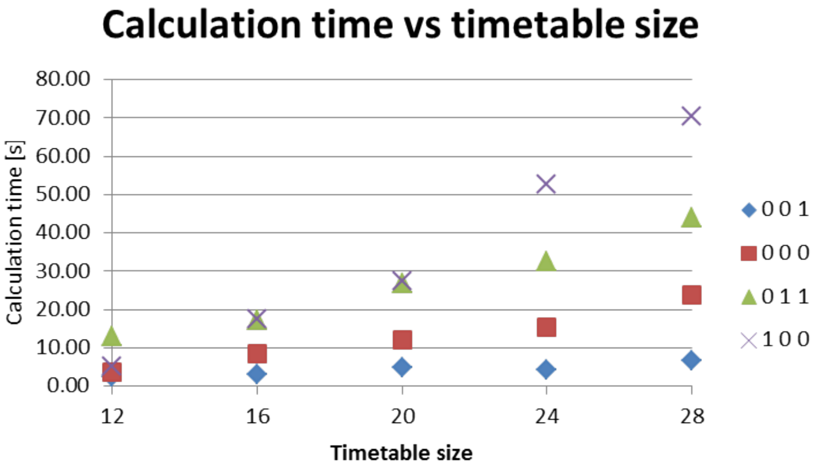

Figure 5.23: The calculation time for 5 different timetable sizes without the two highest model choice combinations.

6

Feedback to macroscopic model

The model presented in this thesis is meant to cooperate with the macroscopic TTAP model that adjusts the timetable for a complete network in case of planned maintenance (complete blockages or a number of platforms closed in a station). This model uses a PESP formulation for event times that are constrained by standard headway times between two succeeding trains based on their relation in the regular timetable. The relation can be between two succeeding trains in the same direction or in the opposing direction. For either situation a fixed headway is available depending on the event (arrival, departure, pass through) of each train. The headway times are then used to generate an alternative timetable based on the possessions and the original timetable. This generated timetable is then checked by the presented microscopic model by creating a route plan at each large station in the network.

Because of maintenance possessions, the relation between two trains can change. When less (platform) tracks are available, the routes of trains in the station area need to change, and can lead to more crossing relations between two trains. It can also lead to trains having a relation that they did not have before, because possessions make level crossings necessary. Therefore, headways used in the microscopic model can be used

This chapter describes four different outputs of the microscopic model and how these outputs can be used as input for the macroscopic model: Headways, cancellations, train length and transfers. The aim is to create a converging iterative process between the two models resulting in a conflict free timetable.

6.1. Headways

Station headways can be updated in the macroscopic model based on the outcome of the microscopic model. A condition for this must be that a feasible route has been found for the two trains from the headway information. Instead of the predefined headways the headways calculated using blocking time theory can be used. If the headways calculated using the blocking time theory are lower than the predefined headways it can be useful to use the shorter headway in the macroscopic model since this gives the model more freedom in scheduling the train (constraint relaxation). However, this feedback should be done with caution since relaxing too many headway constraints, even though this still leads to a feasible timetable, affects robustness of the timetable immensely. Therefore it is important to investigate when headways in the TTAP model can be decreased. Headways can also be increased in the TTAP model if the buffer time between two trains in the microscopic model remains too low. The smallest buffer times are increased as much as possible in the TRAP model, however if this value has not the desired size, then the headway between the trains can be increased. This height of this value should be found, or come from a seperate or integrated robustness evaluation model.

Furthermore, if the time shift module is used and one or more trains are retimed in order to accomodate more trains in the route plan, these new event times should be communicated to the TTAP model. This can be done by updating the headway times between the time shifted train and the trains that have a headway connection between them. At least one of these headways has changed (by either increasing or decreasing) since the event time has changed while those of the adjacent trains have not.

6.2. Cancellations by micro model

When the microscopic model cancels a train, this is done because not enough infrastructure capacity was available to execute the timetable given by the macroscopic model. The cancelled train then leads to the highest objective function at the relevant station, but might not be the most beneficial for the entire network. Therefore a cancellation has to be imposed in the macroscopic model as well, but not necessarily for the same train as cancelled in the microscopic model. A new constraint should therefore state that the number of cancellations for each station must be equal in both models, but the macroscopic model can be given some freedom on which train to cancel. In this way based on the number of necessary cancellations at each station a decision can be made which (part of the) train line to cancel. After every macroscopic step, the microscopic model should check the feasibility of the adjusted timetable.

Retiming one or more trains could also lead to less cancellations that result from the microscopic model. Small retimings are taken into account by the microscopic model directly, but larger time shifts should be imposed by the macroscopic model because they have an impact on the complete network. From a cancellation is is not directly known what the reason is, but increasing the headway between the cancelled train and the preceding and succeeding trains, or by finding an appropriate time slot in the blockingtime diagram, could lead to less cancellations.

6.3. Train length

If a shorter train is chosen by the macroscopic model, this has influence on the complete itinerary of that train because this shorter train length must be used on the complete line of that train. Therefore other stations using the same train line must also use the blocking times generated for the shorter train in order to ensure feasibility. Current results have shown that blocking times (for small station areas) only differ slightly when a shorter train length is used. Together with a sufficient buffer time, these changes do not lead to new conflicts. For larger station areas, especially if an area consists of multiple stops, the difference can become much larger. Because of this, and because feasibility must be certain, it is advised to use the correct rolling stock length for all blocking time calculations.

A solution to mitigate the capacity limitation is to increase the length of the train on a next station by coupling one or more extra train units to the shorter train. In this way only part of the line service suffers from a decreased capacity. Shortening and extending trains should be an extension that can be added in the microscopic model, since it affects platform and route allocation. Shorter train lengths should always be checked for passenger capacity by either a human planner or a passenger distribution model in order to ensure that capacity demands are met.

6.4. Transfers

Infrastructure possessions at a station can lead to different platforms for trains. This influences the distance passengers have to walk between two trains when making a transfer at this station. A longer walking distance (expressed in number of station tracks) can lead to an infeasible transfer if the time between arrival and departure remains the same. A missed transfer is penalized in the microscopic model, but retiming one of both trains of the transfer can make the transfer feasible again. Therefore the headway between the two trains of the transfer is increased up to the minimum transfer time, so that the transfer is also feasible for the longer walking distance. This headway should not be formulated as a strict constraint since it is not an essential headway to ensure a feasible timetable, but does improve passenger service if the headway is satisfied.

7

Conclusion and future work

This chapter gives answers to the formulated research questions from Chapter 1. Next, future work is discussed and finally, recommendations for practice are given.

7.1. Conclusion

The main research question is formulated as follows:

- *How to adjust route plans in station areas that provide the least changes to the original timetable and minimize the passenger dissatisfaction?*

Infrastructure maintenance leads to possessions of infrastructure causing a timetable to become infeasible. Adjustments in the timetable need to be made, so that a feasible timetable is created that minimizes the discomfort for passengers. Since this timetable is adjusted at the macroscopic level, it is necessary to ensure feasibility in station areas by creating a route plan based on blocking time theory.

Using integer programming, constraints and an objective function a route plan is constructed for a given timetable. An iterative heuristic has been described that finds a feasible, robust and passenger friendly timetable. First a route plan is created given a chosen buffer time. Then, based on whether one or more cancellations occurred in the results, time shifts are applied on the routes of the cancelled trains, and the routes that have a small overlap in blocking time with the routes of the cancelled trains. A route plan is created again with the time shifts applied if this is beneficial. Depending on penalties assigned to both routes with time shifts and other objectives, using a route with time shift can lead to less cancelled trains, more feasible transfers or a larger robustness.

After these steps are taken, the smallest buffer time is tried to be increased by adding a buffer time supplement to the blocking times so that the buffer time between all routes must be at least one second higher than the smallest found buffer time. This process is repeated until the objective value of the route plan leads to much worse results.

The case studies have shown that feasible route plans are created, with an acceptable robustness, while taking the original timetable and infrastructure possessions into account. Results are not always equal to adjusted route plans at NS, because no comparison is made to keep platform assignment equal to the original timetable.

- How can a mathematical microscopic model help to adjust the railway timetable during scheduled maintenance?

Using integer programming, constraints and an objective function a feasible route plan that is as much similar to the original route plan is created, taking infrastructure possessions in the station area into account. Infrastructure possessions can be in the form of pieces of regular railway track in the station area, one or more open tracks at the border of the station area, switches, parts of or complete platforms, and fixed switches.

Constraints that are needed to solve the problem ensure that only one route per arrival or departure is chosen, no overlapping blocking times occur, the number of trains in each direction is equal and rolling stock connections correspond to the correct platform occupation.

Objectives of the model consist of scheduling as many trains as possible with the correct train length, using the least time shift as possible, using as many platforms equal to the original timetable, and using the fastest and most preferred route.

Computation times resulting from a case study are always below 130 seconds. For simple cases in which no short turning needs to be applied, computation times are always below 20 seconds. However, analysis has shown that the relation between problem size and computation time is not linear, so it is helpful to keep the total number of routes to be considered under control.

- What practical constraints are to be developed in order to make the model applicable to real life instances?

Several practical constraints are added to the model to make it applicable to cases in Den Bosch, and many other large stations. First, it has been made possible to use both parts of a divided platform at the same time by the the same train. This enables longer trains to use a part of the platform that is too short, while also occupying the other part of the platform. This is beneficial because it gives more possibilities to find a platform for a train.

Another practical addition is to give the possibility to use a shorter train than specified in the original timetable. Due to possessions in the station it is possible only shorter platforms, or simply less platforms are available. Instead of having to cancel a train, it is also possible to schedule a shorter train that does fit on the available platforms.

Furthermore, shunting movements are added to the route plan if needed for short turning. First arrival and departure pairs are found for which shunting from platform to platform is reasonable to be applied. Shunting movements to or from a shunting track can be applied by the model as well. However, a different criterion could be found in order to reduce the total number of considered routes or to find other shunting possibilities.

- How to set the cooperation between macroscopic timetabling and microscopic routing?

Multiple data should be communicated to a macroscopic model. Headways that are considered too small by the macroscopic model should be increased, and headways that are assumed to be larger can be decreased. Also new headways can be added in order to increase the transfer time for passengers when needed.

Cancellations that are imposed by a microscopic model can be given directly to the macroscopic model, but this can also be done in such a way that the number of cancellations found at each station by the microscopic model should at least be equal to the cancellations done by the macroscopic model. In this way the macroscopic model can cancel the least train lines that cover all needed cancellations.

Train lengths that are changed in the microscopic model should be given to the macroscopic model as well, so that it can be checked whether the train length could be extended at another station, or to see whether other trains could compensate the lack of capacity by making these trains longer. Both implementations should afterwards be checked again by the microscopic model of the relevant station areas.

7.2. Future work

The TRAP model uses several assumptions and variables that influence the output. First the weight factors are discussed, followed by other variables in the model. Furthermore a cooperation with a macroscopic model needs is discussed.

7.2.1. Variables and parameter values

The weights used for penalties in the model (for cancellation, shorter trains, shunting movements, missed transfers, platform choice, platform occupation and route choice) have a large influence on the output as well, since they prioritize certain solution directions. Values for the weight factors can differ for each station since size of the station area (number of station tracks) and number of available transfers can be reasons to adjust these values. Values of these weights could lie far apart, leading to a complete hierarchical distribution between the penalties e.g., a cancellation is always worse than missing one or more transfers. However one can argue that one cancellation can be worth multiple transfers leading to the question how many, and which transfers are worth a cancellation to maintain the transfers? This is merely an example to show that these choices are not trivial and need more investigation on either optimizing the weight factors and/or applying an interaction with a human planner to make these kind of decisions.

The penalty height for missed transfers now only depends on the average number of passengers using that transfer. However, the extra waiting time due to a missed transfer is not always the same, and depends on both the frequency of the passenger service and the destination of passengers. Incorporating the waiting time based on both of these inputs can make a better trade off to which transfers are very important to maintain.

The largest platform occupation time is now minimised and added to the objective function. This is added as a robustness measure in order to prevent one platform from being used a lot while another platform is almost or completely unused. Besides this penalty, it is expected to be useful to add the total dwell time at all platforms to the objective function as well. Current results of some intermediate iterations show very long dwell times for short turning trains because this is not penalized separately. Adding the total dwell time would penalize long turn around times and therefore lead to better intermediate results. Another option to eliminate long dwell times at platforms would be to eliminate rolling stock connections with certain long dwell times, but in some cases this could eliminate good solutions.

When different rolling stock connections are chosen, for example because of short turning, the incoming and outgoing train could use a different rolling stock type and/or length. Although the process time for dwelling is checked for both types, it would be more accurate to run the model again after a rolling stock circulation plan has been made according to the results of the found route plan and check possibly slightly changed blocking times and dwell times. No large differences in blocking time are expected, but changed minimum dwell times could lead to different rolling stock connections. Therefore it is useful to have insight in the dwell times for short turning trains resulting from the model and available rolling stock and their minimum dwell times.

If both parts of a divided platform are used simultaneously by one train, not all sectional release times are currently known. The resources that are occupied by the rear end of the train due to its train length are not taken into account by the blocking time calculation for the departure. Incorporating the use of divided platforms in the blocking time calculation will result in more accurate blocking times when this option is used by the model, and will increase several buffer times because now a small overestimation is made to ensure feasibility.

Furthermore the extensions also use multiple variables that both influence the calculation time and the output of the model. Regarding the shunting movements the granularity of its departure time influences the the total number of routes. A smaller granularity can lead to more useful options to add feasible shunting routes, but also leads to more routes to be considered. Also, it is possible that the formulated condition on when shunting movements are applied can lead to the exclusion of good solutions of the routing problem. Since the problem size increases a lot when all possible shunting options are considered, more research is needed on finding when shunting movements in hourly patterns are used and possible other rules on when to apply these routes in the model.

When two shunting movements are operated consecutively, either to and from a shunting track, or making a saw movement along platform tracks, the timing of the second movement can be done in multiple ways. First, it could be a fixed time after the arrival time of the first shunting movement. This does not lead to a higher number of routes compared to when only one shunting movement from platform to platform would be used, but could limit the possibility for solutions too much, since other trains occupying infrastructure can make a longer or shorter dwell time at the shunting track necessary. This can be solved by also varying the departure time of the second shunting movement, but this leads to a much larger number of routes to be considered. Comparing both methods in several case studies will give more insight the results and computation times.

Applying time shifts compensates for the possible wrong assumptions made in the fixed headway times used in the macroscopic model. However this method also increases the calculation time considerably. It is useful to find how the granularity of the applied time shifts affect the number of routes, and how large applied time shifts can be. Larger time shifts can possibly lead to a better route plan at the station area, but affect the timetable for the complete network negatively. Furthermore it should be made clear what are useful maximum values for both the granularity as the maximum shift, or even let the time shift be dependent on the found blocking time overlap. Furthermore, different heuristics for applying time shifts should be tested. An extra iteration could be added that takes new overlaps into account caused by time shifts applied in a previous iteration. This could be done multiple times, but will increase the calculation time so a trade off between calculation time and flexibility in time shifts should be made.

Whether or not rolling stock connections are defined also influences the number of routes. The more rolling stock connections that are fixed, the less number of routes need to be considered. However this also limits the flexibility of the route plan. In the current model each rolling stock connection has to be turned on or off manually. Rules could be defined depending on possession type, station and timetable for when these connections can be used or when it is useful to investigate more flexible rolling stock connections and turn (several) defined rolling stock connections off.

When a shorter train is chosen to be operated because no sufficient long platform is available, it is possible that capacity demands can not be met. Possibly a human planner can assess whether it makes sense to run a shorter train or not. This could also be replaced by a passenger distribution model that calculates the demand in the disturbed network due to the planned maintenance.

Furthermore, when a shorter train is used in one direction. The train from the same series in opposite direction will also be operated with shorter rolling stock. This is not taken into account by the model since it would increase the number of routes considerably, but does not affect the feasibility of the route plan since a shorter rolling stock will always fit on the assigned platform. An iteration to the macroscopic model, or possibly another iteration in the TRAP model in which the input timetable has updated rolling stock information accordingly can solve this issue.

The current approach maximizes the smallest buffer times in the route plan. However, larger buffer times can possibly also be increased by choosing a slightly different route. Therefore a different or adjusted approach to increase the robustness of the route plan will result in improved timetables.

Another note is that when a complete side of a station is closed, changes to the route plan are considerably large so that objectives to keep changes compared to the original route plan as small as possible do not lead to the desired results. Fastest and most preferable routes are still found, and the smallest buffer time is maximized, but when multiple options are available the model chooses a random platform if they lead to the same objective value, i.e., multiple platforms are available that are all not used in the original route plan for a certain train, and all have an equal fast and preferred route available. This leads to route plans in which a train with a frequency of two per period from a certain line number uses a certain platform, and the train from the same line number half an hour later uses another platform. This could be solved by adding a form of regularity constraint or objective to the model.

7.2.2. Cooperation with macroscopic model

Besides variables of the microscopic model, also the interaction between both the macroscopic TTAP and microscopic TRAP model needs further research. The goal is to incorporate both models into one iterative model. In this way feasible route plans for all stations in the network are generated and the adjusted timetable of the complete network can be guaranteed to be feasible. There are however several assumptions or choices that influence the results and therefore need more research.

The size of the station area, as already mentioned in the conclusion of chapter 5 influences the results because it affects the amount of routing possibilities each train has and therefore the calculation time, but larger station areas can also give possibilities for trains to skip stops if multiple stations exist in one station area. This gives again more possibilities to adjust the timetable, but also leads to the situation that multiple macroscopic timetabling points exist inside the same station area.

Furthermore, the extension of the station area to include the intersections of Vught aansluiting (Vga), would give trains more routing possibilities for short turning and will let the TRAP model also check feasibility at this location. Since multiple routes of trains intersect at Vught aansluiting, it is a useful addition to check the feasibility of the adjusted timetable at this location as well. Including Vga in the station area of Den Bosch will therefore lead to a more reliable timetable because conflicts are checked and also, the two sets of double track from Vga to Tilburg and Eindhoven can be possessed separately.

Another topic related to the integration of the two models that needs more research is to adjust timetables in case of more than two tracks between stations. It has to be decided in which model it is beneficial to make the decision which track to use when multiple options are available. This decision affects both routing on a local level and the timetabling of the rest of the network, since headways between trains will differ based on the track choice.

The costs for operating the adjusted timetable and route plans should be considered as well. Currently adjusting route plans and timetables focusses on minimizing passenger discomfort, while not taking costs explicitly into account. It is expected to be useful to get more insight in the timetable that minimizes costs for the railway company since different rolling stock and personnel schedules can lead to different costs, and cancelling trains or providing alternative services leads to diminished revenues. Differences in both timetables can provide a better support to make trade-offs based on cost efficiency when adjusting timetables.

7.3. Recommendations

It is essential to model station areas of busy railway networks microscopically, so that headway relations between trains can be given more accurately. The proposed microscopic TRAP model should be run independently for each complex station area to find accurate, feasible and robust route plans. In addition, it is recommended to let the proposed microscopic model cooperate with a macroscopic model in order to give an accurate, feasible timetable for the complete railway network.

It is important to keep the number of routes per station area under control by applying shunting movements or finding new rolling stock connections only when these are expected to be useful. In large station areas it could also be helpful not to consider a number of unrealistic itineraries, especially for trains that still need a rolling stock connection.

Applying time shifts to all trains and finding rolling stock connections leads to very high computation times, while applying time shifts only for small blocking time overlaps decreases the problem size greatly. It is recommended to limit number of options for connecting rolling stocks for very large station areas. This could be done by a) predefining a number of rolling stock connections as an input, or b) give each train only a few rolling stock connections to choose from instead of the complete set as is done in the current model.

Since for every station area multiple iterations are needed in order to result in a robust timetable, it is estimated that is is helpful to try to keep calculation time below 5 minutes. This means the number of routes for each station area should be below 8000. These values are expected to lead to both a feasible timetable and routings for the complete Dutch network in an acceptable amount of time.

Appendix A: Shunting operations

In this appendix the considered shunting operations for the optimization model in station Den Bosch are described using a schematic layout. Only shunting from platform to another platform is considered because no separate shunting track is available in Den Bosch that could be used in an hourly timetable. In the station layout the shunting movement is drawn in orange. All operations are divided into the direction to which they accommodate short turning, and only consider short turning to the direction of the arriving train for simplicity. Other outgoing directions can be considered as well once the method has proved to work. Figures 1,2 and 3 describe the shunting movements for trains short turning to/from Oss, Figures 4,5 and 6 describe the shunting movements for trains short turning to/from Vugt aansluiting, and Figures 7 and 8 describe the shunting movements for trains short turning to/from Utrecht.

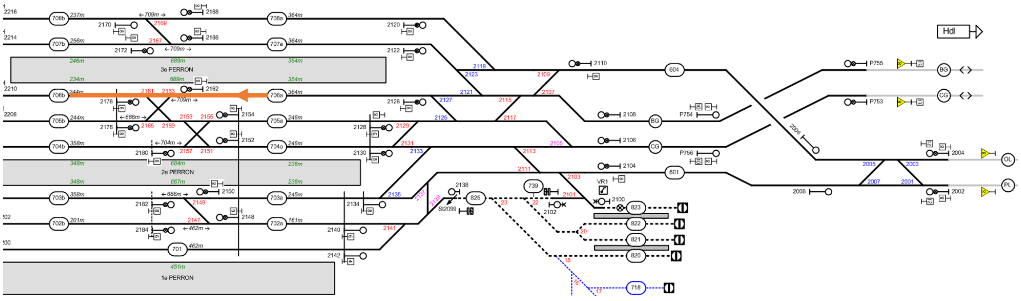

Figure 1: Schematic description of an identified shunting procedure used to short turn trains to and from Oss. This operation can be used after a train has arrived from Oss at platform 6A. A shunting movement can than be done to platform 6B, where the train will depart to Oss.

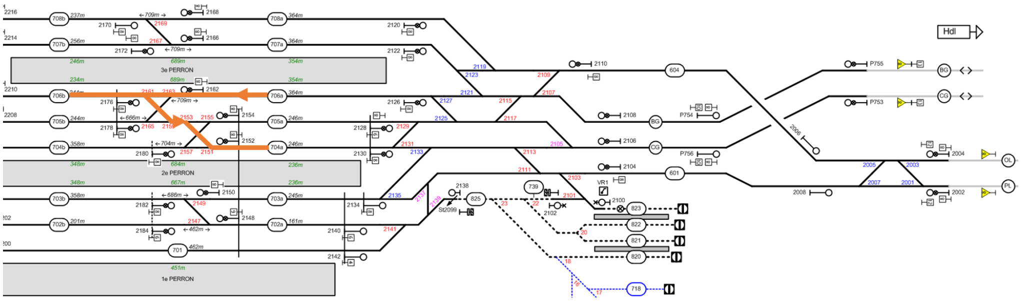

Figure 2: Schematic description of an identified shunting procedure used to short turn trains to and from Oss. This operation can be used after a train has arrived from Oss at platform 6A. A shunting movement can than be done to platform 6B, followed by a shunting movement to platform 4A, where the train will depart to Oss. This is the only identified shunting operation that is not used in the case study, since it was decided to stick to only one shunting movement.

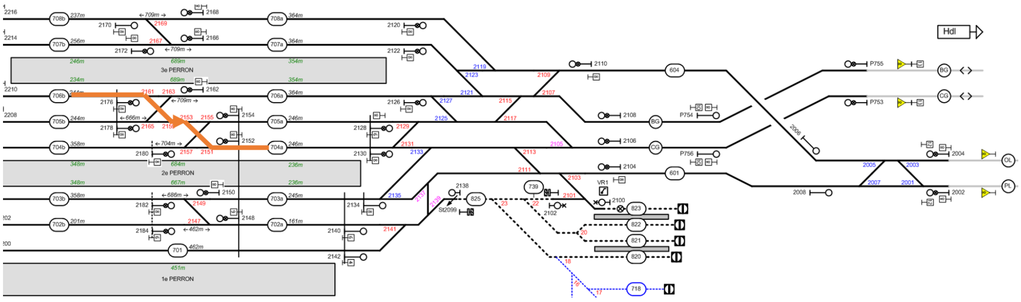

Figure 3: Schematic description of an identified shunting procedure used to short turn trains to and from Oss. This operation can be used after a train has arrived from Oss at platform 6B. A shunting movement can than be done to platform 4A, where the train will depart to Oss.

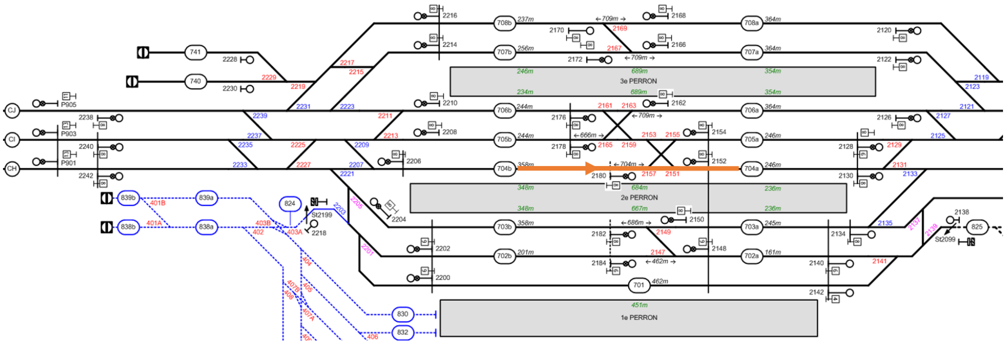

Figure 4: Schematic description of an identified shunting procedure used to short turn trains to and from Vugt aansluiting. This operation can be used after a train has arrived from Vugt aansluiting at platform 4B. A shunting movement can than be done to platform 4A, where the train will depart to Vugt aansluiting.

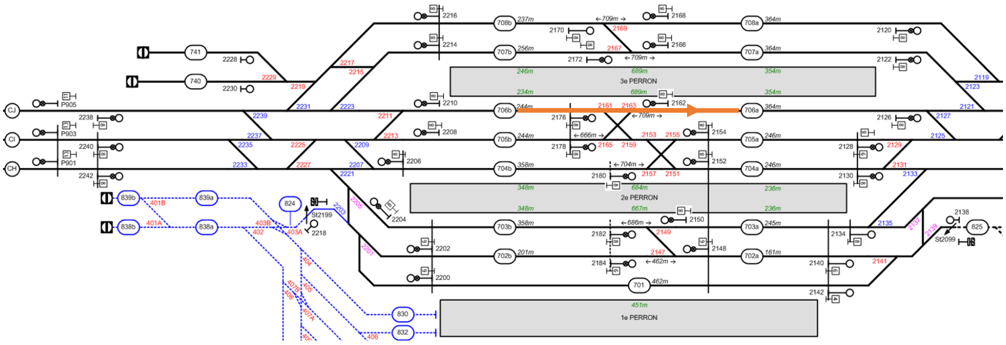

Figure 5: Schematic description of an identified shunting procedure used to short turn trains to and from Vugt aansluiting. This operation can be used after a train has arrived from Vugt aansluiting at platform 6B. A shunting movement can than be done to platform 6A, where the train will depart to Vugt aansluiting.

