Disruption Strategy Management for the Utrecht Light Rail System: A simulation Approach

Master Thesis

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Abstract

In this thesis disruption management strategies are created for the Utrecht light rail system. In order to check the effectiveness of these strategies a simulation is developed that behaves similarly to the light rail system in real life. In this simulation disruptions are mimicked by disabling elements of the track and stopping the nearby traffic. Three different disruption scenarios are analyzed each with one or more disruption management strategies. Although this analysis points out that major differences between strategies are scarce some strategies work better than others. Using the optimal disruption strategy can mitigate the effect a disruption has on the rest of the system almost completely.

Contents

1 Introduction

The main goal of a public transportation system is to get all passenger to their destination as quickly and efficiently as possible. In a perfect world this could be done by creating an optimal timetable. However Pender et al. (2013) says that because in practice there are many factors out of human control all systems face unplanned service disruptions. Medical emergencies, rolling stock defects and even the weather can influence the timetable in a negative manner. Minimizing the occurrences of these problems can be done, but an accident can always happen and the traffic controllers need to be prepared for when it does. Disruption management strategies, or disruption strategies, are created to guide the traffic controllers through these kind of situations. Due to the importance of a disruption strategies a lot of research has been done to enhance their performance. Examples of those researches are Serra (2022) and Cacchiani et al. (2014).

When a disruption happens the goal is to transfer the system into a stable disrupted timetable. This can either be stopping all trains or redirecting the trains so they can still drive within the limitations of the disruption. Although the length of a disruption can be predicted based on past experiences, a disrupted timetable should have no time limitation. When the disruption is passed the system will transfer back to the regular timetable and when that is done the disruption is completely resolved. This approach is called the bathtub model and is depicted in Figure 1. A disruption strategy should specify how each of the phases will be handled. A good balance must be found between the three phases, because as mentioned in Chu and Oetting (2013) a short phase 1 can cause a lot of problems in the other phases.

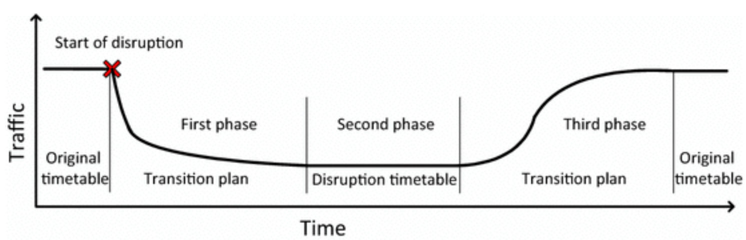

Figure 1: The Bathtub model

The best way of determining a disruption strategy is to start with phase 2. Finding a timetable that can still be driven during the disruption is the most limiting aspect of the strategy. It also impossible to make a strategy for phase 1 if there is no desired end result. It can however be rather difficult to find a timetable for the disrupted system. In such cases a linear programming solution can help. This is done in the papers Cadarso et al. (2013), Cadarso and Marin (2014), Placido et al. (2014), and D'Acierno et al. (2013) where a timetable is planned according to a mixed integer linear program. In Louwerse and Huisman (2014) an integer programming model is used to create a timetable for phase 2 and in Veelenturf et al. (2016) this model is updated so it can be used for all phases. This model is created for larger rail way networks, but can be down-scaled in order to fit a light rail system.

1.1 Problem Description

In December 2019 the Utrecht light rail system was extended with a new section called the Uithoflijn. The Uithoflijn connects the university district of the city with its central station. At first this new section drove separately from the old section, the UNSIJlijn, but starting from the summer of 2022 trains will drive through both sections. This new situation can cause new problems, but can also provide new possibilities in terms of disruption strategies. In this thesis three disruption scenarios will analyzed for key elements in a potential disruption strategy. These three scenarios are picked in order to highlight potential differences in the new situation. This research can be beneficial for traffic controllers, so they can get a grasp on what the consequences can be for certain choices in a disruption strategy.

2 The Utrecht Light Rail System

2.1 Intro

The Utrecht light rail system consists out of 32 stops, eight track crossings, two tram depots, and one track split. The system is a double-track railway where each track is used for only one direction of travel. The trains on this system mostly ride on the driver's sight. This means that for most of the track the driver is responsible for adhering to the speed limits and keeping a safe distance to the train in front. There are also sections of the light rail system that are monitored by traffic control. These sections are at the track crossings and at the train depots. The split is not one of the controlled sections. The controlled sections are the most interesting places in regards to disruption management. A train can be stopped at any location or slowed anywhere, but only in these controlled section more complicated actions can be done.

2.2 Trains and Lines

The trains used in Utrecht consist out of one or two units with a total combined length of at most 75 meter. There are two types of train units, one is 31 and the other 41 meter long. This means that a train has minimum length of 31 meter and a maximum length of 72 meters, a combination of a 31 meter and a 41 meter unit. In this research all trains will be identical and have a capacity of 420 passengers.

A train unit is symmetrical and has a steering cabin on both sides. This means that a train can be driven in both directions, however it is required that the driver is facing forward. The train is never allowed to drive backwards. So if a train has to turn around the driver needs to shutdown the train at one side and walk to the other steering cabin. This process takes about three minutes.