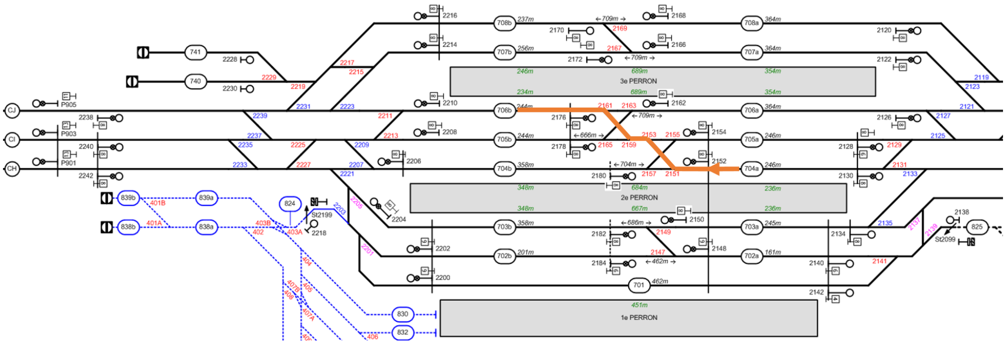

Figure 6: Schematic description of an identified shunting procedure used to short turn trains to and from Vugt aansluiting. This operation can be used after a train has arrived from Vugt aansluiting at platform 4A. A shunting movement can than be done to platform 6B, where the train will depart to Vugt aansluiting.

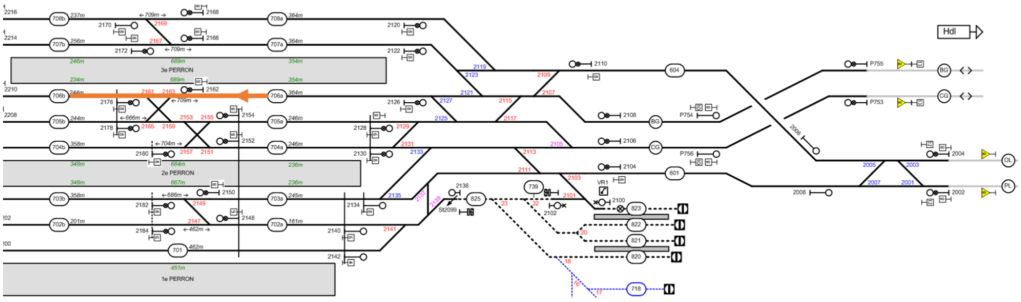

Figure 7: Schematic description of an identified shunting procedure used to short turn trains to and from Utrecht. This operation can be used after a train has arrived from Utrecht at platform 6A. A shunting movement can than be done to platform 6B, where the train will depart to Utrecht.

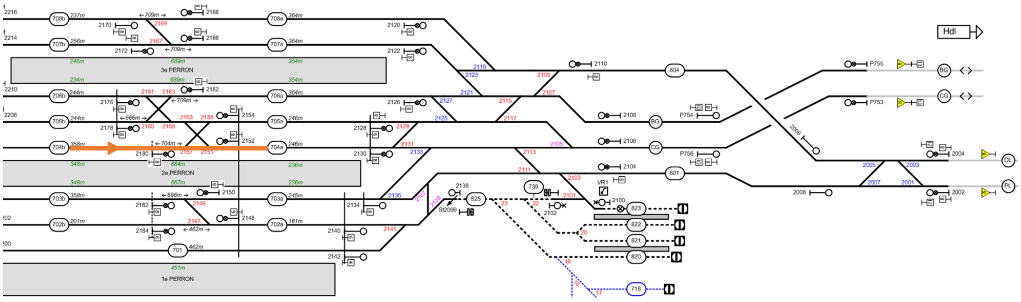

Figure 8: Schematic description of an identified shunting procedure used to short turn trains to and from Utrecht. This operation can be used after a train has arrived from Utrecht at platform 4B. A shunting movement can than be done to platform 4A, where the train will depart to Utrecht.

Appendix B: Results from problem size assessment

The table below shows the summarised results of the considered cases to assess the problem size and calculation time for multiple timetable sizes and model choice combinations. The table lists the scenario name, timetable size, smallest found buffer time in seconds, the found objective value, number of routes considered, preprocessing time in seconds, calculation time in seconds. The scenarioname contains a 3 digit binary code, indicating the model choice combinations in the same order as in Tables 5.7 and 5.8: Shunting movements, time shifts, rolling stock connections. Furthermore the table lists how much the route plan has changed compared to the original timetable: The number of cancelled trains, the number of changed platforms, the number of changed routes, and the number of time shifted trains.

Scenario	Timetable size	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
pf3closed000	12	97	945	301	224.16	3.25	0	0	1	0	0
pf3closed001	12	97	945	172	220.25	2.03	0	0	1	0	0
pf3closed010	12	97	1305	2013	300.42	32.09	0	0	1	0	0
pf3closed011	12	97	1305	1002	252.59	10.03	0	0	1	0	0
pf3closed100	12	97	945	540	233.27	6.42	0	0	1	0	0
pf3closed110	12	97	1305	2602	353.84	42.72	0	0	1	0	0
pf3closed000	12	155	31409	446	279.86	4.11	0	6	0	0	0
pf3closed001	12	155	31409	223	232.23	3.47	0	6	0	0	0
pf3closed010	12	155	31769	3118	457.47	51.30	0	6	0	0	0
pf3closed011	12	155	31769	1329	308.61	18.09	0	6	0	0	0
pf3closed100	12	155	31409	446	237.23	4.39	0	6	0	0	0
pf3closed110	12	155	31769	3118	464.83	50.94	0	6	0	0	0
pf3closed000	12	96	10676	378	245.80	3.83	0	2	0	0	0
pf3closed001	12	96	10676	202	235.11	2.06	0	2	0	0	0
pf3closed010	12	96	11036	2572	349.50	37.59	0	2	0	0	0
pf3closed011	12	96	11036	1212	279.52	13.06	0	2	0	0	0
pf3closed100	12	96	10676	617	235.94	6.78	0	2	0	0	0
pf3closed110	12	96	11036	3161	412.09	61.08	0	2	0	0	0
pf3closed000	12	114	10869	329	263.41	3.06	0	2	0	0	0
pf3closed001	12	114	10869	189	218.73	2.50	0	2	0	0	0
pf3closed010	12	114	11229	2205	321.06	29.53	0	2	0	0	0
pf3closed011	12	114	11229	1095	280.36	11.78	0	2	0	0	0
pf3closed100	12	114	10869	329	238.50	4.31	0	2	0	0	0
pf3closed110	12	114	11229	2205	334.67	29.78	0	2	0	0	0
pf3closed000	12	114	21118	430	242.06	4.17	0	4	0	0	0
pf3closed001	12	114	21118	193	228.88	2.63	0	4	0	0	0
pf3closed010	12	114	21478	3054	436.84	45.89	0	4	0	0	0
pf3closed011	12	114	21478	1119	287.38	11.91	0	4	0	0	0
pf3closed100	12	114	21118	430	231.89	4.17	0	4	0	0	0
pf3closed110	12	114	21478	3054	429.16	45.91	0	4	0	0	0
pf3closed000	16	49	11373	693	252.75	10.27	0	2	0	0	0
pf3closed001	16	49	11373	257	243.27	3.84	0	2	0	0	0
pf3closed010	16	49	11853	4980	521.22	111.28	0	2	0	0	0
pf3closed011	16	49	11853	1549	308.86	16.97	0	2	0	0	0

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Scenario	Timetable size	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
pf3closed100	16	49	11373	1160	308.30	17.61	0	2	0	0	0
pf3closed110	16	49	11853	6133	636.77	190.80	0	2	0	0	0
pf3closed000	16	147	11003	657	256.73	6.25	0	2	1	0	0
pf3closed001	16	147	11003	261	235.11	2.55	0	2	1	0	0
pf3closed010	16	147	11483	4697	496.94	94.61	0	2	1	0	0
pf3closed011	16	147	11483	1561	287.45	15.25	0	2	1	0	0
pf3closed100	16	147	11003	1124	257.70	12.80	0	2	1	0	0
pf3closed110	16	147	11483	5850	595.67	174.41	0	2	1	0	0
pf3closed000	16	133	11003	700	261.78	6.14	0	2	1	0	0
pf3closed001	16	133	11003	261	251.16	3.33	0	2	1	0	0
pf3closed010	16	133	11483	5024	555.39	115.61	0	2	1	0	0
pf3closed011	16	133	11483	1561	303.89	17.09	0	2	1	0	0
pf3closed100	16	133	11003	1395	287.28	20.19	0	2	1	0	0
pf3closed110	16	133	11483	6741	713.25	266.33	0	2	1	0	0
pf3closed000	16	464	11351	1006	283.17	13.69	0	2	0	0	0
pf3closed001	16	464	11351	270	236.50	2.63	0	2	0	0	0
pf3closed010	16	464	11831	7455	905.92	355.14	0	2	0	0	0
pf3closed011	16	464	11831	1618	410.94	17.44	0	2	0	0	0
pf3closed100	16	464	11351	1462	486.16	31.48	0	2	0	0	0
pf3closed110	16	464	11831	8583	1022.02	351.98	0	2	0	0	0
pf3closed000	16	114	21157	576	263.56	5.23	0	4	0	0	0
pf3closed001	16	114	21157	256	226.77	2.56	0	4	0	0	0
pf3closed010	16	114	21637	4072	539.66	84.80	0	4	0	0	0
pf3closed011	16	114	21637	1480	329.03	19.72	0	4	0	0	0
pf3closed100	16	114	21157	576	271.66	6.09	0	4	0	0	0
pf3closed110	16	114	21637	4072	568.81	77.30	0	4	0	0	0
pf3closed000	20	155	42027	975	296.17	9.66	0	8	0	0	0
pf3closed001	20	155	42027	362	255.09	3.69	0	8	0	0	0
pf3closed010	20	155	42627	7149	945.17	224.80	0	8	0	0	0
pf3closed011	20	155	42627	2180	398.89	29.63	0	8	0	0	0
pf3closed100	20	155	42027	1718	353.05	25.59	0	8	0	0	0
pf3closed110	20	155	42627	9010	1241.70	557.02	0	8	0	0	0
pf3closed000	20	97	21102	1144	283.05	10.30	0	4	1	0	0
pf3closed001	20	97	21102	350	268.94	4.92	0	4	1	0	0

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Scenario	Timetable size	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
pf3closed010	20	97	21702	8471	978.47	354.42	0	4	1	0	0
pf3closed011	20	97	21702	2120	372.55	26.70	0	4	1	0	0
pf3closed100	20	97	21102	2115	361.23	36.05	0	4	1	0	0
pf3closed110	20	97	21702	10896	1347.94	816.59	0	4	1	0	0
pf3closed000	20	96	21307	869	267.92	7.81	0	4	0	0	0
pf3closed001	20	96	21307	328	231.00	3.53	0	4	0	0	0
pf3closed010	20	96	21907	6275	677.17	175.36	0	4	0	0	0
pf3closed011	20	96	21907	1946	357.28	23.25	0	4	0	0	0
pf3closed100	20	96	21307	1336	290.61	16.25	0	4	0	0	0
pf3closed110	20	96	21907	7428	954.70	409.75	0	4	0	0	0
pf3closed000	20	114	11708	1003	267.50	9.06	0	2	0	0	0
pf3closed001	20	114	11708	311	236.73	3.22	0	2	0	0	0
pf3closed010	20	114	12308	7283	716.28	230.52	0	2	0	0	0
pf3closed011	20	114	12308	1805	339.33	18.53	0	2	0	0	0
pf3closed100	20	114	11708	1459	284.05	17.14	0	2	0	0	0
pf3closed110	20	114	12308	8411	792.17	361.64	0	2	0	0	0
pf3closed000	20	97	11457	1081	364.23	23.98	0	2	1	0	0
pf3closed001	20	97	11457	320	401.16	8.44	0	2	1	0	0
pf3closed010	20	97	12057	7942	1145.19	349.53	0	2	1	0	0
pf3closed011	20	97	12057	1910	445.25	36.30	0	2	1	0	0
pf3closed100	20	97	11457	1776	499.23	42.08	0	2	1	0	0
pf3closed110	20	97	12057	9659	1466.88	437.25	0	2	1	0	0
pf3closed000	24	49	31590	1406	289.48	13.36	0	6	0	0	0
pf3closed001	24	96	31590	417	226.17	4.16	0	6	0	0	0
pf3closed010	24	49	32310	10439	1051.95	409.08	0	6	0	0	0
pf3closed011	24	96	32310	2505	382.91	29.98	0	6	0	0	0
pf3closed100	24	96	31590	2605	372.84	48.39	0	6	0	0	0
pf3closed110	24	49	32310	13428	1639.55	927.52	0	6	0	0	0
pf3closed000	24	97	21515	1698	345.61	20.64	0	4	1	0	0
pf3closed001	24	97	21515	409	230.67	6.45	0	4	1	0	0
pf3closed010	24	97	22235	12772	1257.70	467.84	0	4	1	0	0
pf3closed011	24	97	22235	2469	391.39	31.09	0	4	1	0	0
pf3closed100	24	97	21515	3125	478.94	81.95	0	4	1	0	0
pf3closed110	24	97	22235	16325	2638.69	1348.64	0	4	1	0	0

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Scenario	Timetable size	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
pf3closed000	24	49	31775	1257	317.69	11.59	0	6	0	0	0
pf3closed001	24	49	31775	395	227.88	3.73	0	6	0	0	0
pf3closed010	24	49	32495	9262	1020.47	468.47	0	6	0	0	0
pf3closed011	24	49	32495	2331	383.19	31.64	0	6	0	0	0
pf3closed100	24	49	31775	1724	344.89	27.47	0	6	0	0	0
pf3closed110	24	49	32495	10415	1190.73	795.81	0	6	0	0	0
pf3closed000	24	97	21515	1698	543.86	18.03	0	4	1	0	0
pf3closed001	24	97	21515	409	235.52	3.69	0	4	1	0	0
pf3closed010	24	97	22235	12772	1308.50	761.61	0	4	1	0	0
pf3closed011	24	97	22235	2469	377.72	30.28	0	4	1	0	0
pf3closed100	24	97	21515	3125	436.08	72.47	0	4	1	0	0
pf3closed110	24	97	22235	16325	2292.77	1524.67	0	4	1	0	0
pf3closed000	24	114	21487	1278	317.52	13.61	0	4	1	0	0
pf3closed001	24	114	21487	387	251.47	3.53	0	4	1	0	0
pf3closed010	24	114	22207	9383	959.48	747.91	0	4	1	0	0
pf3closed011	24	114	22207	2295	412.67	39.97	0	4	1	0	0
pf3closed100	24	114	21487	1973	349.63	33.11	0	4	1	0	0
pf3closed110	24	114	22207	11100	1330.48	1220.70	0	4	1	0	0
pf3closed000	28	114	21802	1778	335.58	19.02	0	4	1	0	0
pf3closed001	28	114	21802	450	246.06	4.17	0	4	1	0	0
pf3closed010	28	114	22642	13233	1398.20	1010.36	0	4	1	0	0
pf3closed011	28	114	22642	2656	469.73	44.56	0	4	1	0	0
pf3closed100	28	114	21802	2701	434.13	50.27	0	4	1	0	0
pf3closed110	28	114	22642	15514	2178.77	1590.58	0	4	1	0	0
pf3closed000	28	49	21916	1843	352.77	25.58	0	4	1	0	0
pf3closed001	28	49	21916	459	254.63	7.88	0	4	1	0	0
pf3closed010	28	49	22756	13889	1448.78	595.89	0	4	1	0	0
pf3closed011	28	49	22756	2761	411.58	35.81	0	4	1	0	0
pf3closed100	28	49	21916	3509	476.08	97.25	0	4	1	0	0
pf3closed110	28	49	22756	18031	2664.33	1647.78	0	4	1	0	0
pf3closed000	28	49	21888	1539	542.78	28.56	0	4	1	0	0
pf3closed001	28	49	21888	437	265.48	4.45	0	4	1	0	0
pf3closed010	28	49	22728	11462	1426.45	764.14	0	4	1	0	0
pf3closed011	28	49	22728	2587	518.42	65.19	0	4	1	0	0

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Scenario	Timetable size	Buffer time [s]	Objective value	Number of routes	Preprocessing time [s]	Calculation time [s]	Cancelled trains	Changed platforms	Changed routes	Time shifted trains	Shorter trains
pf3closed100	28	49	21888	2473	594.16	74.58	0	4	1	0	0
pf3closed110	28	49	22728	13768	1885.03	1201.73	0	4	1	0	0
pf3closed000	28	49	21916	1843	433.00	31.06	0	4	1	0	0
pf3closed001	28	49	21916	459	380.97	13.02	0	4	1	0	0
pf3closed010	28	49	22756	13889	3336.89	664.19	0	4	1	0	0
pf3closed011	28	49	22756	2761	404.05	35.77	0	4	1	0	0
pf3closed100	28	49	21916	3509	610.53	83.30	0	4	1	0	0
pf3closed110	28	49	22756	18031	2763.64	1672.95	0	4	1	0	0
pf3closed000	28	49	21888	1539	308.11	15.42	0	4	1	0	0
pf3closed001	28	49	21888	437	256.09	4.50	0	4	1	0	0
pf3closed010	28	49	22728	11462	1188.34	647.16	0	4	1	0	0
pf3closed011	28	49	22728	2587	395.55	38.06	0	4	1	0	0
pf3closed100	28	49	21888	2473	374.34	45.98	0	4	1	0	0
pf3closed110	28	49	22728	13768	2207.72	1163.47	0	4	1	0	0

Table 1: This table shows all iterations to obtain the results described in 5.5

Appendix C: Results of each case study

In this appendix the platform occupation diagram of each step in the iteration process of the case studies can be found, along with a blocking time diagram of the train having the least buffer time in that route plan. All images are sorted in the same order as shown in Table 5.4. More data about the results is available upon request.

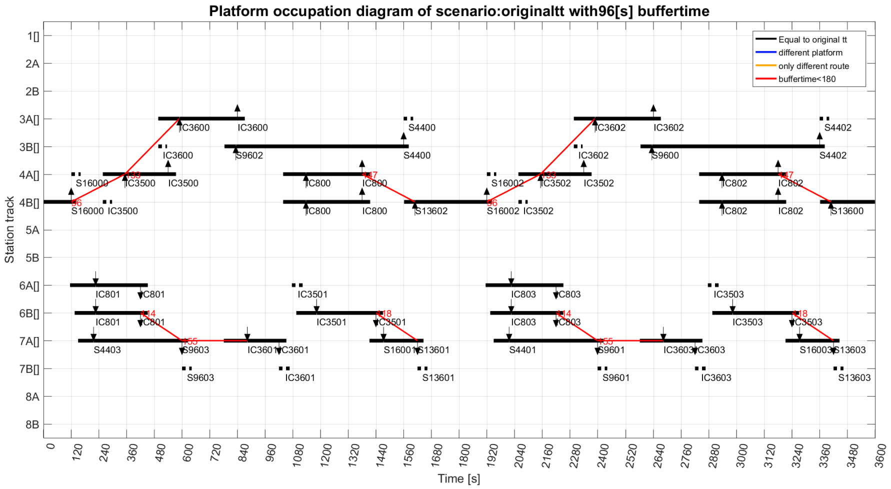


Figure 9: Platform occupation diagram of Den Bosch of the original timetable.

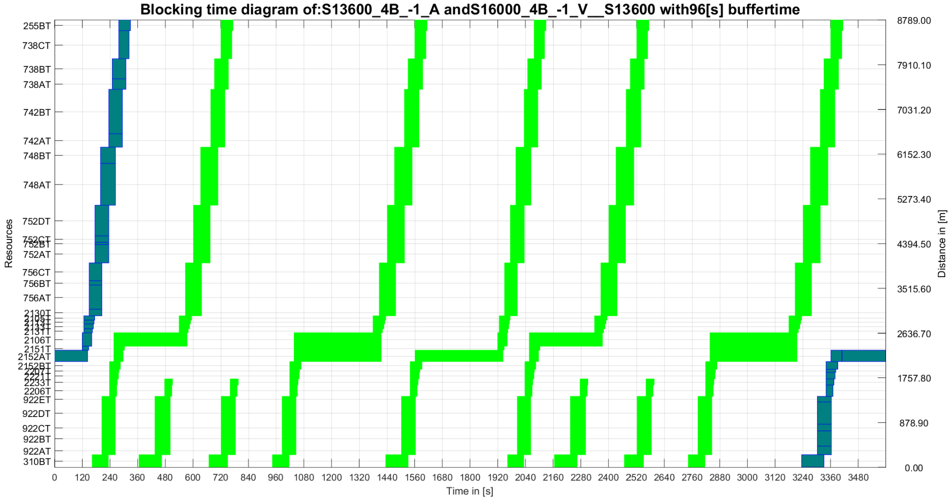


Figure 10: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

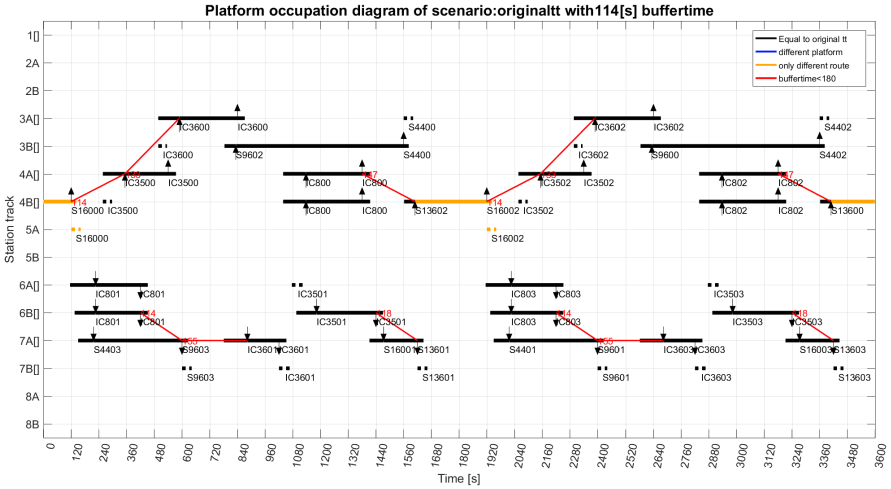


Figure 11: Platform occupation diagram of Den Bosch of the original timetable.

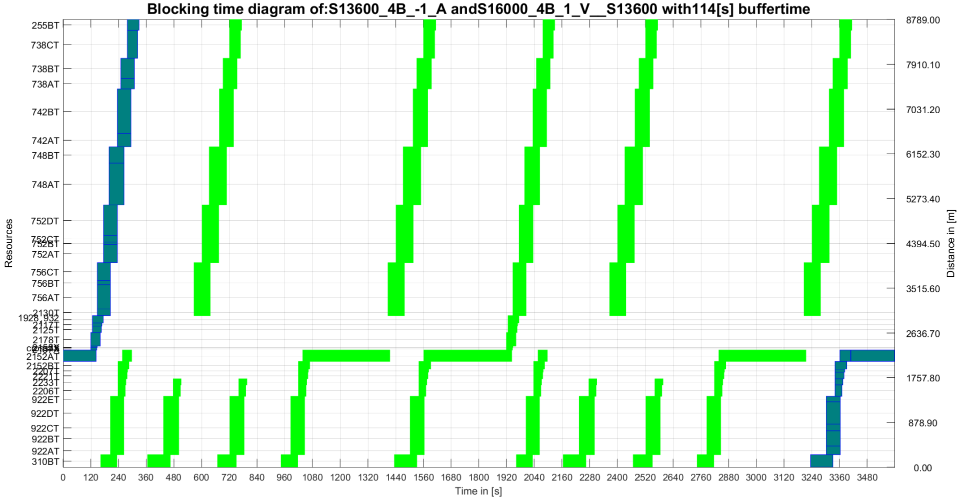


Figure 12: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

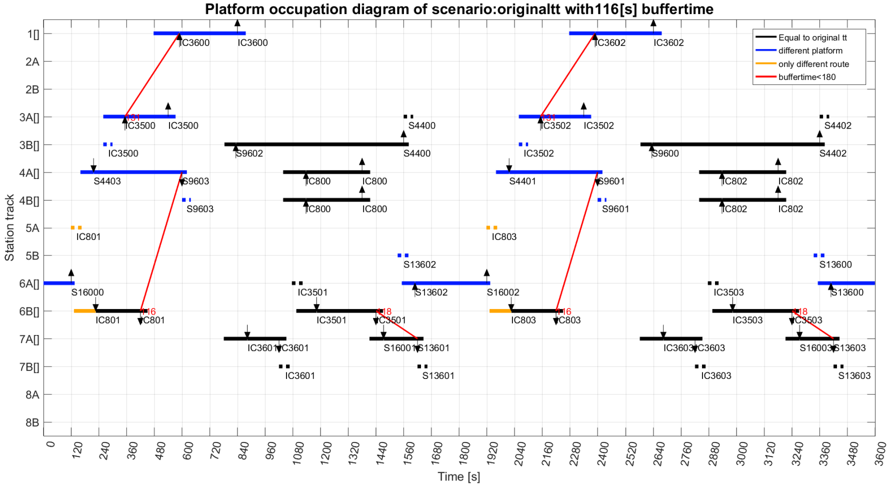


Figure 13: Platform occupation diagram of Den Bosch of the original timetable.

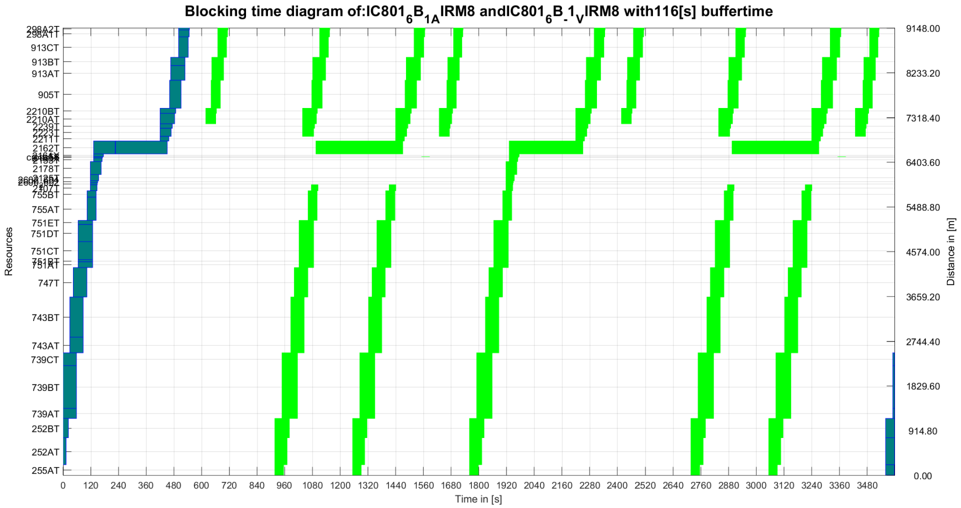


Figure 14: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

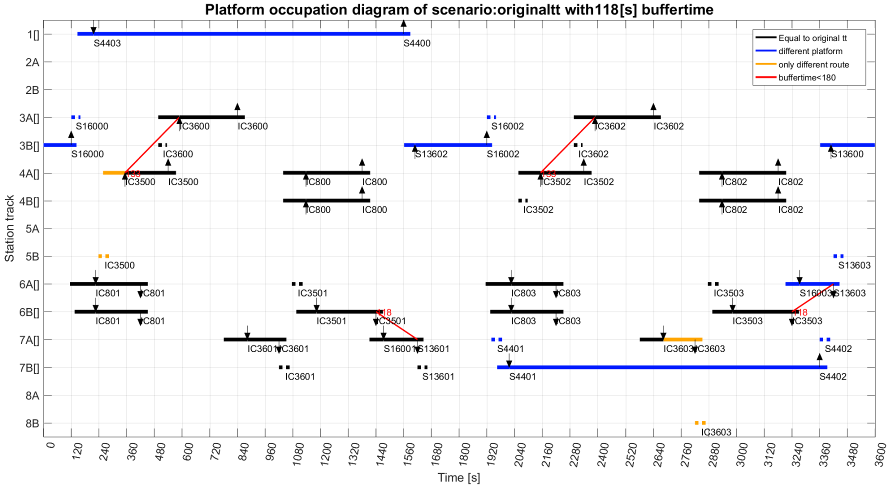


Figure 15: Platform occupation diagram of Den Bosch of the original timetable.

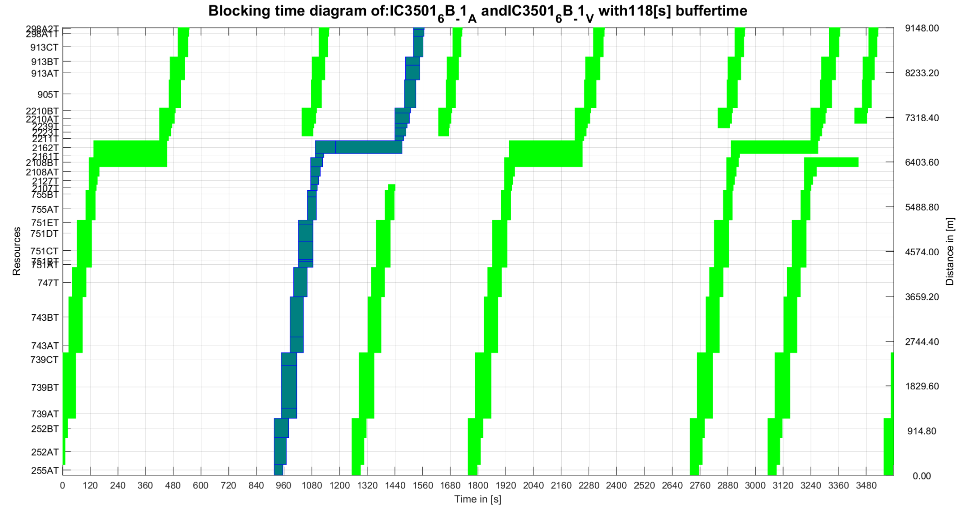


Figure 16: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

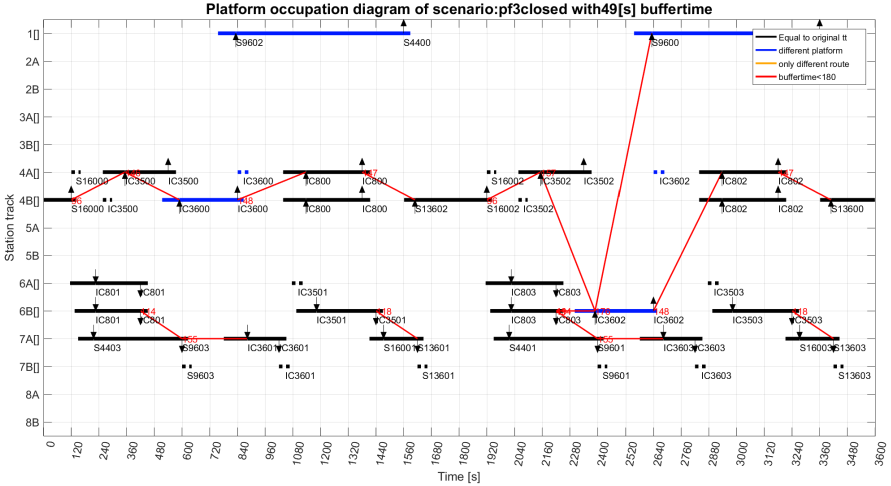


Figure 17: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed.

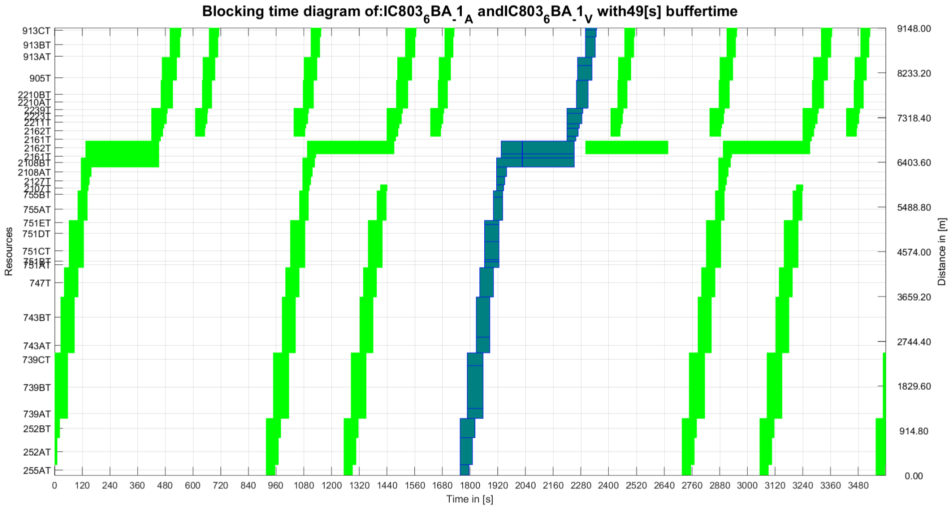


Figure 18: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

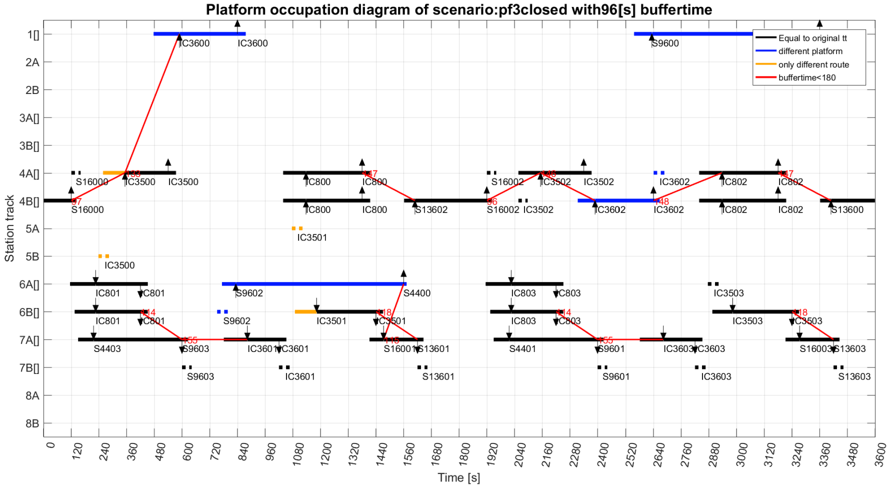


Figure 19: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed.

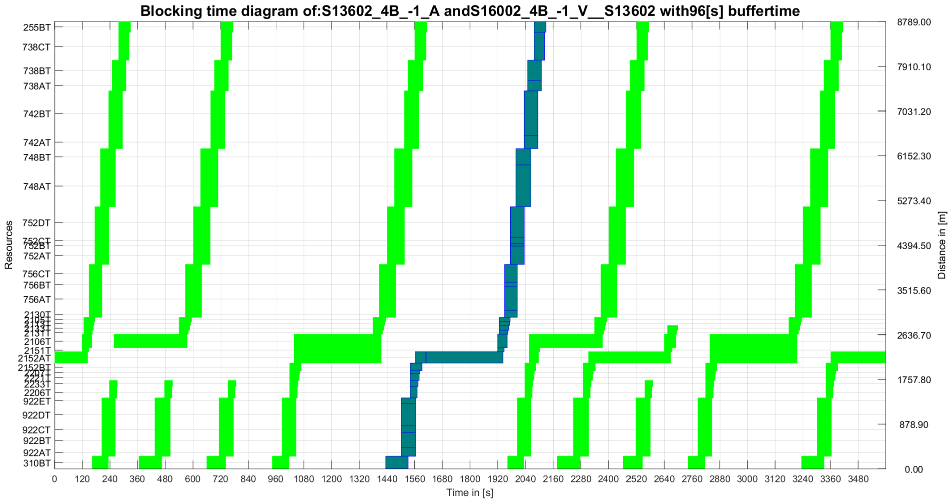


Figure 20: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

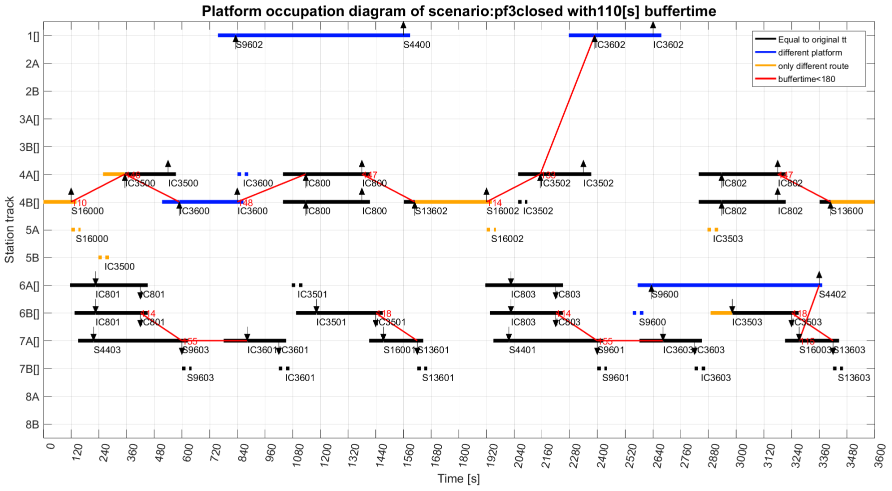


Figure 21: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed.

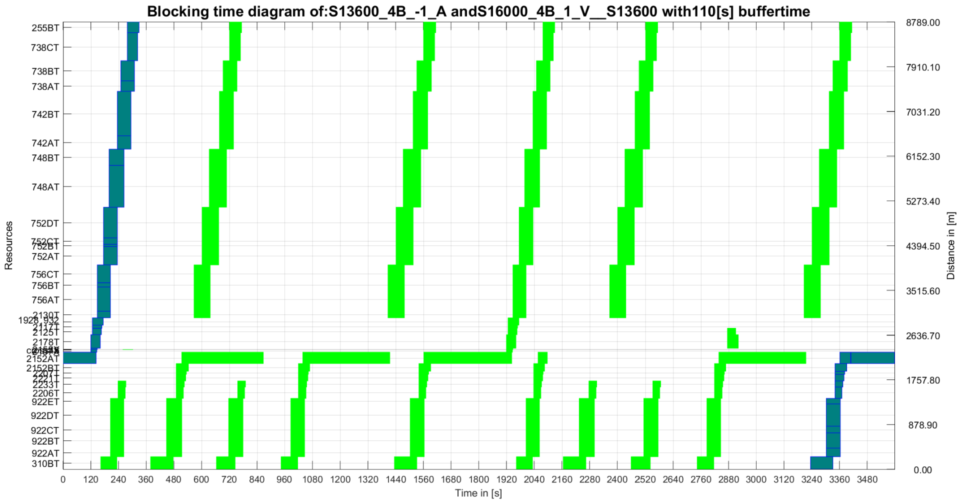


Figure 22: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

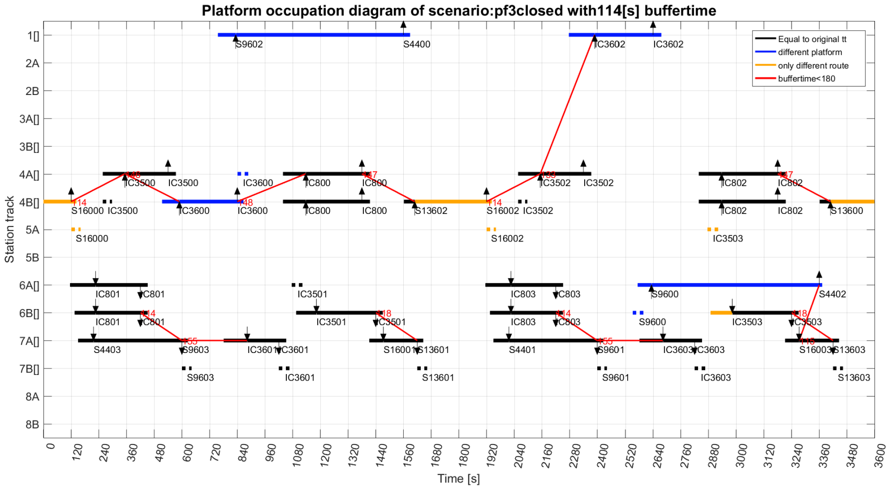


Figure 23: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed.

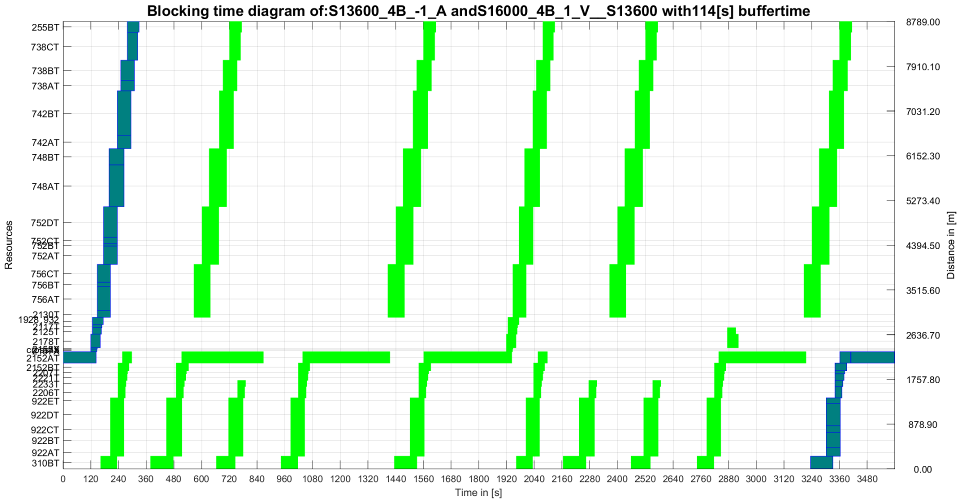


Figure 24: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

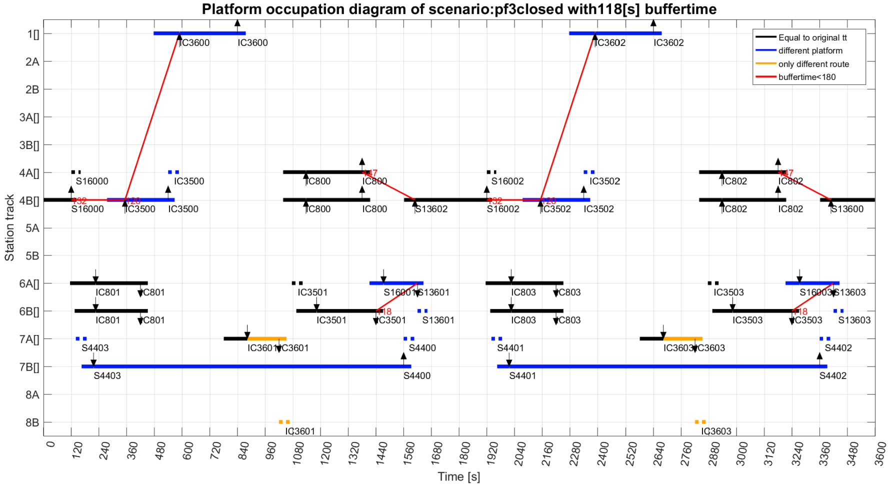


Figure 25: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed.

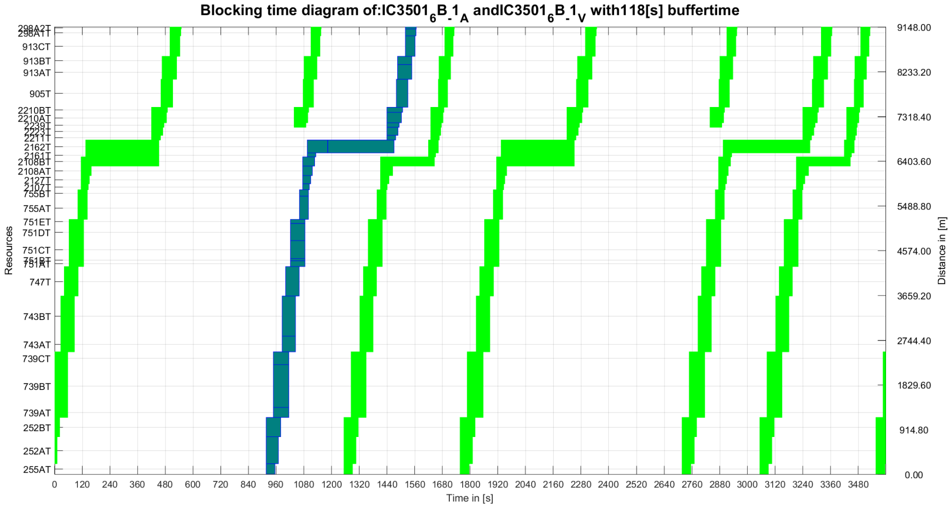


Figure 26: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

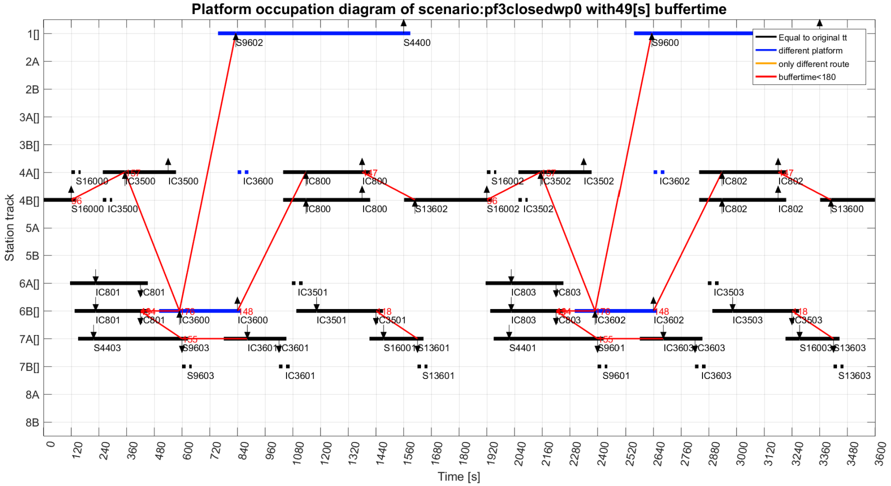


Figure 27: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed with the objective of minimizing the largest platform occupation turned off.

Figure 28: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

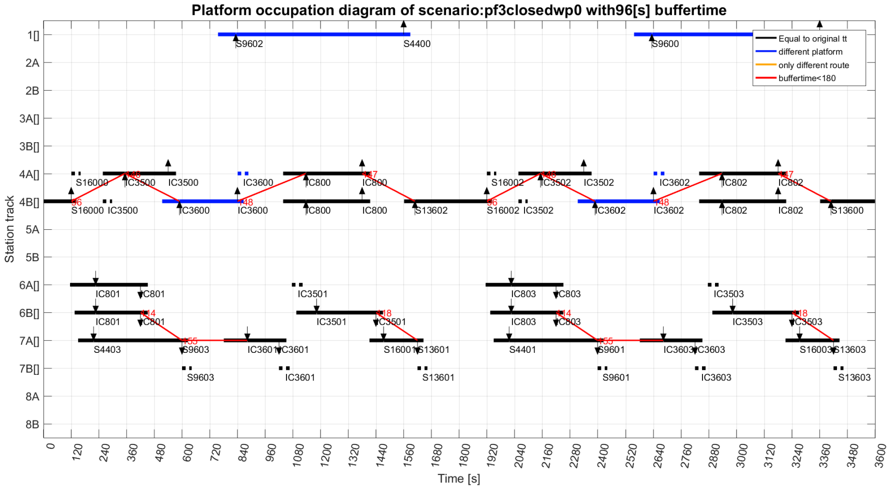


Figure 29: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed with the objective of minimizing the largest platform occupation turned off.

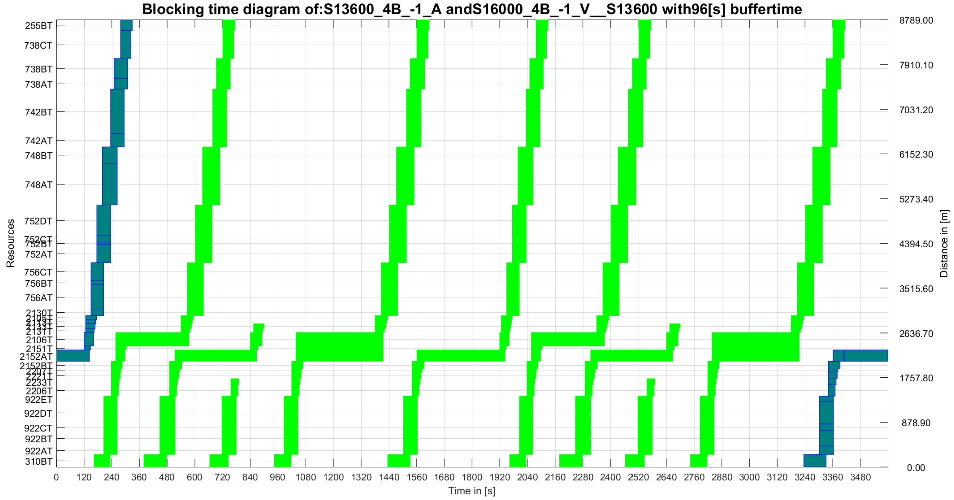


Figure 30: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

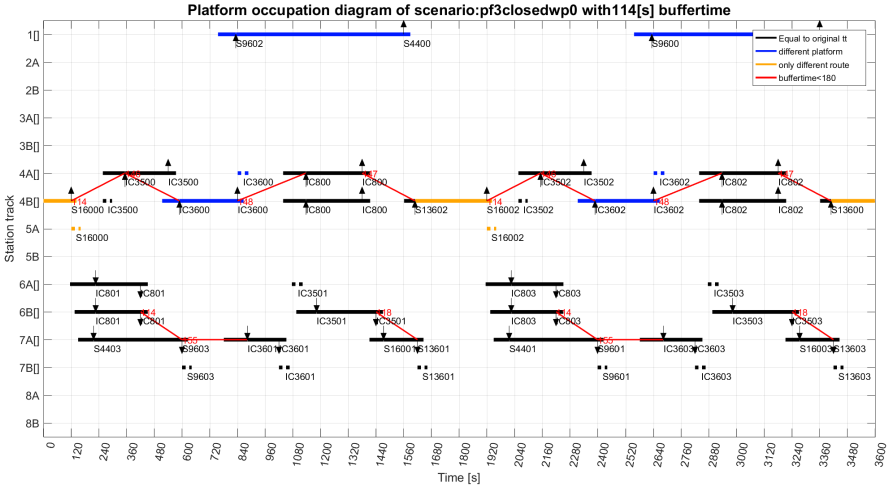


Figure 31: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed with the objective of minimizing the largest platform occupation turned off.

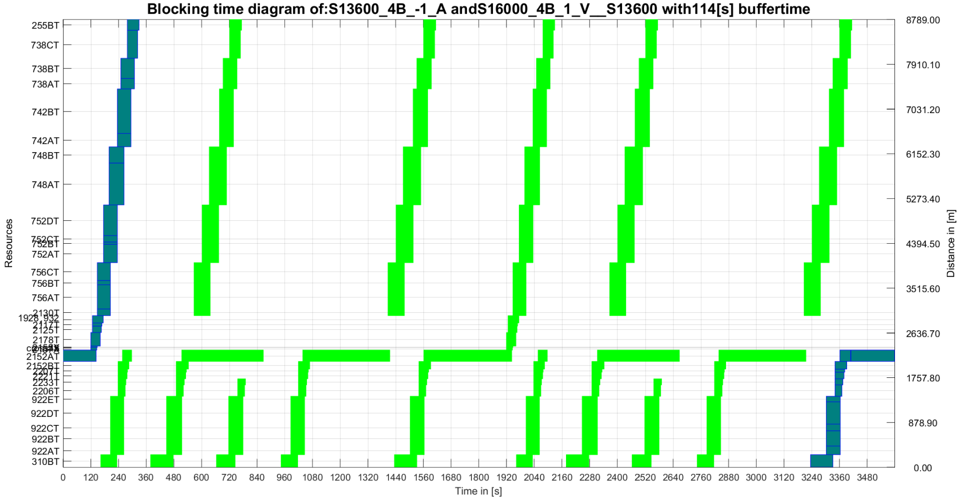


Figure 32: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

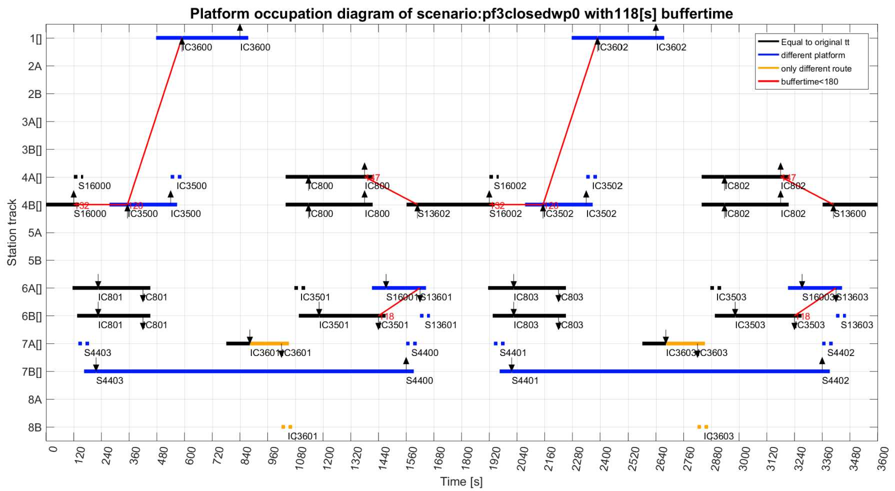


Figure 33: Platform occupation diagram of Den Bosch with platform tracks 3A and 3B are closed with the objective of minimizing the largest platform occupation turned off.

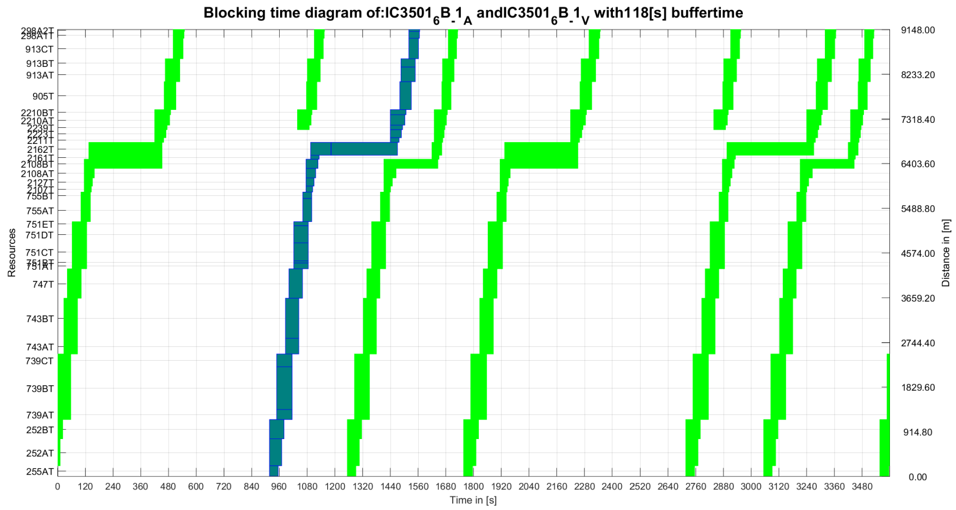


Figure 34: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

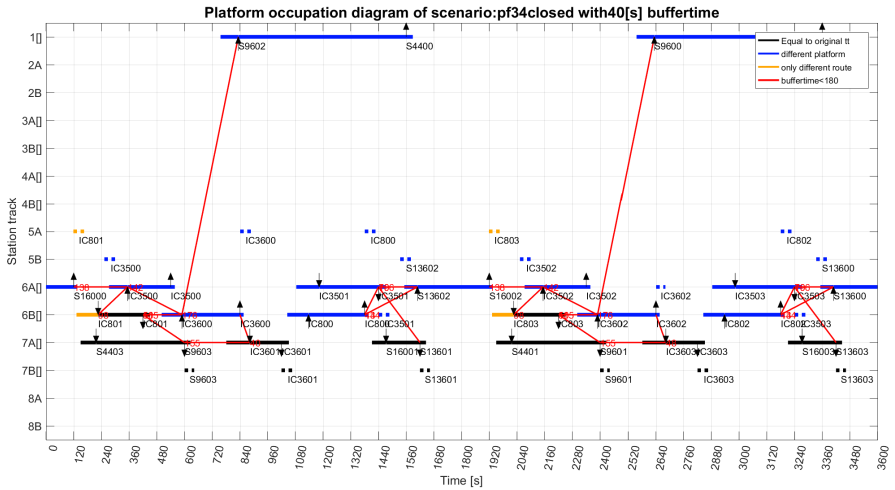


Figure 35: Platform occupation diagram of Den Bosch with platform tracks 3A, 3B, 4A and 4B are closed.

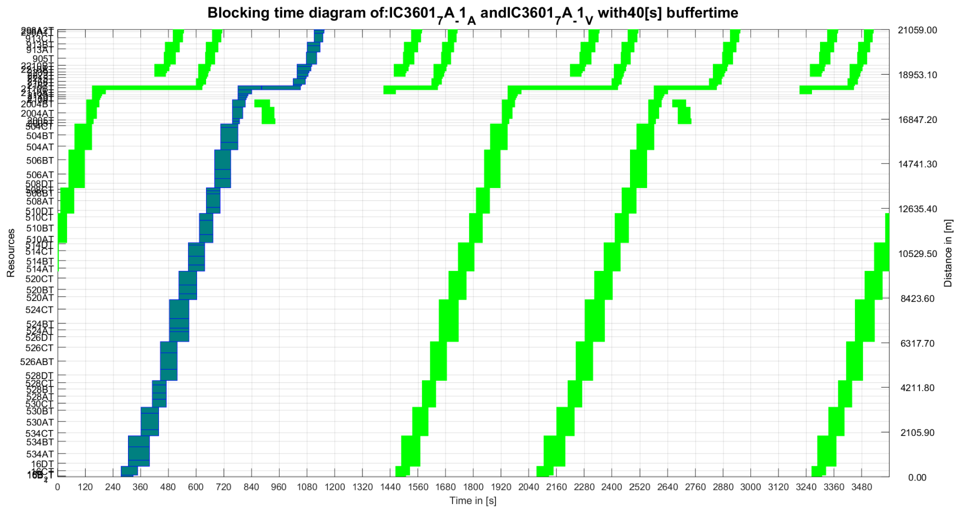


Figure 36: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

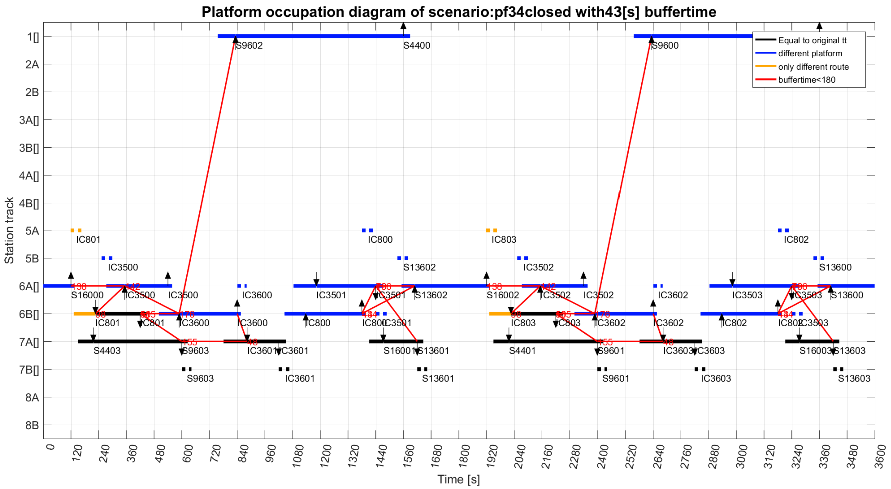


Figure 37: Platform occupation diagram of Den Bosch with platform tracks 3A, 3B, 4A and 4B are closed.

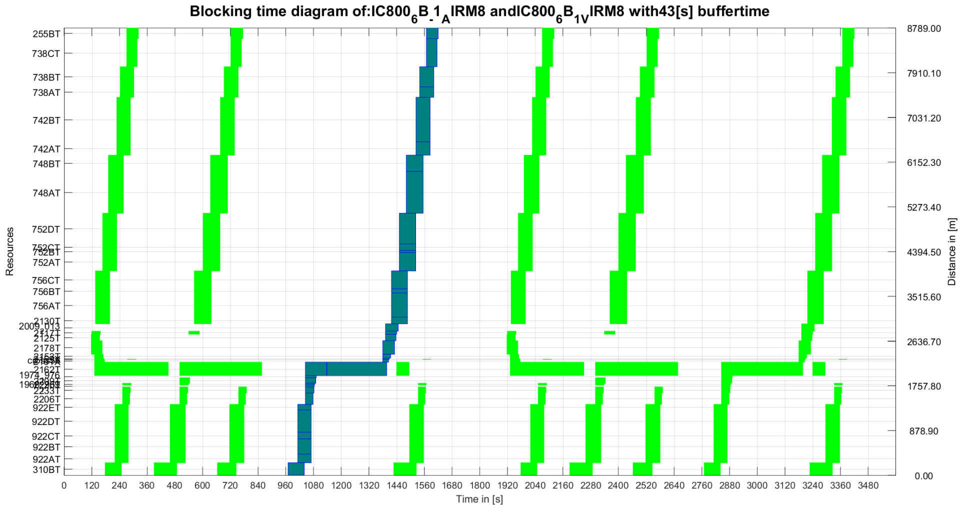


Figure 38: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

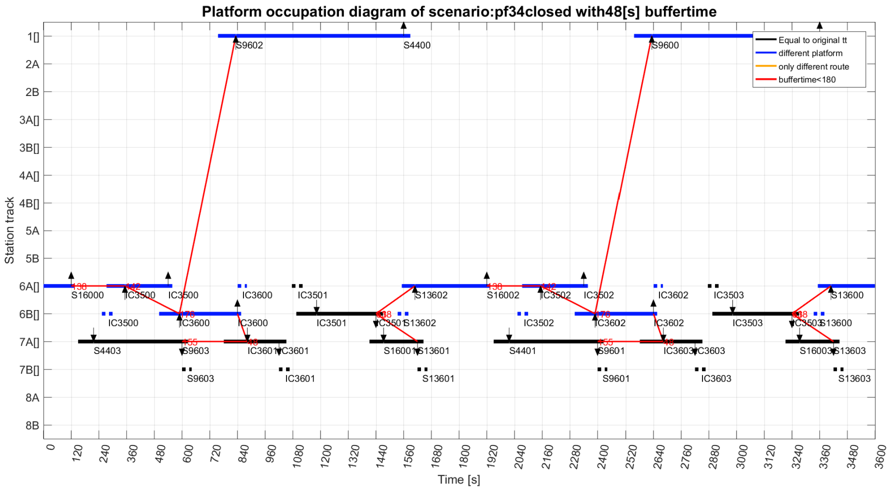


Figure 39: Platform occupation diagram of Den Bosch with platform tracks 3A, 3B, 4A and 4B are closed.

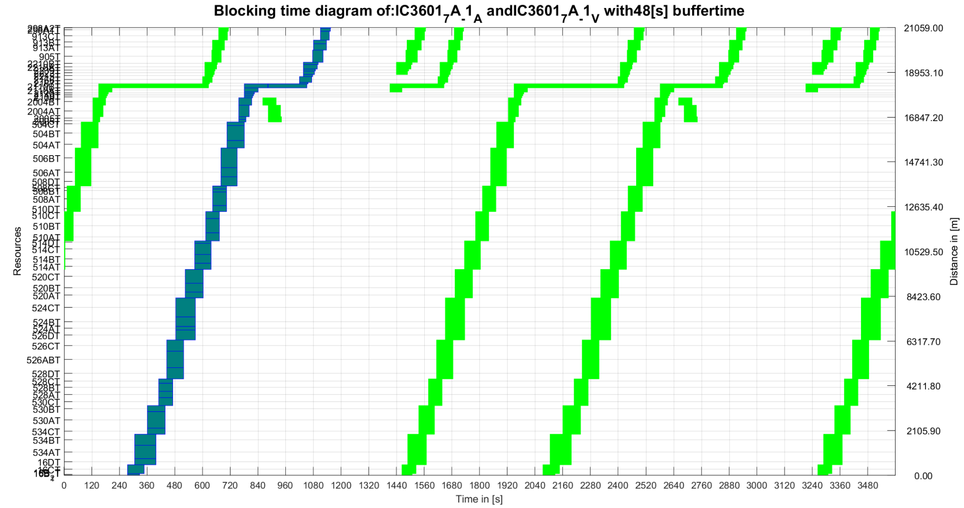


Figure 40: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

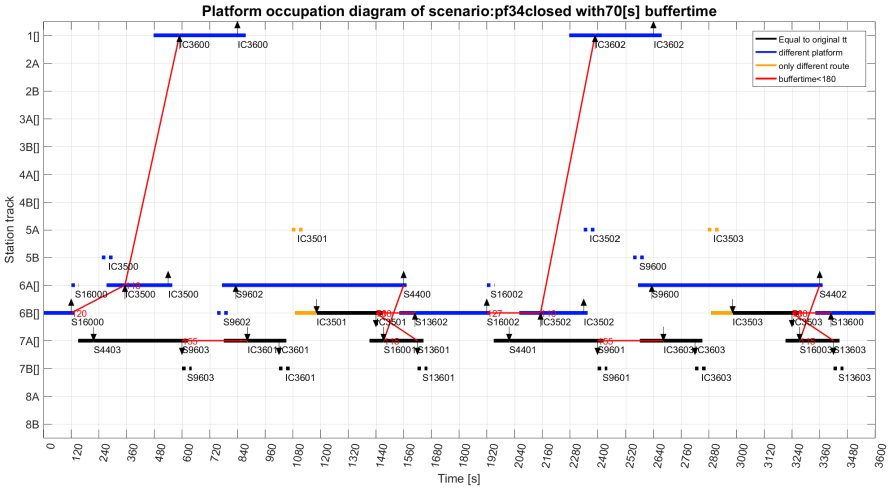


Figure 41: Platform occupation diagram of Den Bosch with platform tracks 3A, 3B, 4A and 4B are closed.

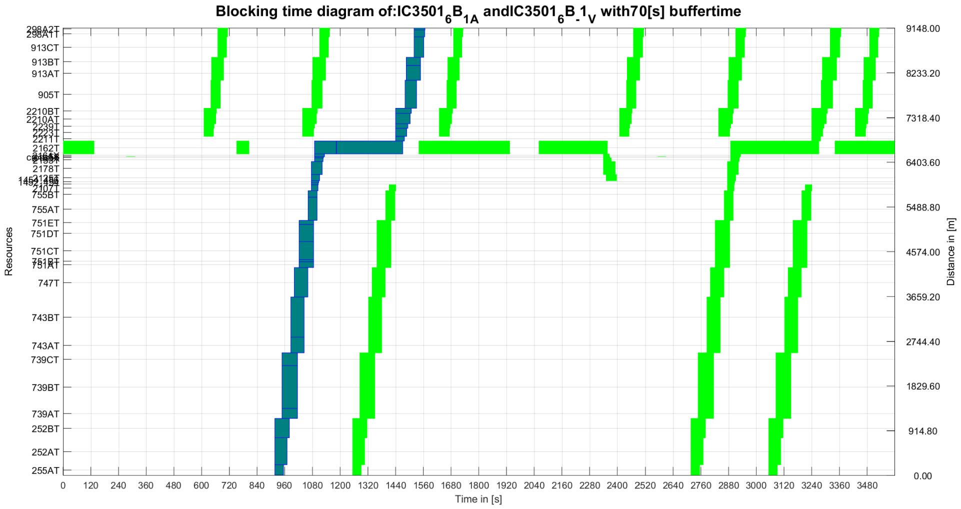


Figure 42: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

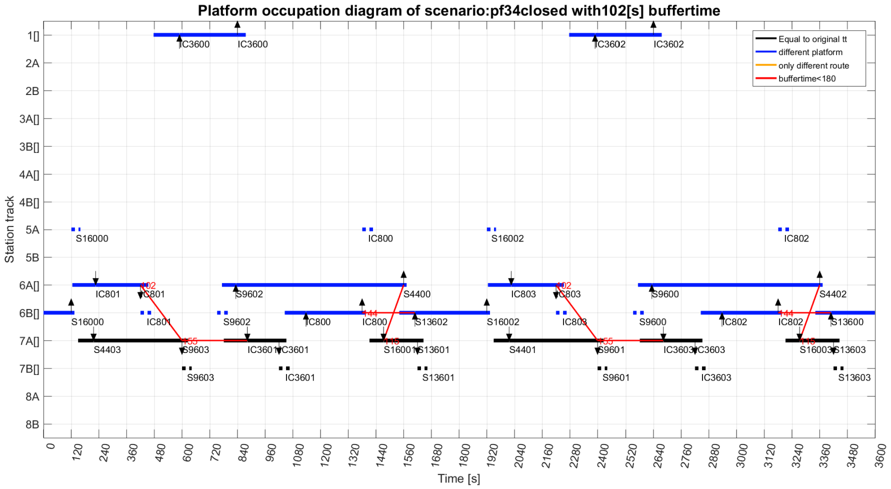


Figure 43: Platform occupation diagram of Den Bosch with platform tracks 3A, 3B, 4A and 4B are closed.

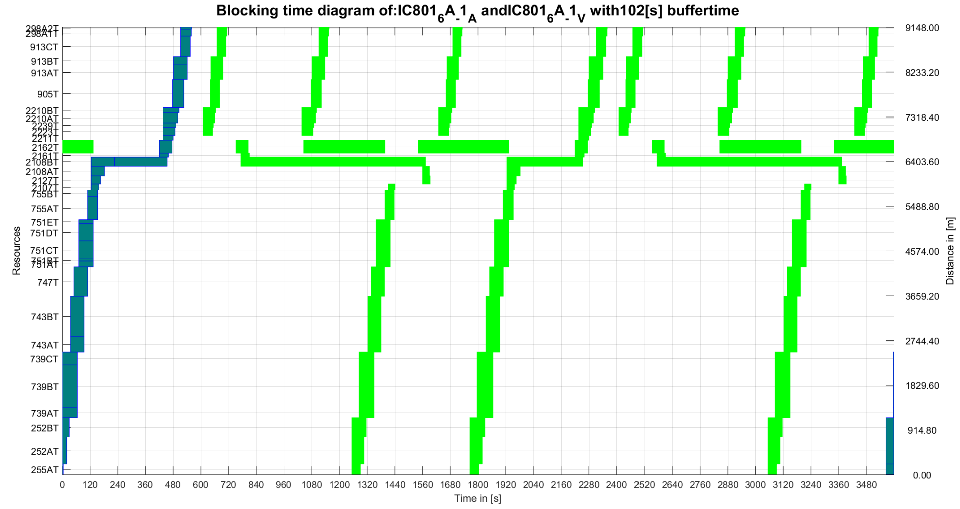


Figure 44: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

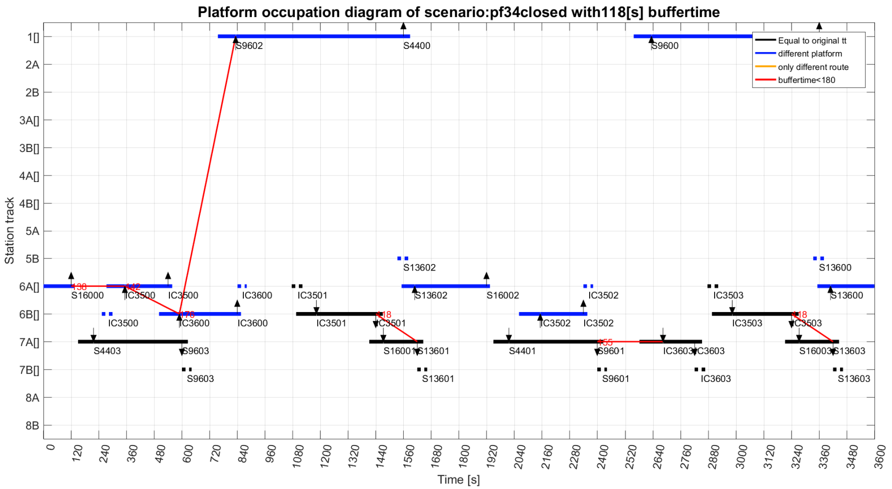


Figure 45: Platform occupation diagram of Den Bosch with platform tracks 3A, 3B, 4A and 4B are closed.

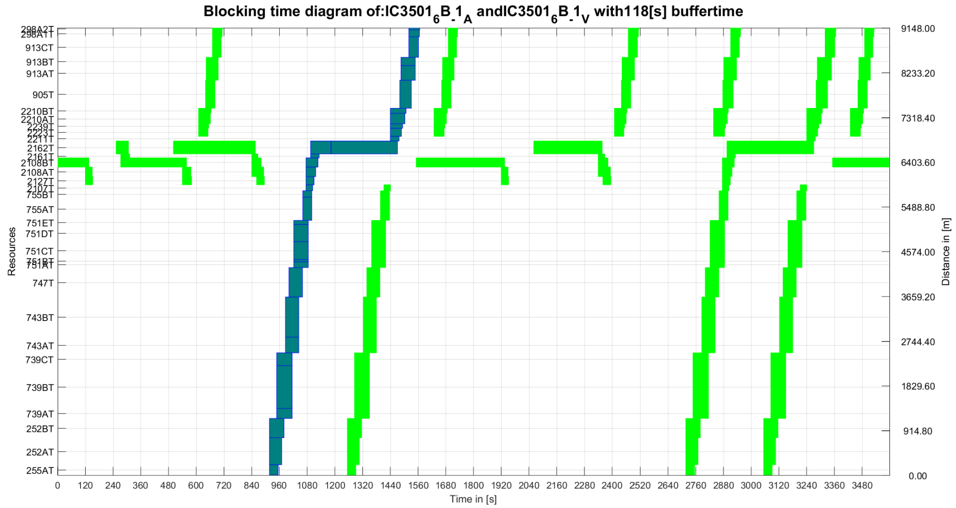


Figure 46: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

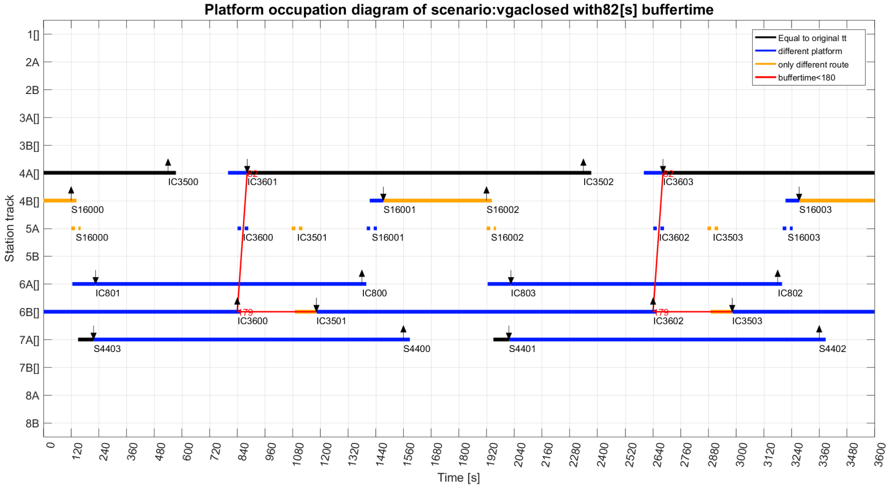


Figure 47: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

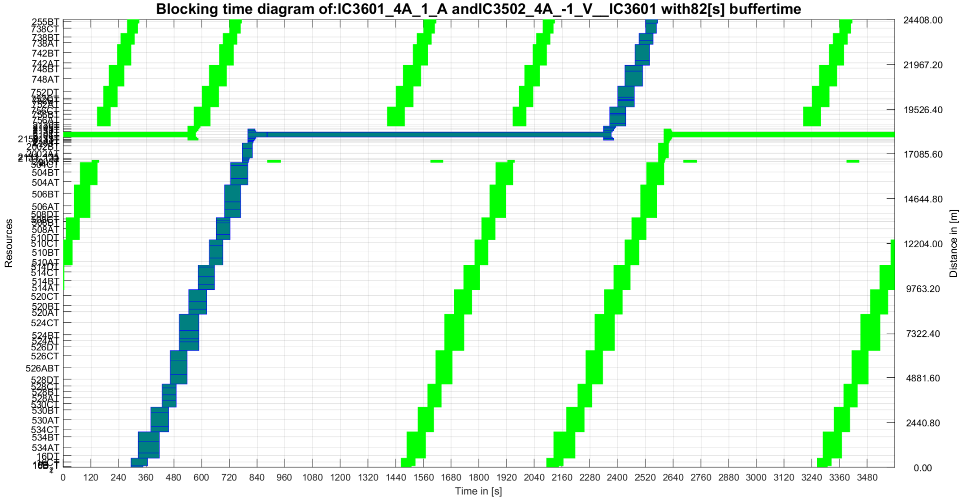


Figure 48: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

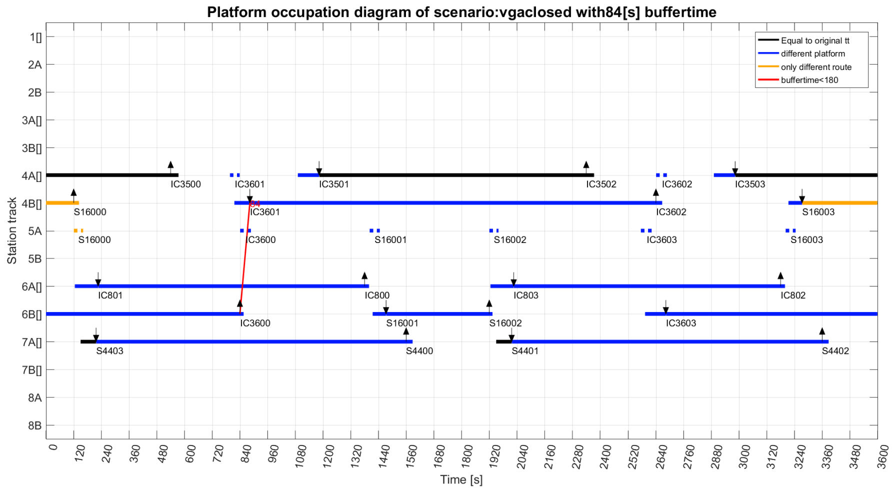


Figure 49: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

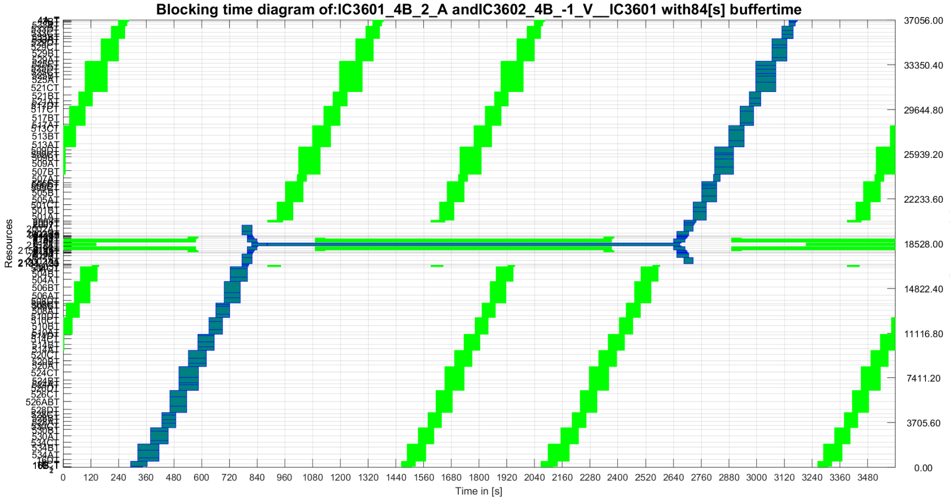


Figure 50: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

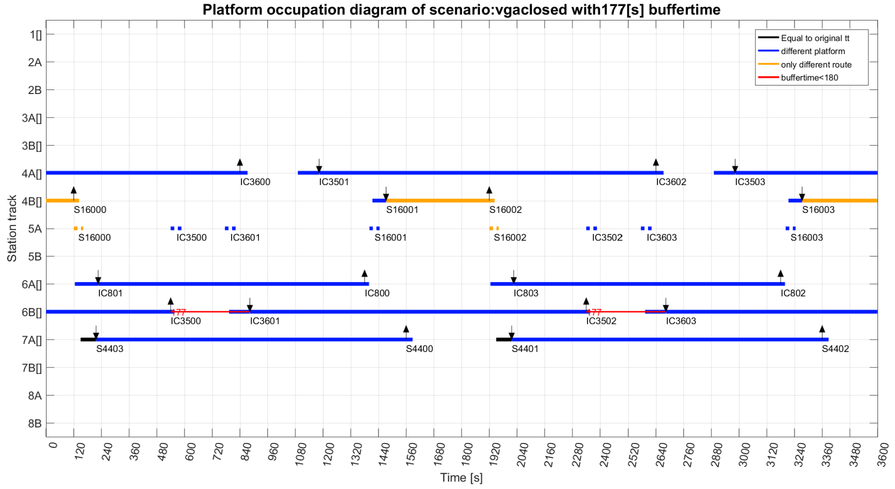


Figure 51: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

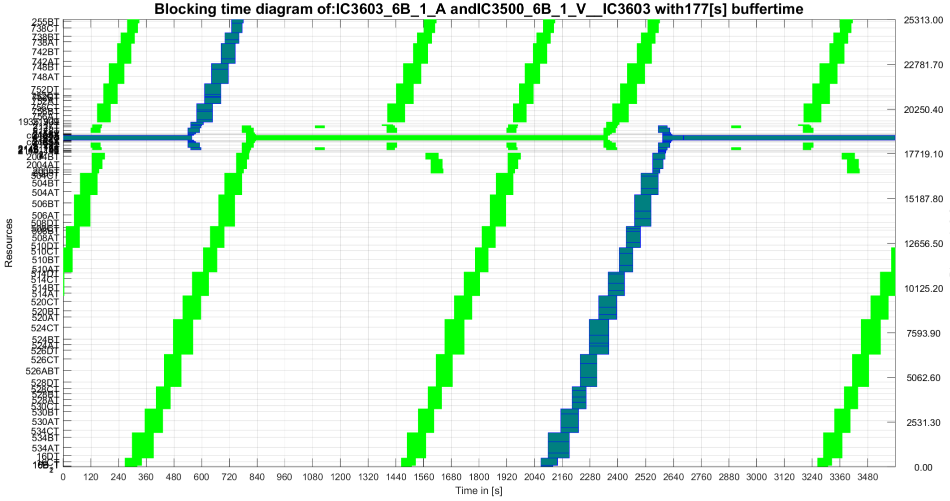


Figure 52: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

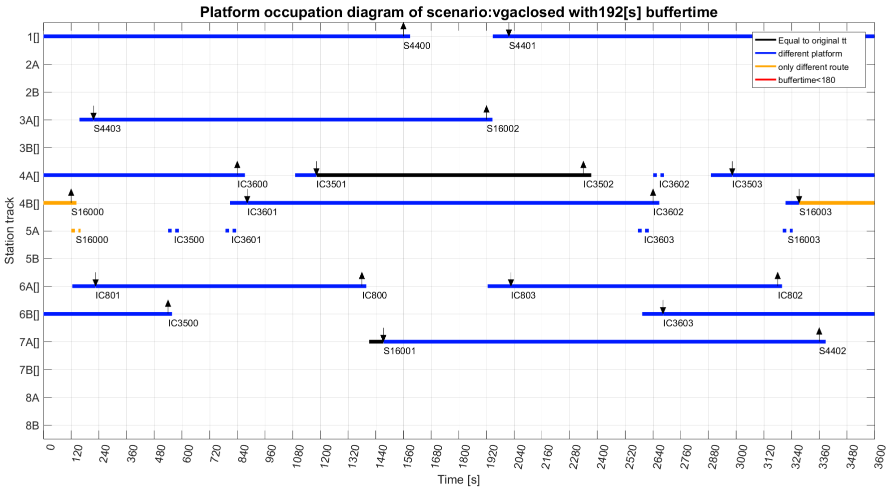


Figure 53: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

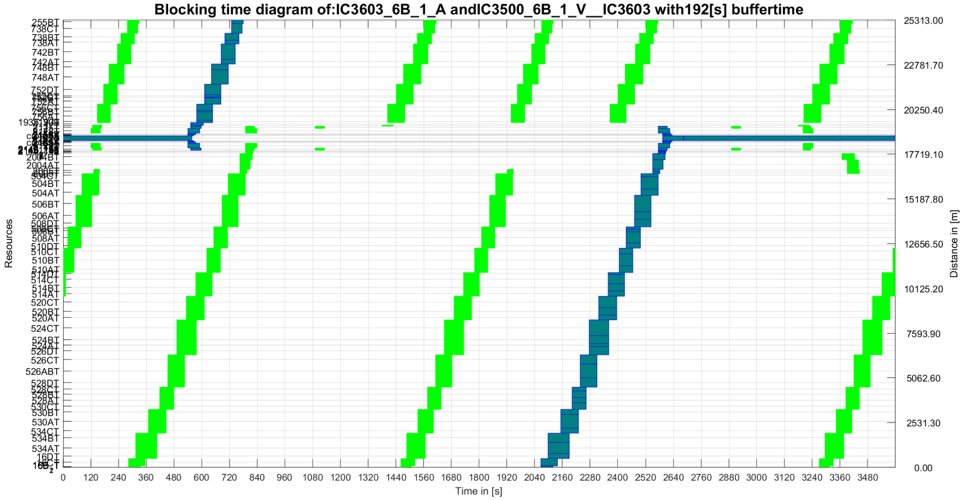


Figure 54: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

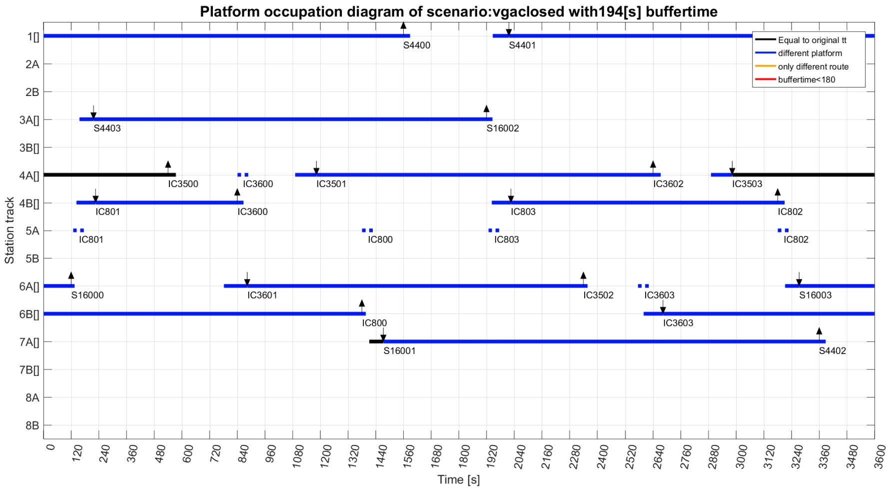


Figure 55: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

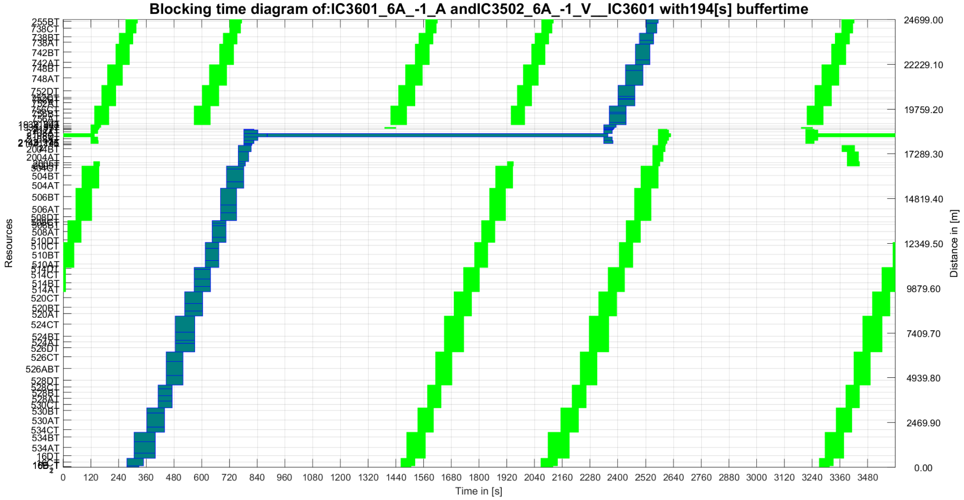


Figure 56: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

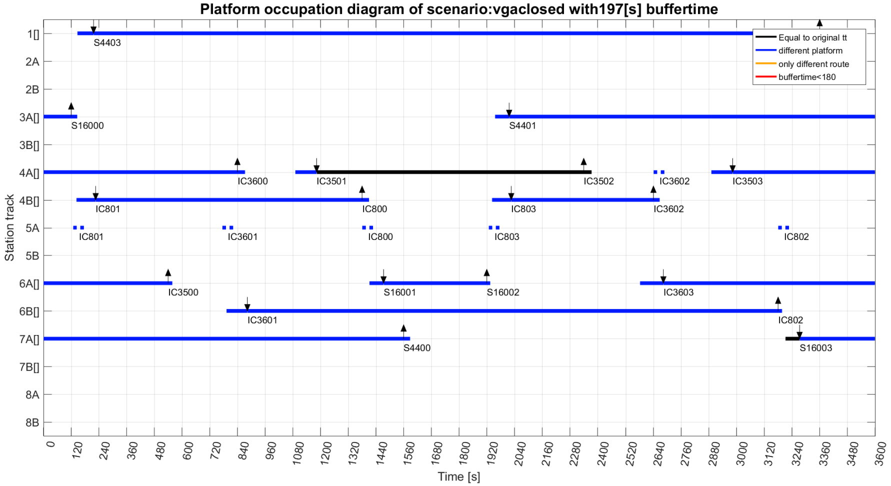


Figure 57: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

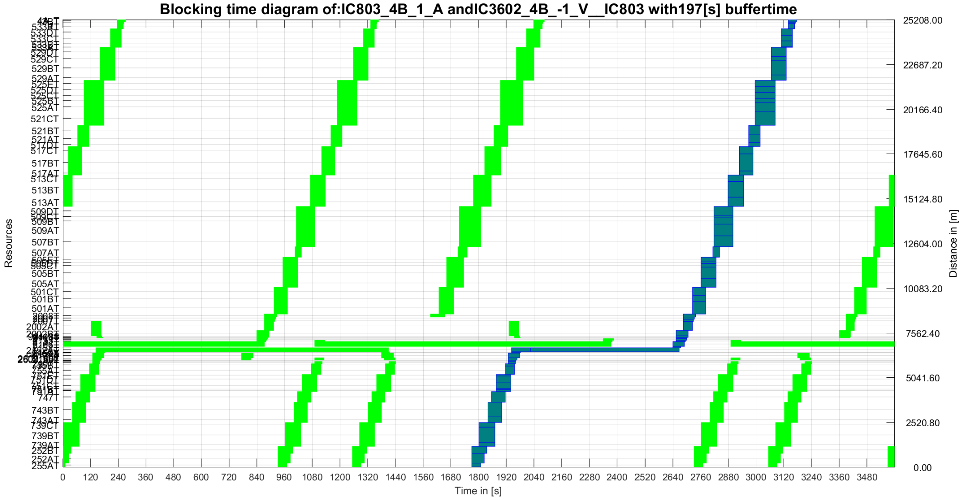


Figure 58: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

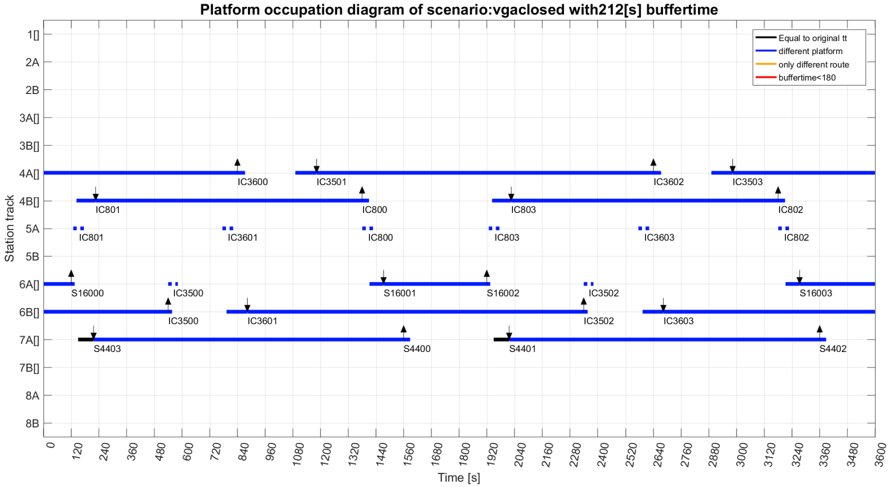


Figure 59: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

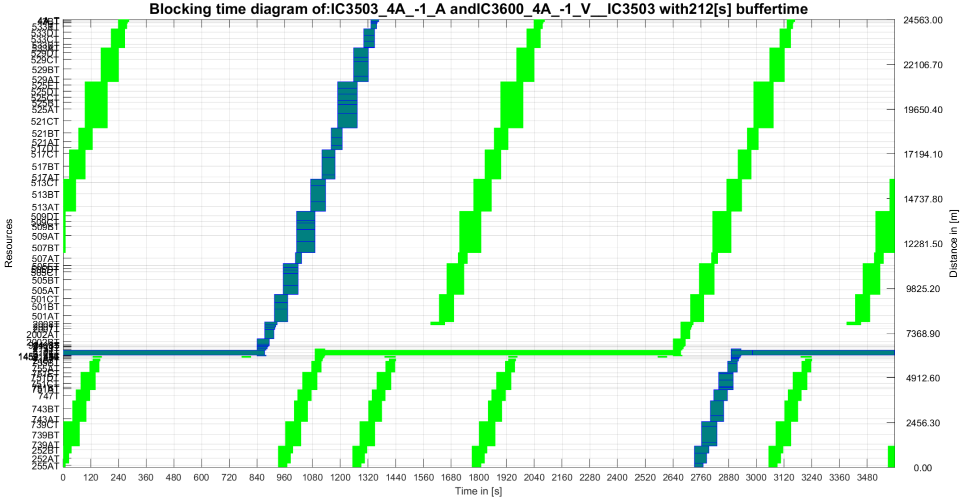


Figure 60: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

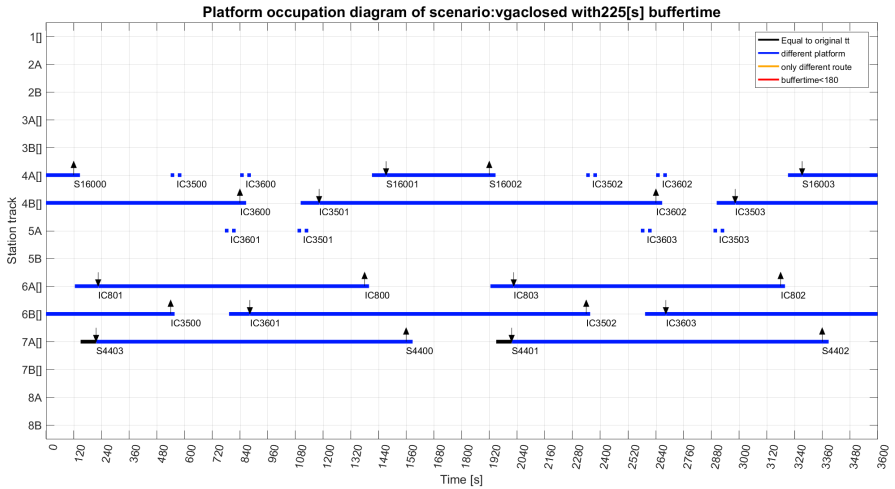


Figure 61: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

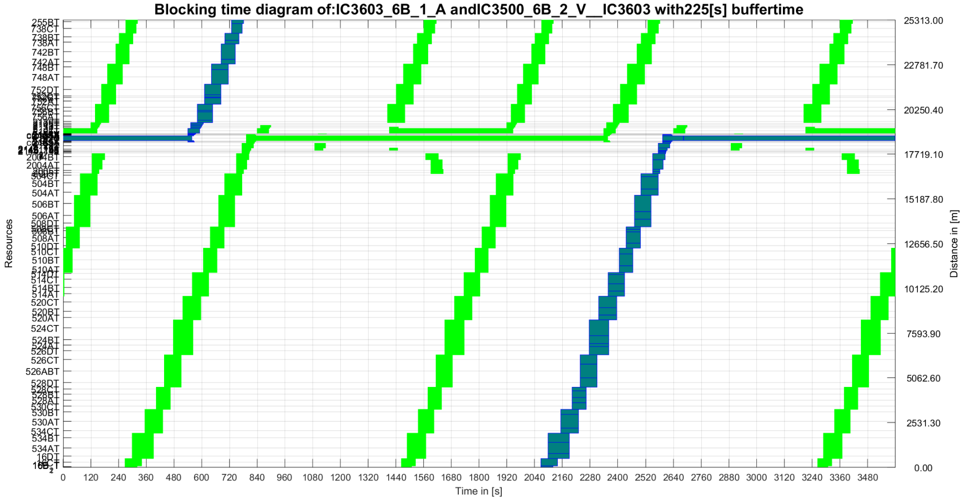


Figure 62: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

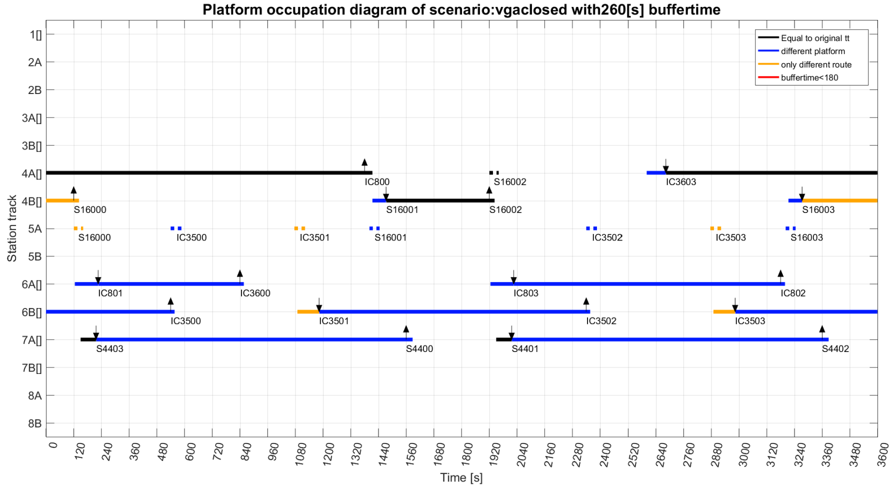


Figure 63: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed.

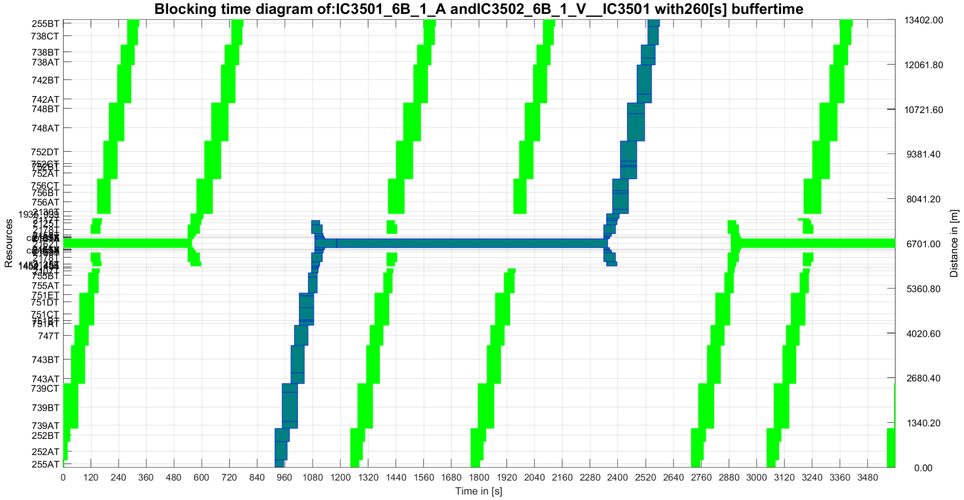
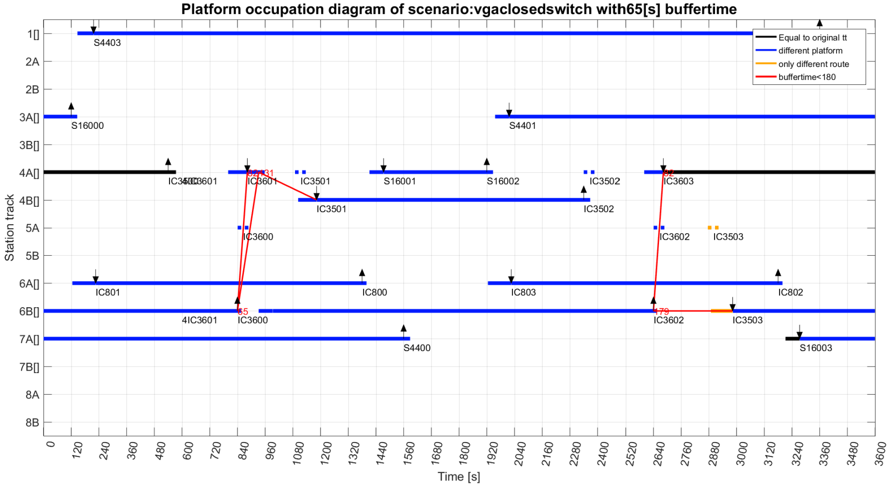


Figure 64: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.



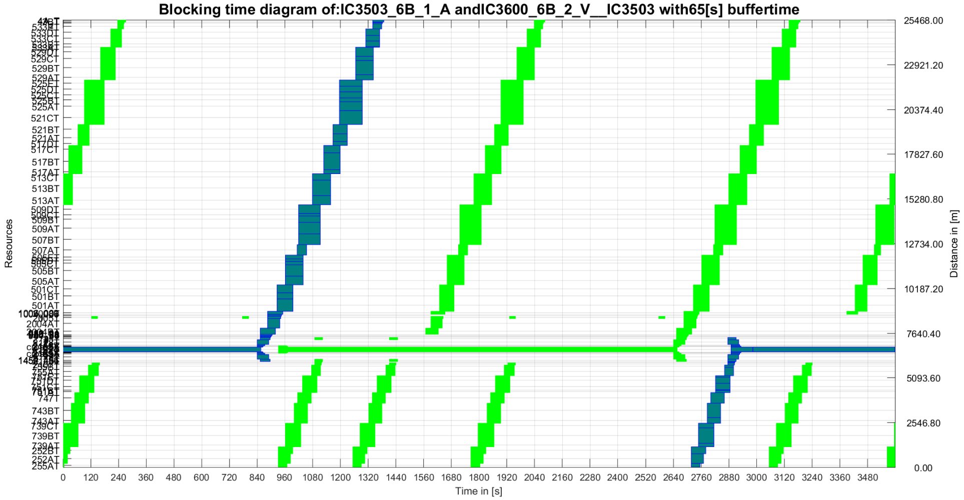
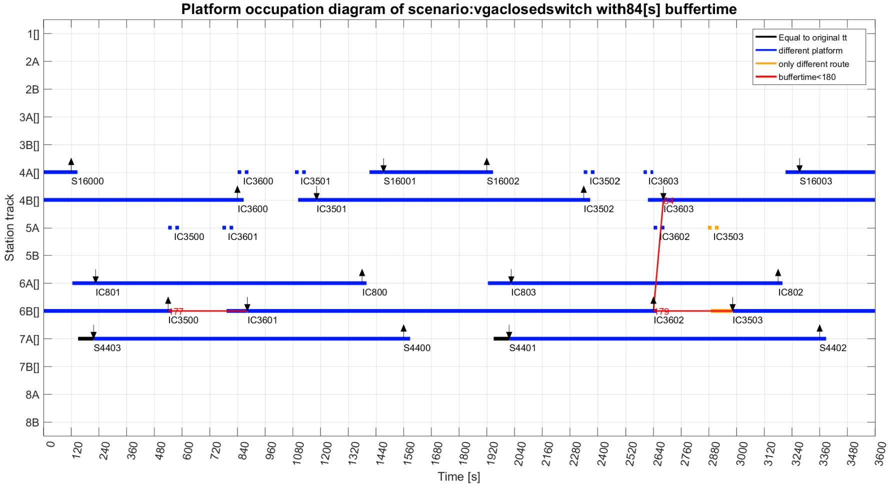


Figure 65: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed combined with a fixed switch making routes using both of tracks 4B and 5A impossible.

Figure 66: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.



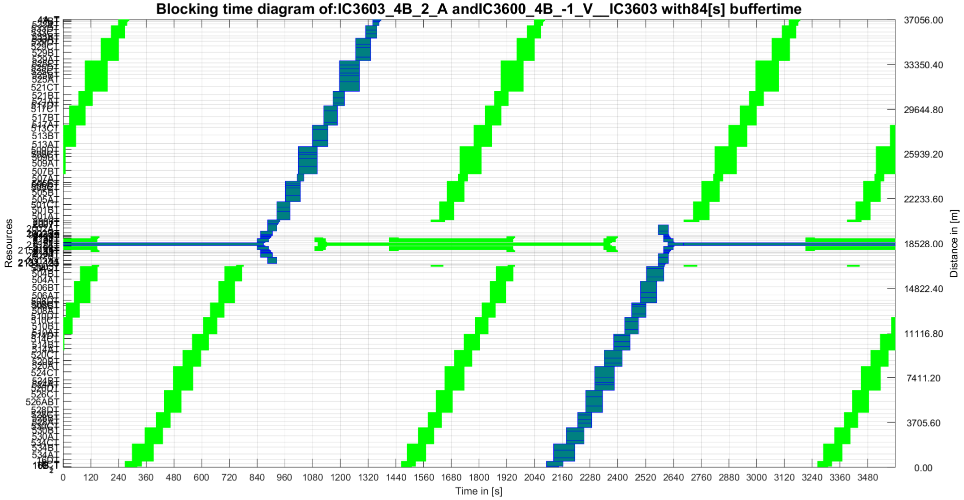


Figure 67: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed combined with a fixed switch making routes using both of tracks 4B and 5A impossible.

Figure 68: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

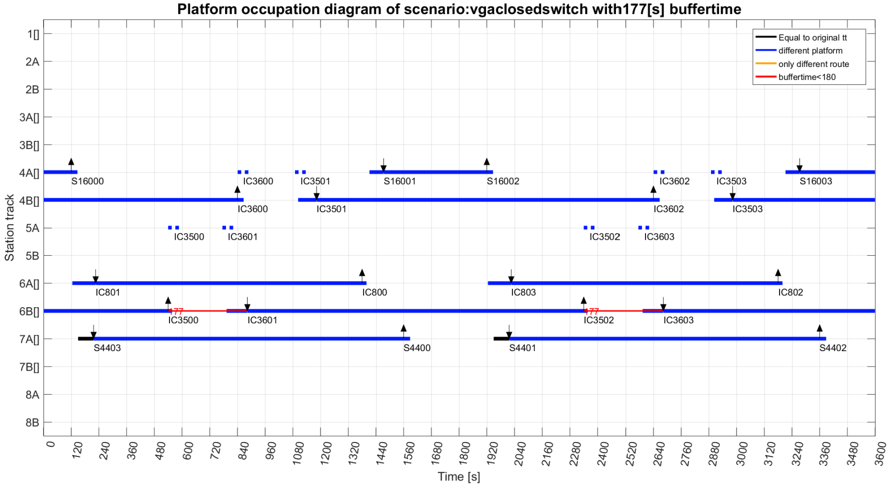


Figure 69: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed combined with a fixed switch making routes using both of tracks 4B and 5A impossible.

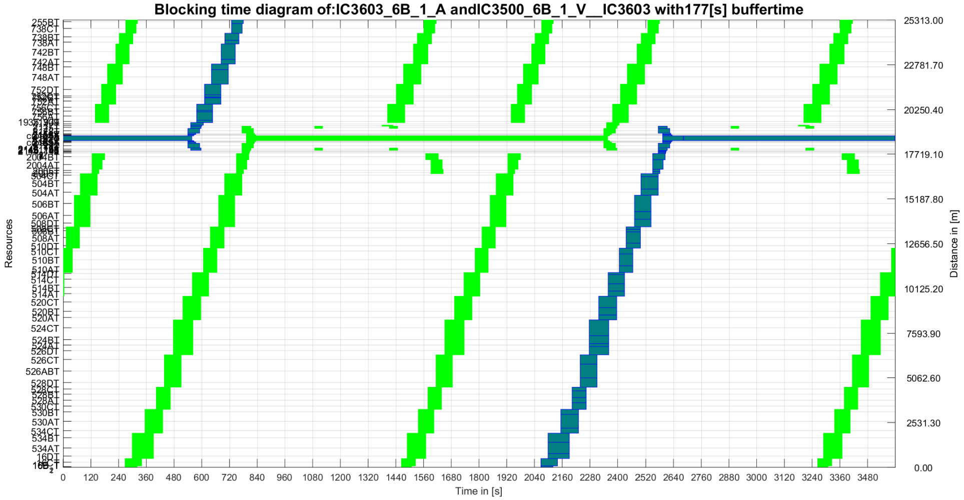


Figure 70: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

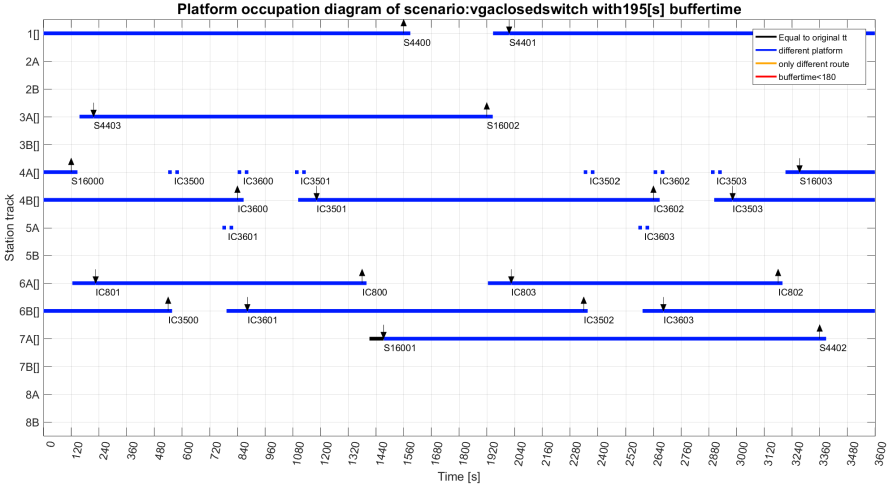


Figure 71: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed combined with a fixed switch making routes using both of tracks 4B and 5A impossible.

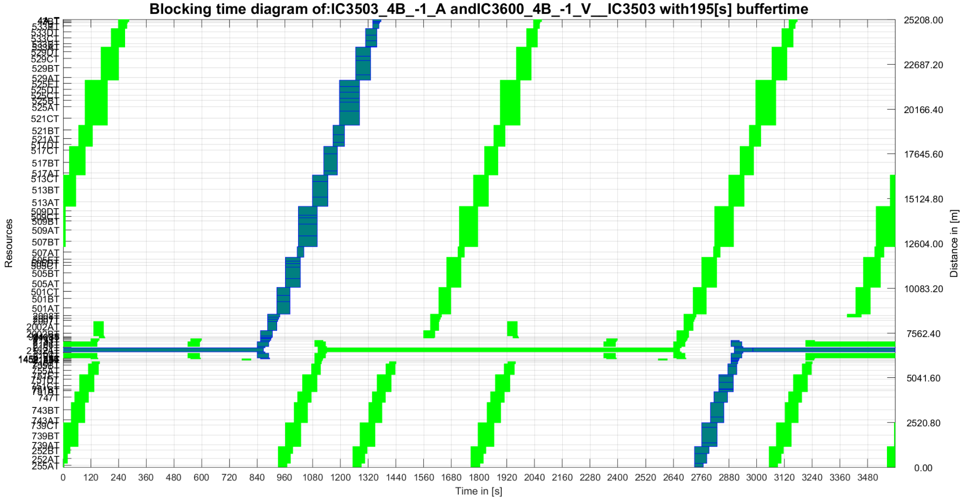


Figure 72: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

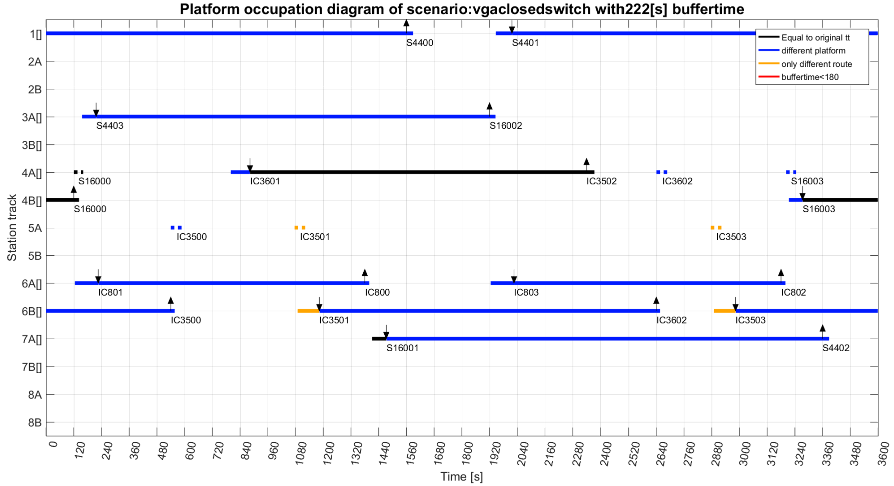


Figure 73: Platform occupation diagram of Den Bosch when all open tracks to Vught aansluiting are closed combined with a fixed switch making routes using both of tracks 4B and 5A impossible.

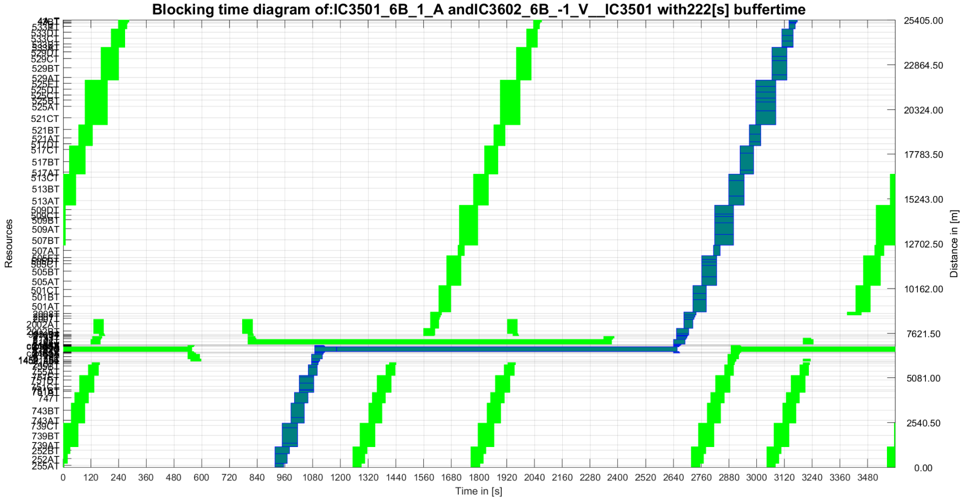


Figure 74: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

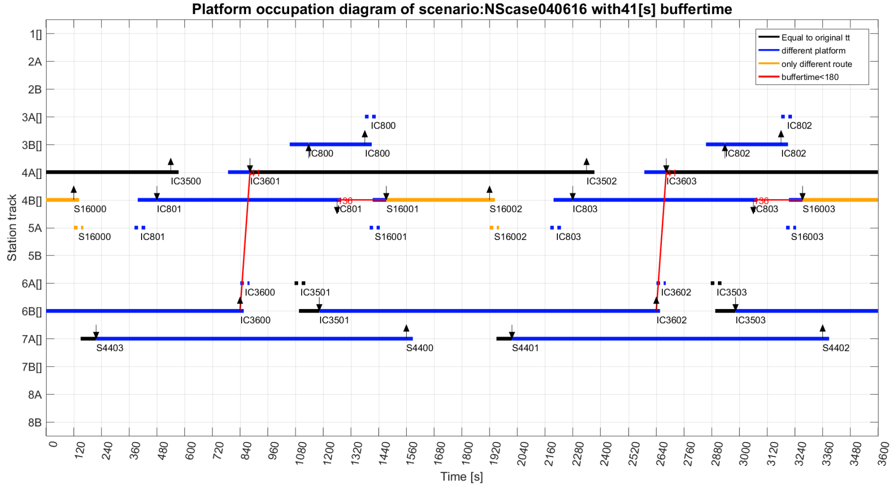


Figure 75: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

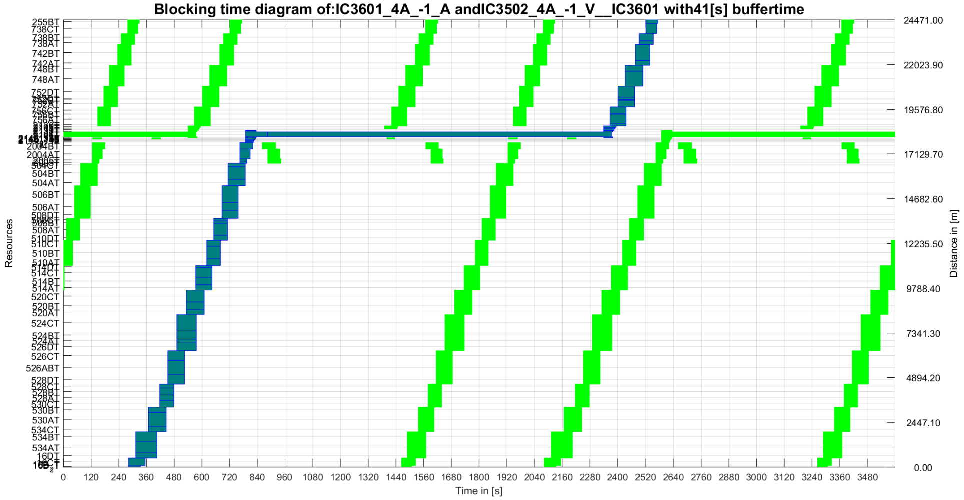


Figure 76: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

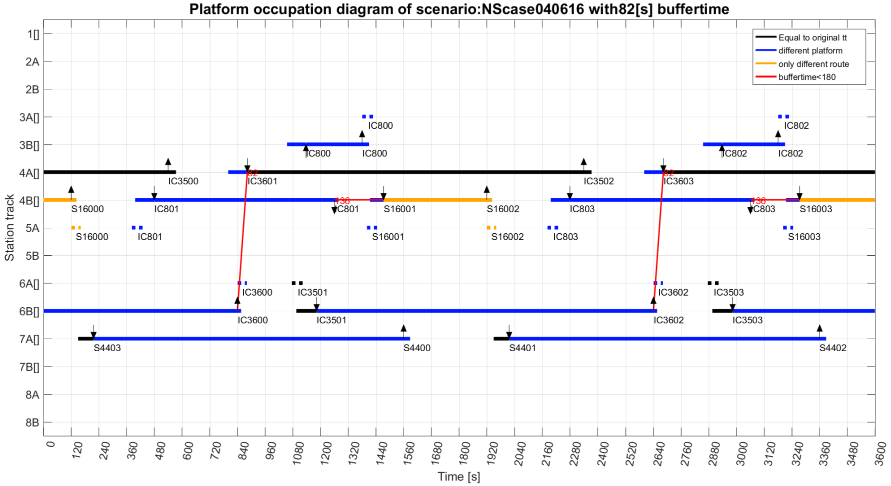


Figure 77: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

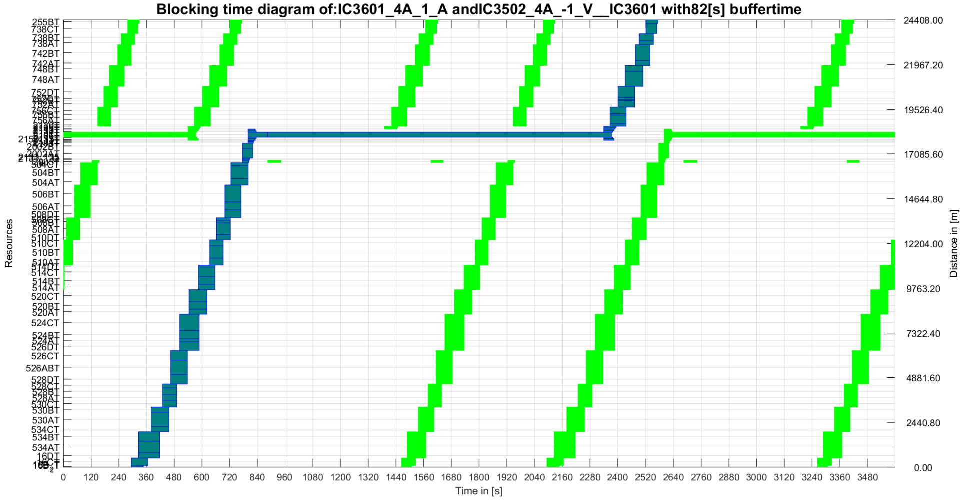


Figure 78: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

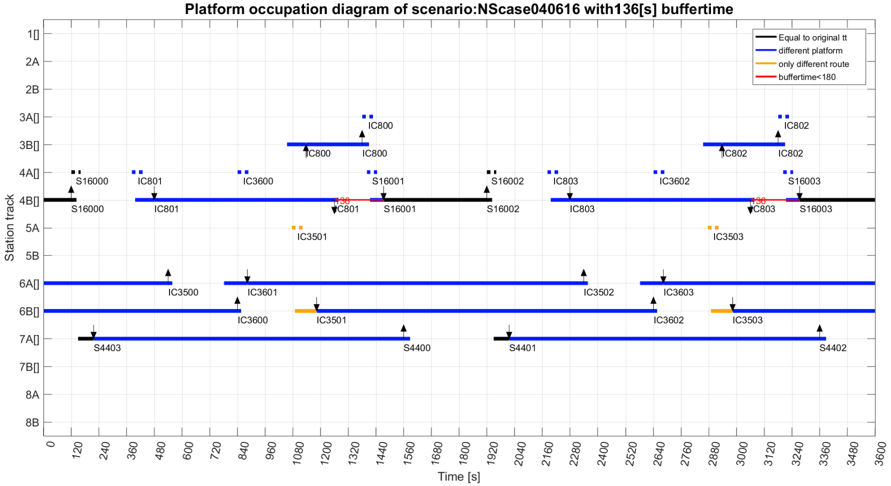


Figure 79: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

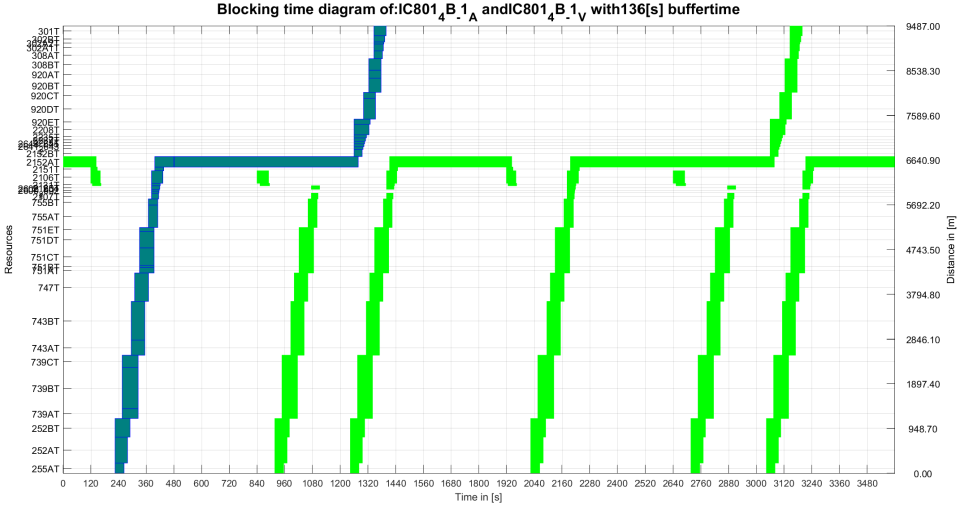


Figure 80: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

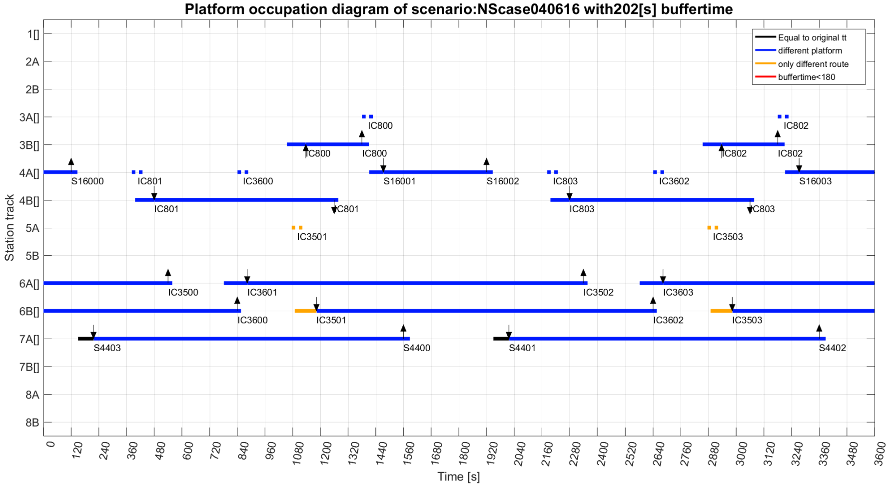


Figure 81: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

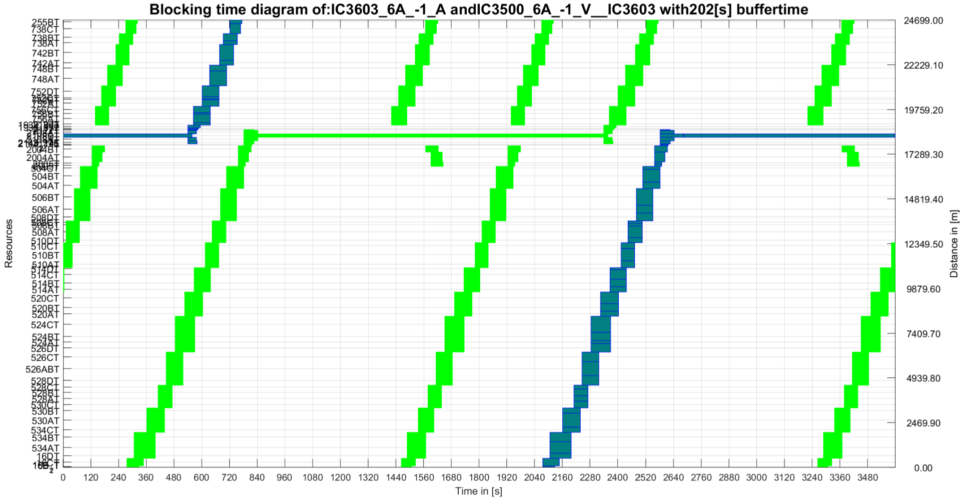


Figure 82: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

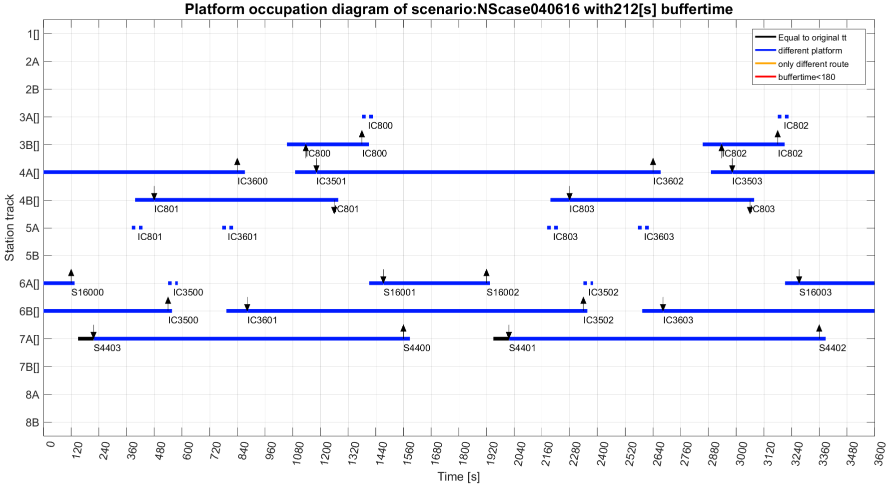


Figure 83: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

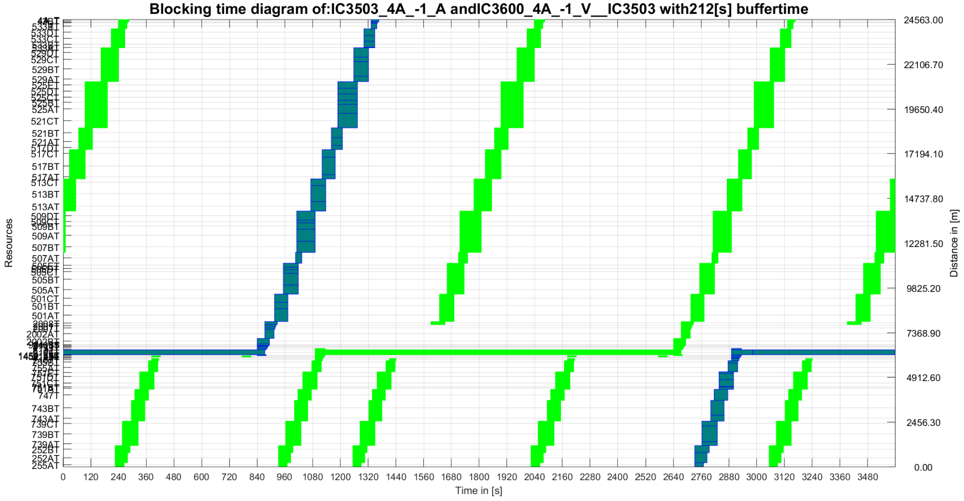


Figure 84: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

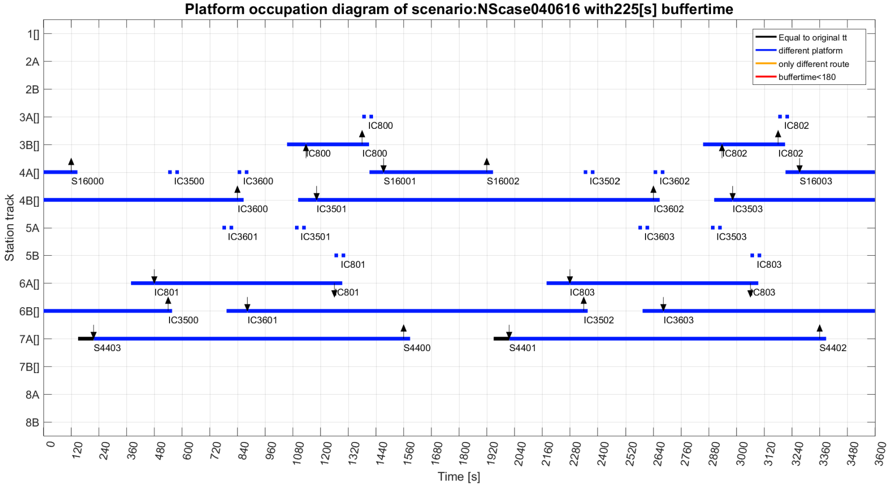


Figure 85: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

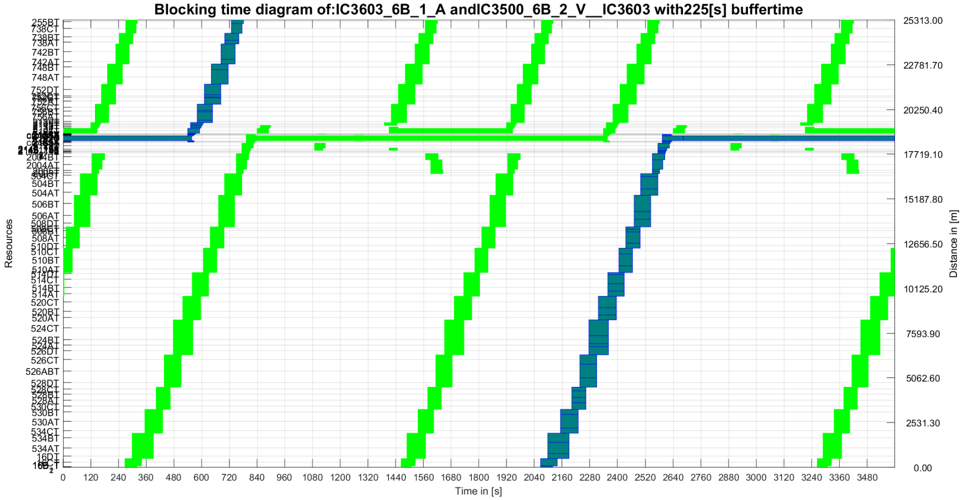


Figure 86: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

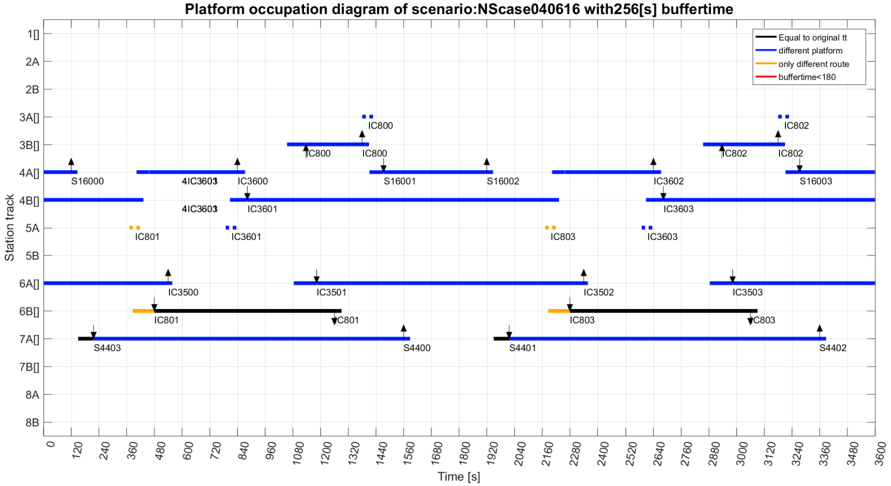


Figure 87: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

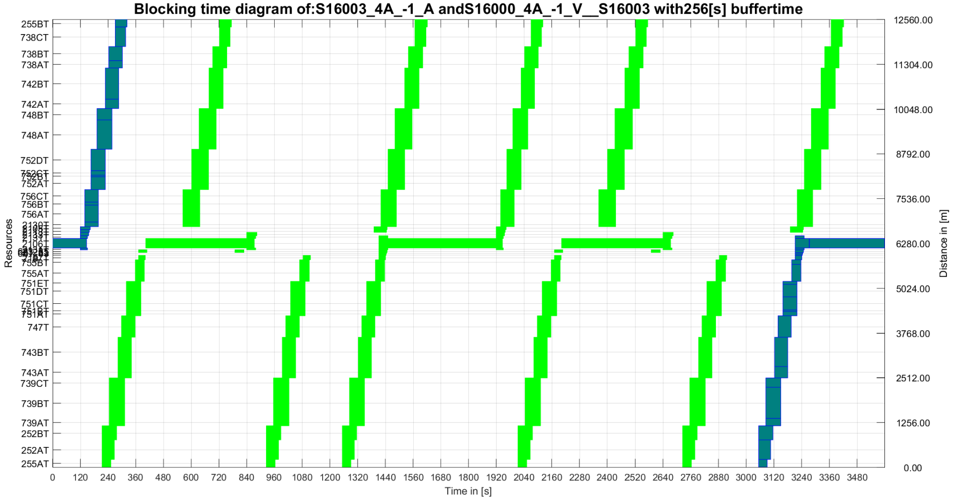


Figure 88: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

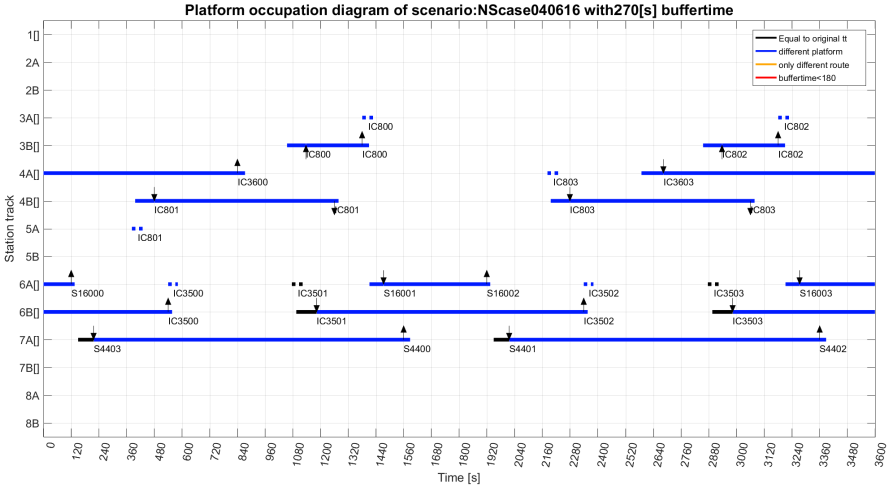


Figure 89: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught.

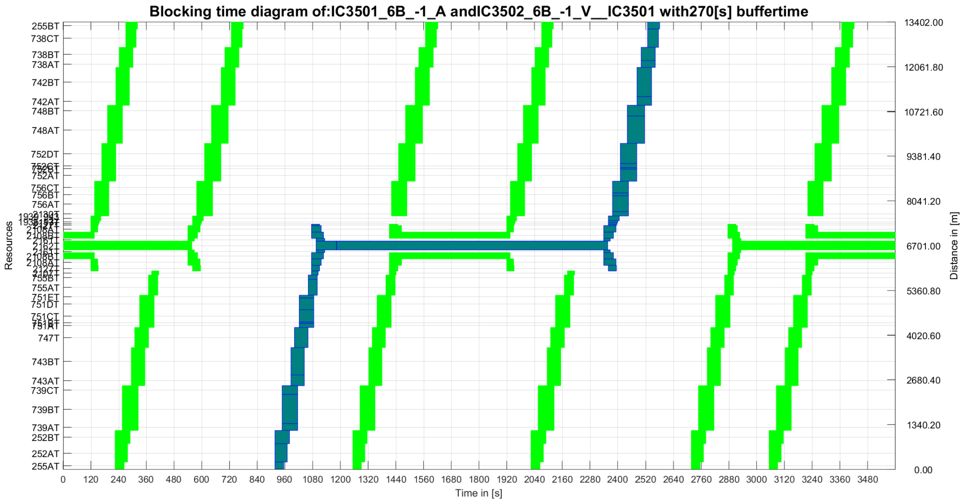


Figure 90: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

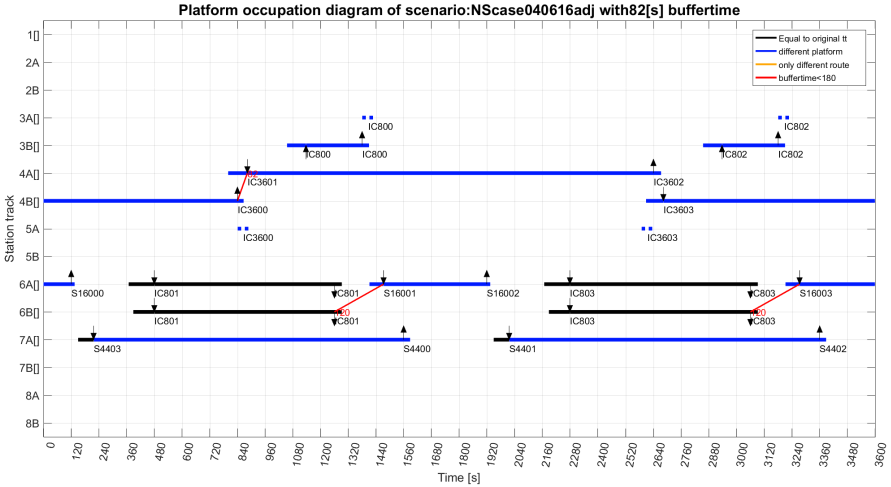


Figure 91: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

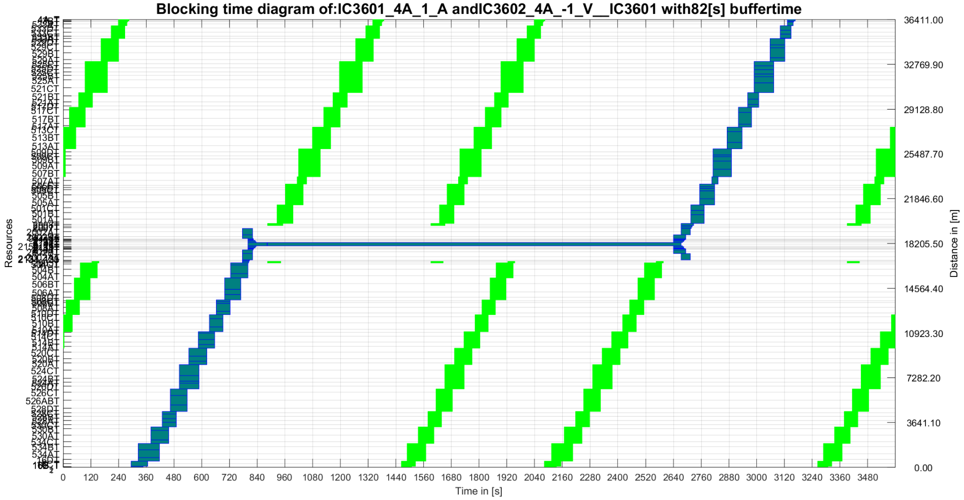


Figure 92: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

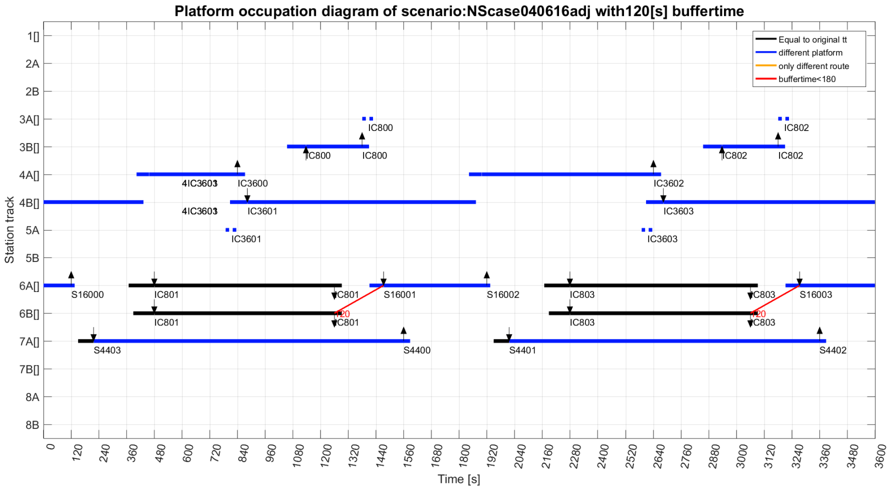


Figure 93: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

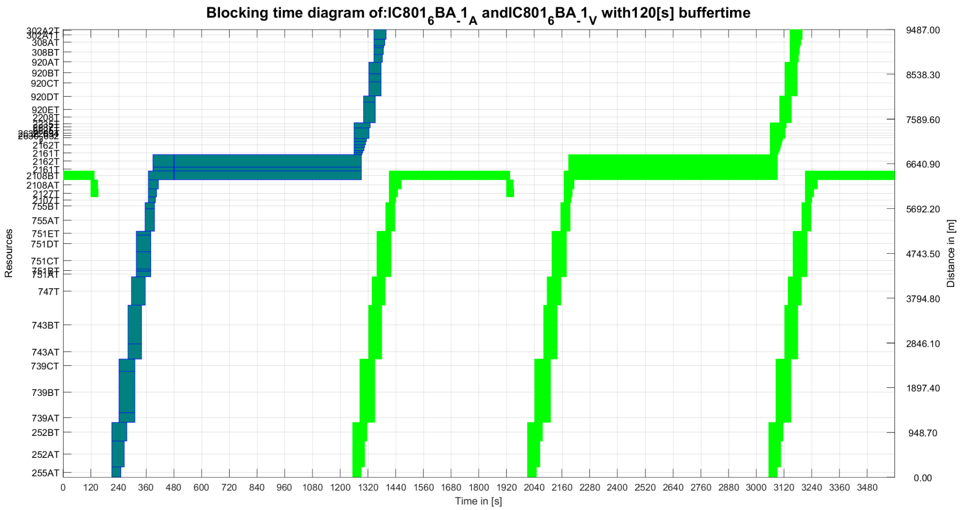


Figure 94: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

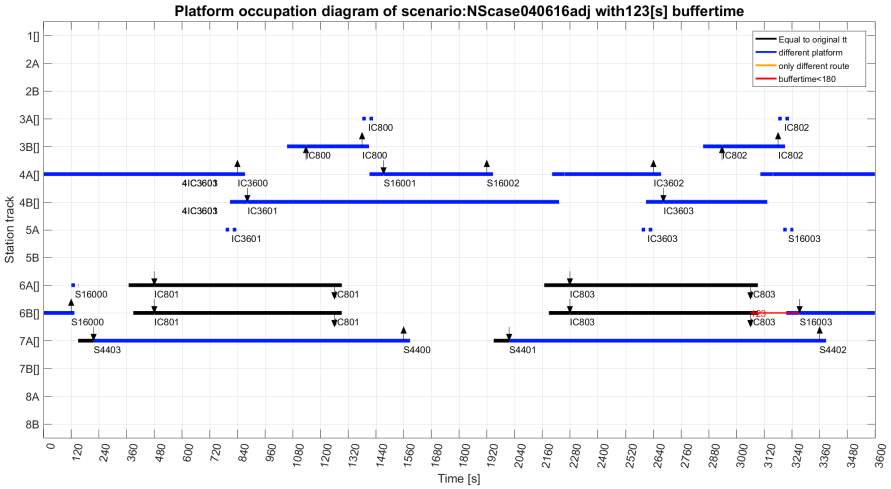


Figure 95: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

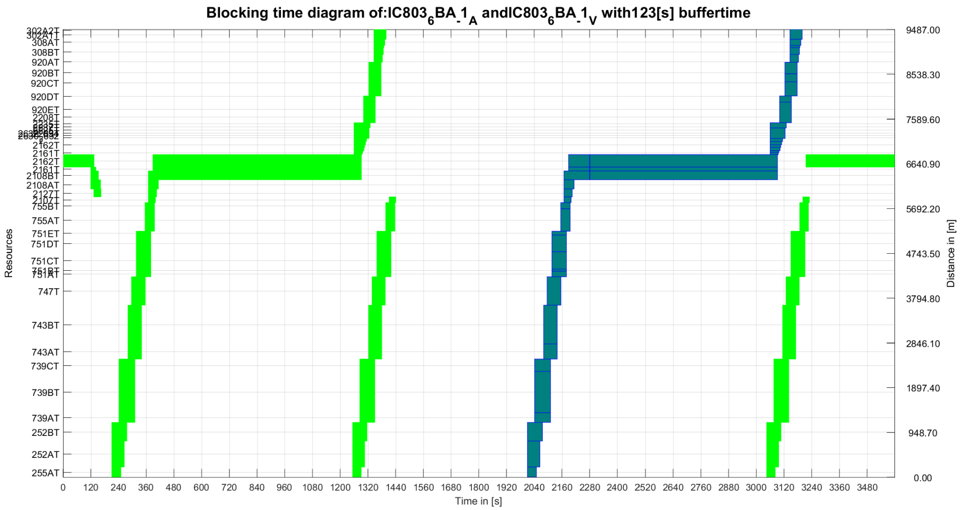


Figure 96: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

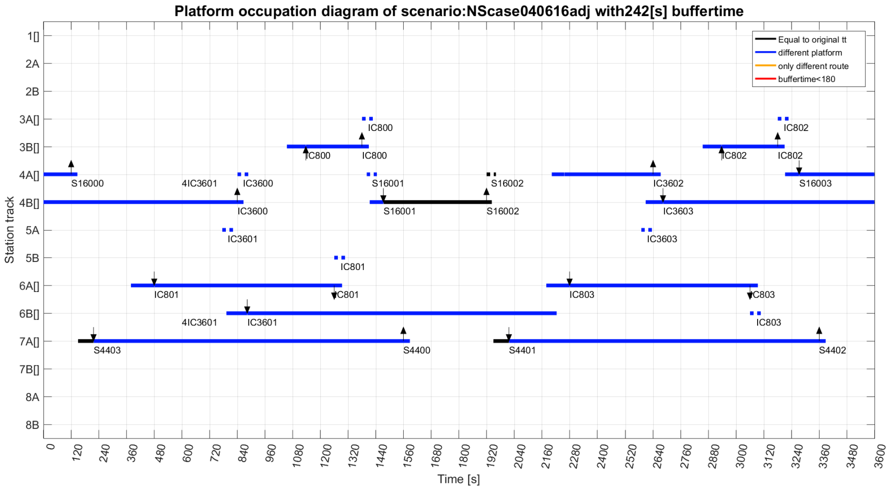


Figure 97: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

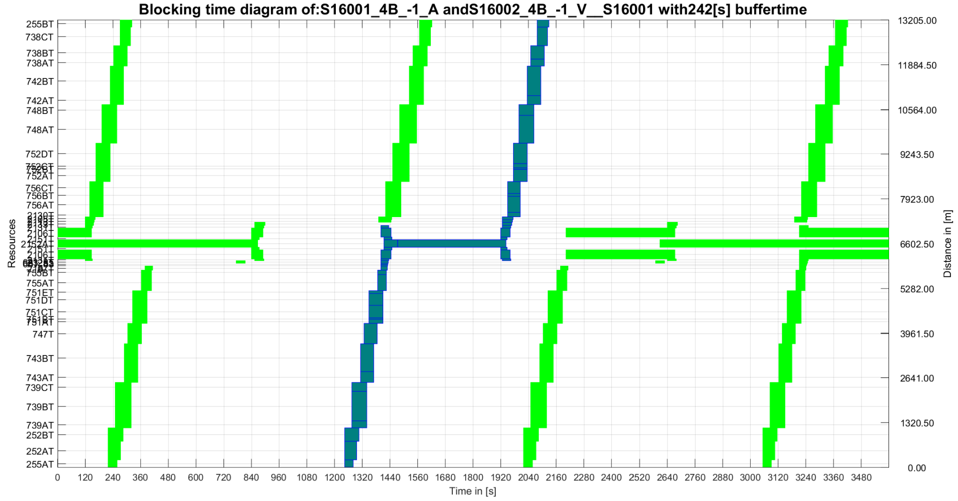


Figure 98: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

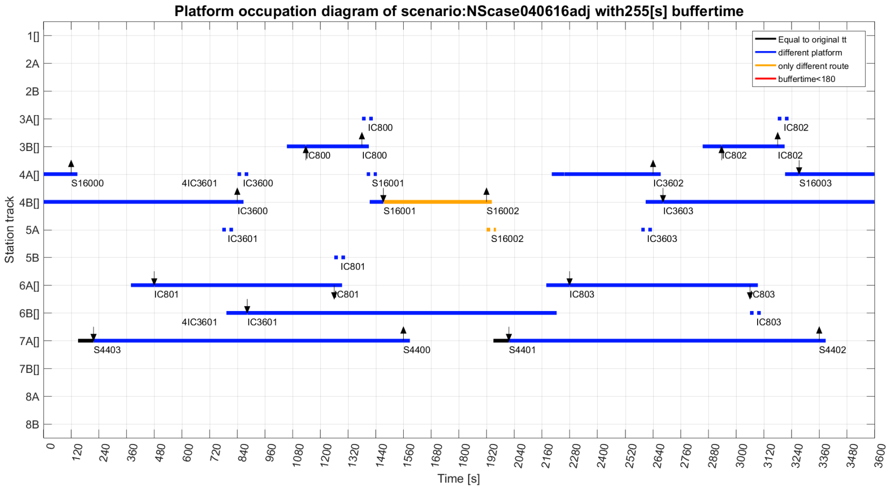


Figure 99: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

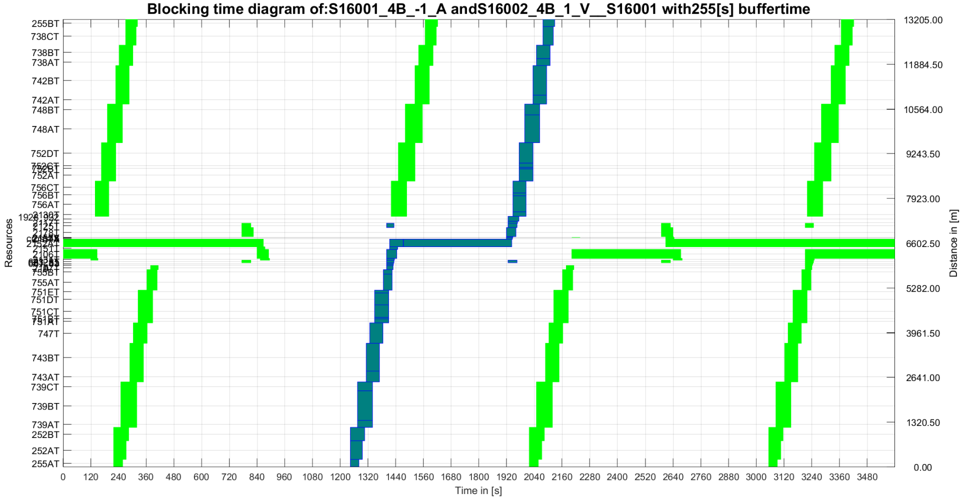


Figure 100: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

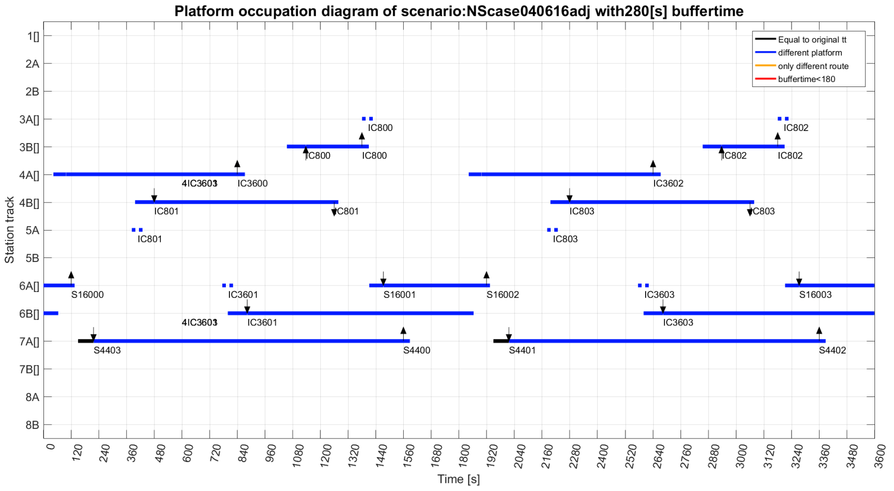


Figure 101: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

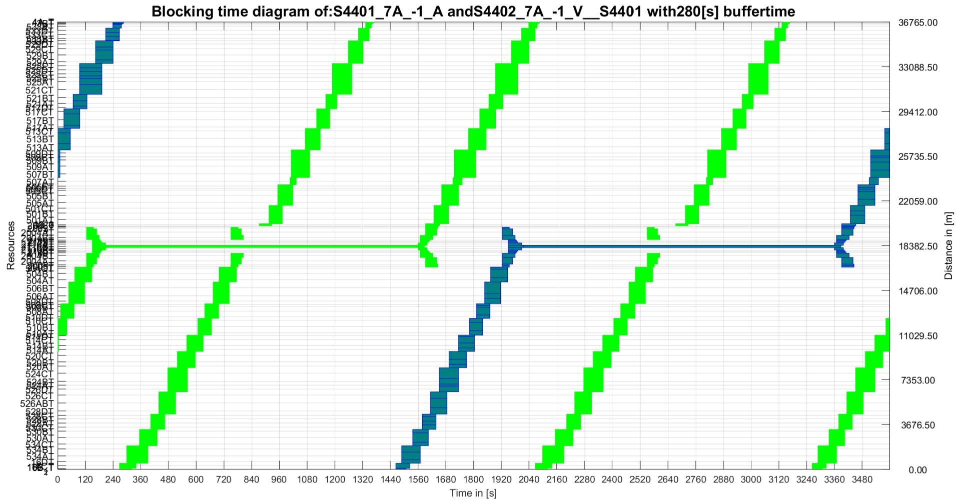


Figure 102: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

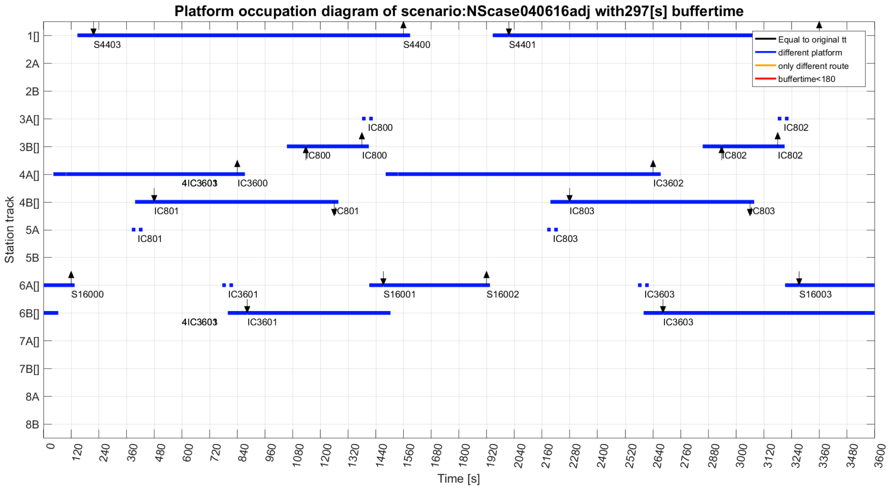


Figure 103: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

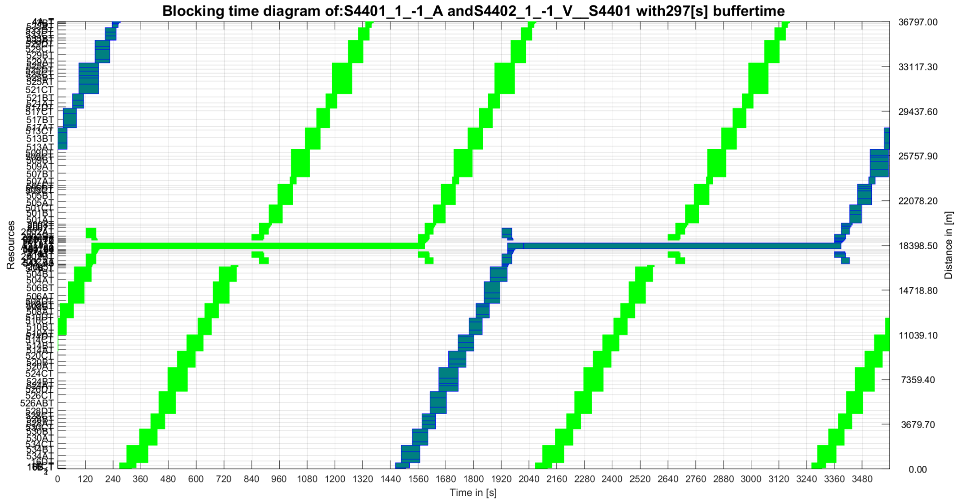


Figure 104: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

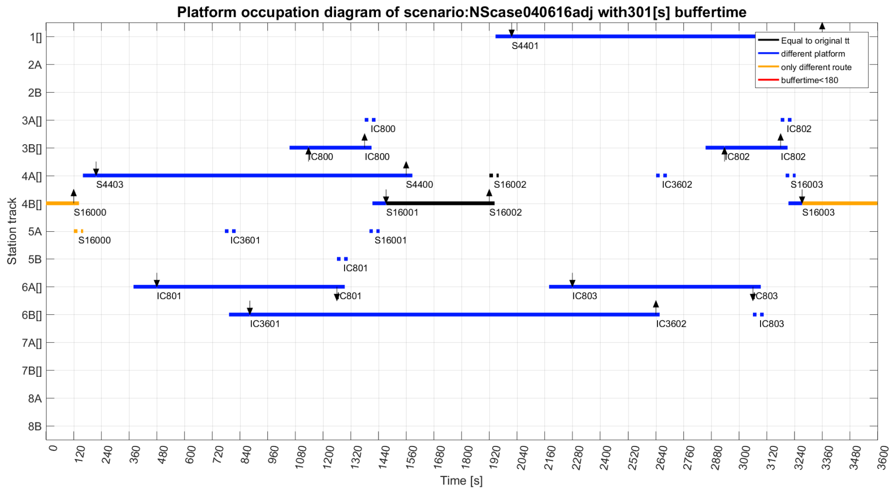


Figure 105: Platform occupation diagram of Den Bosch when 2 tracks in the direction of Vught aansluiting are closed, and a manually adjusted timetable is used that provides single track operation to/from Vught. Series 3500 is now manually cancelled.

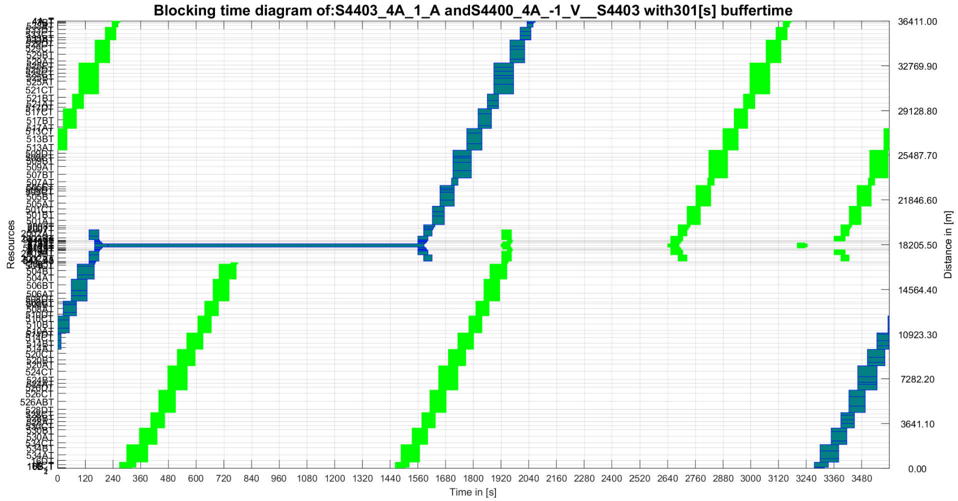


Figure 106: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

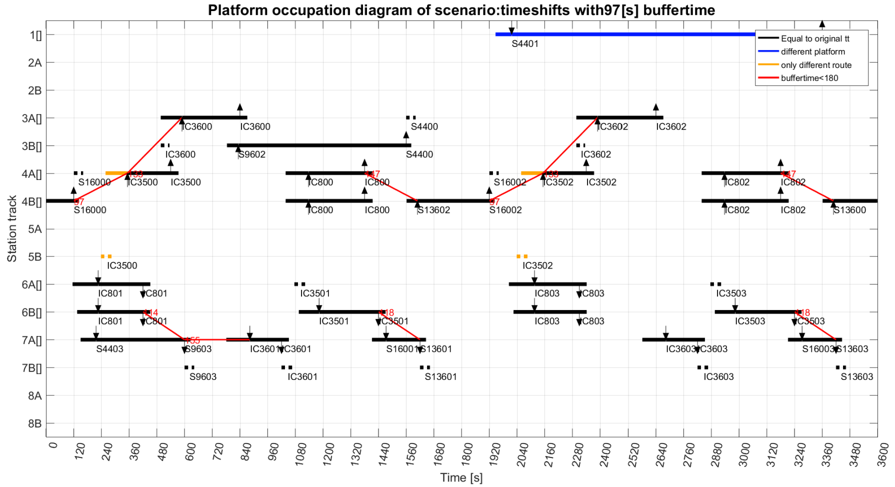


Figure 107: Platform occupation diagram of Den Bosch when an adjusted timetable is used so that not all trains can be scheduled.

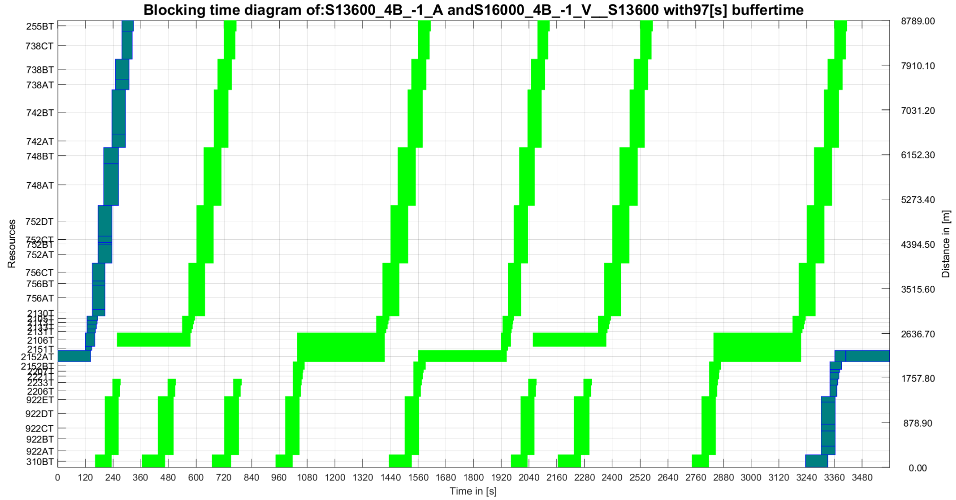


Figure 108: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

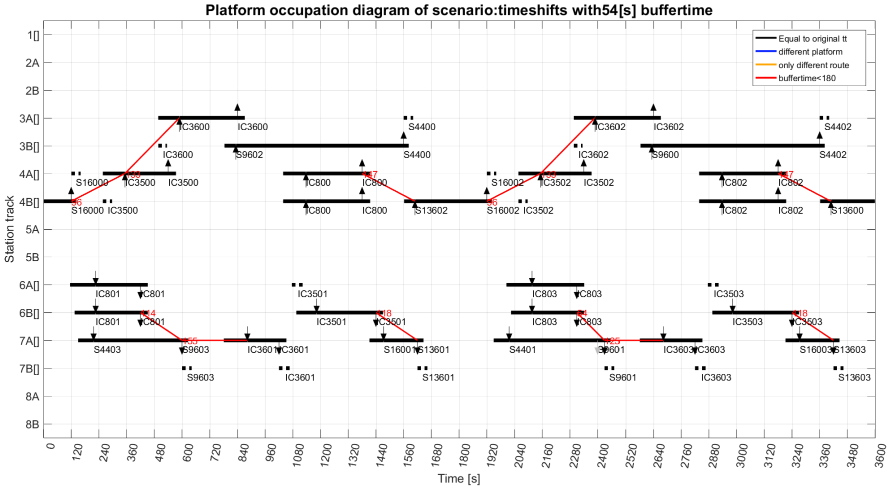


Figure 109: Platform occupation diagram of Den Bosch of an adjusted timetable with a time shift applied to train 9601 so that all conflicts are eliminated.

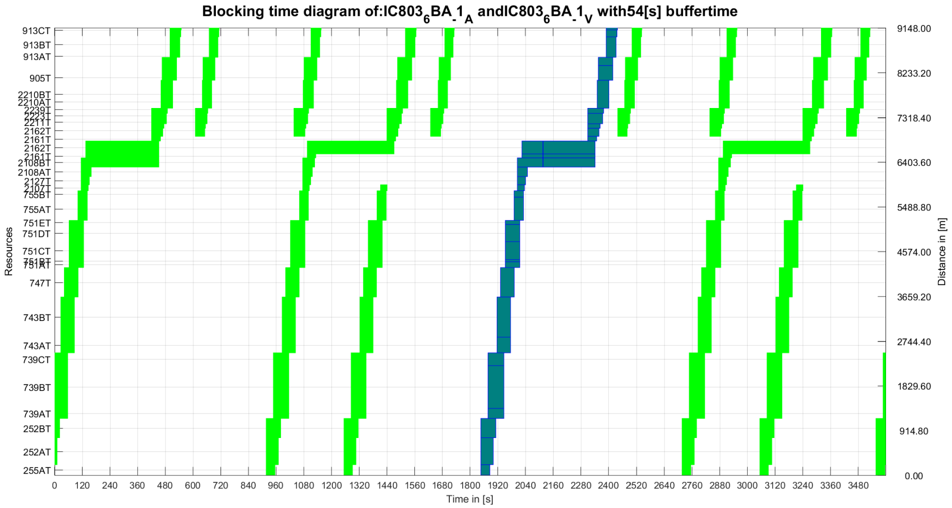


Figure 110: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

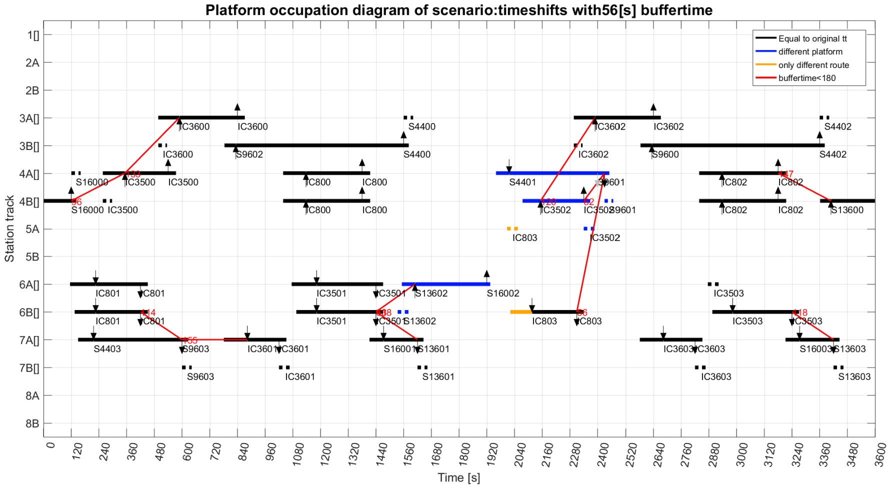


Figure 111: Platform occupation diagram of Den Bosch of an adjusted timetable to demonstrate the application of time shifts.

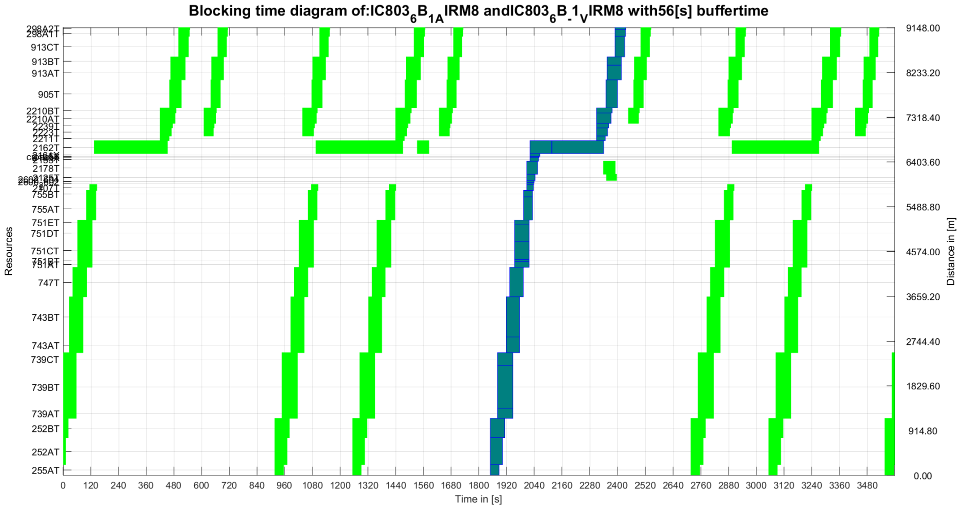


Figure 112: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

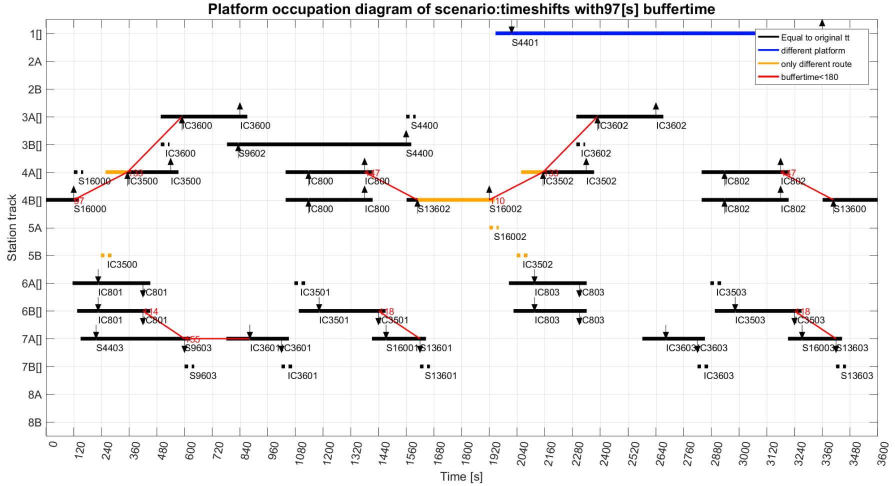


Figure 113: Platform occupation diagram of Den Bosch of an adjusted timetable to demonstrate the application of time shifts.

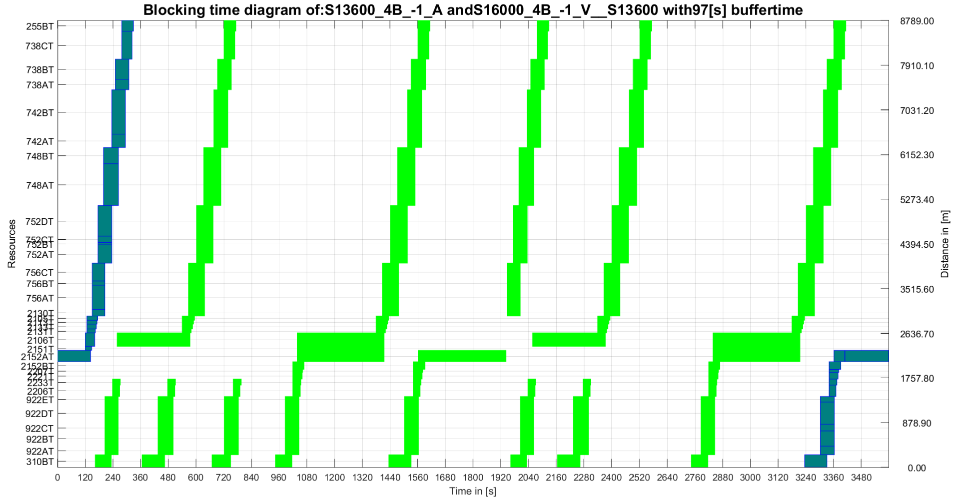


Figure 114: Blocking time diagram of the train with the lowest buffer time in the route plan shown on the left.

Appendix D: Data sources

Data	Format	Obtained from	Instructions on processing	Description
InfraPlanData	.xml	NS	Remco Nijs (NS)	NS Timetable
adjusted timetable	.mat	TU Delft	Sander van Aken	adjusted timetable from TTAP model
Isidoor	.xlsx	NS	Swen van den Berg (NS)	NS Rules for dwelling and changing directions based on rolling stock
Overstappen 2017	.xlsx	NS	Swen van den Berg (NS)	List of all passenger transfers
Perron- en spoorlengten 2016	.xlsx	NS	Swen van den Berg (NS)	List of all platform and track lengths
Blocking times	.mat	TU Delft	Nikola Bešinović (TU Delft)	List of routes with corresponding resources and blocking times
Alternative routes	.mat	TU Delft	Nadjla Ghaemi	All alternative routes in Den Bosch
InfraMonitor		ProRail	Nadjla Ghaemi	Interface to find infrastructure topology

Table 2: This table shows which data sources have been used for this thesis. If applicable, a reference is included if the data is publicly available.

Bibliography

Amie R Albrecht, DM Panton, and DH Lee. Rescheduling rail networks with maintenance disruptions using problem space search. *Computers & Operations Research*, 40(3):703–712, 2013.

Nikola Bešinović, Egidio Quaglietta, and Rob MP Goverde. A simulation-based optimization approach for the calibration of dynamic train speed profiles. *Journal of Rail Transport Planning & Management*, 3(4): 126–136, 2013.

Nikola Bešinović, Rob MP Goverde, Egidio Quaglietta, and Roberto Roberti. An integrated micro–macro approach to robust railway timetabling. *Transportation Research Part B: Methodological*, 87:14–32, 2016.

Nikola Bešinović, Rob MP Goverde, and Egidio Quaglietta. Microscopic models and network transformations for automated railway traffic planning. *Computer-Aided Civil and Infrastructure Engineering*, 32(2):89–106, 2017.

Peter Brucker, Silvia Heitmann, and Sigrid Knust. Scheduling railway traffic at a construction site. *Or Spectrum*, 24(1):19–30, 2002.

Sofie Burggraeve and Pieter Vansteenwegen. Robust routing and timetabling in complex railway stations. *Transportation Research Part B: Methodological*, 101:228 – 244, 2017. ISSN 0191-2615. doi: http://dx.doi.org/10.1016/j.trb.2017.04.007. URL `http://www.sciencedirect.com/science/article/pii/S0191261516305768`.

Gabrio Caimi, Dan Burkolter, and Thomas Herrmann. Finding delay-tolerant train routings through stations. In *Operations Research Proceedings 2004*, pages 136–143. Springer, 2005.

Gabrio Caimi, F Chudak, Martin Fuchsberger, Marco Laumanns, and Rico Zenklusen. A new resource-constrained multicommodity flow model for conflict-free train routing and scheduling. *Transportation science*, 45(2):212–227, 2011a.

Gabrio Caimi, Martin Fuchsberger, Marco Laumanns, and Kaspar Schüpbach. A multi-level framework for generating train schedules in highly utilised networks. *Public transport*, 3(1):3, 2011b.

Alberto Caprara, Leo Kroon, Michele Monaci, Marc Peeters, and Paolo Toth. Chapter 3 passenger railway optimization. *Handbooks in Operations Research and Management Science*, 14:129 – 187, 2007. ISSN 0927-0507. doi: http://dx.doi.org/10.1016/S0927-0507(06)14003-7. URL `http://www.sciencedirect.com/science/article/pii/S0927050706140037`. Transportation.

Alberto Caprara, Laura Galli, and Paolo Toth. Solution of the train platforming problem. *Transportation Science*, 45(2):246–257, 2011.

Thijs Dewilde, Peter Sels, Dirk Cattrysse, and Pieter Vansteenwegen. Robust railway station planning: An interaction between routing, timetabling and platforming. *Journal of Rail Transport Planning & Management*, 3(3):68–77, 2013.

Selim Dündar and İsmail Şahin. Train re-scheduling with genetic algorithms and artificial neural networks for single-track railways. *Transportation Research Part C: Emerging Technologies*, 27:1–15, 2013.

Railnet Europe. Network statement glossary. Technical report, RailNetEurope, 2014.

Martin Fuchsberger and Prof Dr Hans-Jakob Lüthi. Solving the train scheduling problem in a main station area via a resource constrained space-time integer multi-commodity flow. *Institute for Operations Research ETH Zurich*, 2007.

Rob MP Goverde, Nikola Bešinović, Anne Binder, Valentina Cacchiani, Egidio Quaglietta, Roberto Roberti, and Paolo Toth. A three-level framework for performance-based railway timetabling. *Transportation Research Part C: Emerging Technologies*, 67:62–83, 2016.

I.A. Hansen, P.B.L. Wiggenraad, and J.W. Wolff. Parlementair onderzoek onderhoud en innovatie, deelonderzoek ii: Inrichting, gebruik en onderhoud nederlands spoorsysteem, internationale vergelijking. Technical report, Tweede Kamer, 2012.

Ingo A Hansen and Jörn Pachl. *Railway timetabling & operations: analysis, modelling, optimisation, simulation, performance evaluation*. Eurailpress, 2014.

I&M. Beheer, onderhoud en vervanging en toekomstbestendig en efficient onderhoud van het spoor. Technical report, I&M, 2016.

Leo Kroon, Dennis Huisman, and Gábor Maróti. Optimisation models for railway timetabling. *Hansen and Pachl (Eds.): Railway Timetable & Traffic. Analysis, Modelling, Simulation, Hamburg: Eurailpress*, 2008.

Tomas Lidén. Railway infrastructure maintenance-a survey of planning problems and conducted research. *Transportation Research Procedia*, 10:574–583, 2015.

Tomas Lidén and Martin Joborn. Dimensioning windows for railway infrastructure maintenance: Cost efficiency versus traffic impact. *Journal of Rail Transport Planning & Management*, 6(1):32–47, 2016.

Tomas Lidén and Martin Joborn. An optimization model for integrated planning of railway traffic and network maintenance. *Transportation Research Part C: Emerging Technologies*, 74:327–347, 2017.

Richard Lusby, Jesper Larsen, David Ryan, and Matthias Ehrgott. Routing trains through railway junctions: a new set-packing approach. *Transportation Science*, 45(2):228–245, 2011.

Sundaravalli Narayanaswami and Narayan Rangaraj. A mas architecture for dynamic, realtime rescheduling and learning applied to railway transportation. *Expert Systems with Applications*, 42(5):2638–2656, 2015.

NS. Annual report 2016. Technical report, NS, 2016.

TJ Planting. Ontwerpmethoden van dienstregelingen, verkennend onderzoek naar de ontwerpmethodiek per fase in het planningsproces bij ns & prorail. Master's thesis, TU Delft, 2016.

ProRail. Megaklus den bosch uit de startblokken. Technical report, ProRail, 2013.

ProRail. Netverklaring 2016. Technical report, ProRail, 2016.

Marcella Samà, Paola Pellegrini, Andrea D'Ariano, Joaquin Rodriguez, and Dario Pacciarelli. On the tactical and operational train routing selection problem. *Transportation Research Part C: Emerging Technologies*, 76:1–15, 2017.

Peter Sels, Pieter Vansteenwegen, Thijs Dewilde, Dirk Cattrysse, Bertrand Waquet, and Antoine Joubert. The train platforming problem: The infrastructure management company perspective. *Transportation Research Part B: Methodological*, 61:55–72, 2014.

Peter Sels, Dirk Cattrysse, and Pieter Vansteenwegen. Automated platforming & routing of trains in all belgian railway stations. *Expert Systems with Applications*, 62:302–316, 2016.

Zhou Taoyong, Hu Bin, Wang Xuejun, and Yan Bo. Discrete element method analysis of mechanical properties of railway ballast during tamping process under different vibration frequency. *Applied Mechanics and Materials*, 190:191, 2012.

Sander Van Aken. Assessment of the potential of a macroscopic model for the automated generation of alternative hour patterns (aups). Technical report, NS Reizigers, 2016.

Sander Van Aken, Nikola Bešinović, and Rob MP Goverde. Designing alternative railway timetables under infrastructure maintenance possessions. *Transportation Research Part B: Methodological*, 98:224–238, 2017a.

Sander Van Aken, Nikola Bešinović, and Rob MP Goverde. Solving large-scale train timetable adjustment problems under infrastructure maintenance possessions. *Journal of Rail Transport Planning & Management*, 2017b.

DM Van de Velde, J Drew, and J Ludewig. Reforming europe's railways–learning from experience: The netherlands. *Reforming Europe's Railways–Learning from experience, CER (Community of European Railway and Infrastructure), Brussels*, pages 137–148, 2011.

John Van Den Broek and Leo Kroon. A capacity test for shunting movements. In *Algorithmic Methods for Railway Optimization*, pages 108–125. Springer, 2007.

Pieter Vansteenwegen, Thijs Dewilde, Sofie Burggraeve, and Dirk Cattrysse. An iterative approach for reducing the impact of infrastructure maintenance on the performance of railway systems. *European Journal of Operational Research*, 252(1):39–53, 2016.

Rafael Velasquez, Matthias Ehrgott, David Ryan, and Anita Schöbel. A set-packing approach to routing trains through railway stations. In *Proceedings of the 40th annual conference of the operational research society of New Zealand*, pages 305–314, 2005.

Sven Zeegers. Sporenplan van den bosch. `www.sporenplan.nl`, 2017. Accessed: 07-04-2017.

Peter J Zwaneveld, Leo G Kroon, and Stan PM Van Hoesel. Routing trains through a railway station based on a node packing model. *European Journal of Operational Research*, 128(1):14–33, 2001.