The plans for the future are that on a regular timetable the trains will drive according to three lines. Line 22, previously known as the Uithoflijn, will drive between P+R Science Park and CS-Centrumzijde. Line 20 will drive from P+R Science Park to Nieuwegein Zuid and lastly line 21 which goes from P+R Science Park to IJsselstein Zuid. In shared sections there is a consistent headway between trains from different lines.

2.3 Stops

Most of the 32 stops are very similar. They have two platforms, one for each direction the trains are travelling in. Each platform can only be used by one train at a time and only if that train is travelling in the corresponding direction. The special stops are CS-Centrumzijde and the stops at the end points of the track IJsselstein Zuid, Nieuwegein Zuid, and P+R Science park.

At the end point stops the train has to turn around to start a new trip. The trains could potentially continue at P+R Science Park, but it would enter the depot. Since the trains turn around at these stop both platforms can be

Figure 2: Map of the Utrecht Light Rail System

used. The option to use both platforms goes hand-in-hand with a track crossing. Each of these stops are adjacent to a switch system, which it has to cross when leaving and entering the station. When choosing the platform for an arriving train there is a preference. Being able to go straight through the track crossing causes less obstruction for arriving trains, so the platform from which this is possible is preferred.

The other exception to the normal stops is the stop at CS-Centrumzijde. This stop has four platforms. Two platforms are used as regular stops connecting Vaartsche Rijn and Jaarbeursplein and the other two platforms are used as an end point for line 22. on the side of Vaartsche Rijn CS-Centrumzijde has a more complicated track crossing to accommodate for these extra platforms.

2.4 Track Crossings

A track crossing is the location where a train can change tracks. Since driving against the flow of traffic is not allowed, track crossings are only used when trains are turned around i.e. at the end points and at the stop CS-Centrumzijde, or when two tracks merge i.e. at the split and CS-Centrumzijde. A crossing consists of 4 switches that steer the train straight or across. In order to succesfully cross a crossing two aligning switches need to be in the same mode. It takes only a few seconds to change the direction of a switch. If all switches are in their straight position it is possible for two trains to drive across at the same time. These trains need to drive in opposite directions and on different sides of the track.

In Figure 3 an overview of the most common type of track crossing can be seen. The lines between the squares are the platforms and the lines indicates track where the arrows is the direction of the flow of traffic. These kind of crossings are at the end stops but they are also in front of Vaartsche Rijn and Jaarbeursplein. This means that those places can also be used to short-turn the train, however this can only be done at the side of the stop where the cross is located.

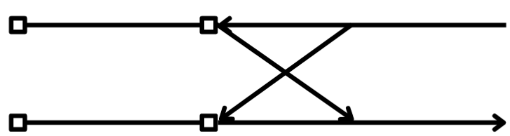

Figure 3: Overview of a regular switch

The split at Nieuwegein Stadscentrum is a special kind of track crossing. It is a merge/split of the track. When arriving there from the Nieuwegein Stadscentrum side you can go to two different tracks, but when arriving from the other side the two tracks merge in the direction of Nieuwegein Stadscentrum..

It is not possible to turn your train here or drive from Nieuwegein Zuid to IJsselstein Zuid without getting to another crossing first. The split can be used by two trains at the same time if both trains either go to or come from the same place. The split can also be used by two trains at the same time if one is coming from Nieuwegein Zuid and the other is going towards IJsselstein. An overview of the split can be seen in Figure 4.

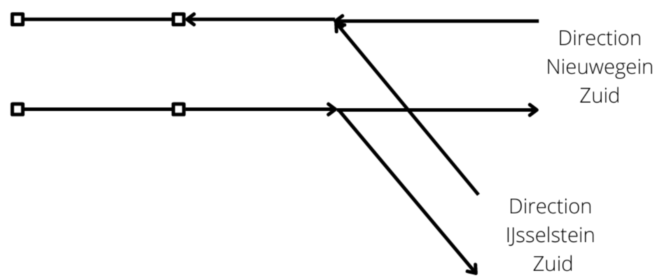

Figure 4: Overview of the split at Nieuwegein Stadscentrum

The crossing before stop CS-Centrumzijde is the most complicated crossing. In this crossing there are two tracks on one side and four platforms on the other. An overview can be seen in Figure 5. On one side there is a split for incoming traffic and a merge for outgoing traffic. These are used for the lines going to Nieuwegein Zuid and the IJsselstein Zuid and will get the trains to the outer platforms. The inner platforms are used for turning the trains around for line 22 and the crossing in front works the same as a regular crossing. It also possible for this crossing to be used by two trains at the same time as long as their paths do not intersect.

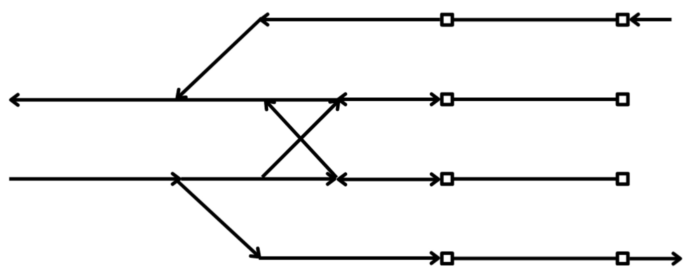

Figure 5: Overview of the switch at CS-Centrumzijde

2.5 The Depot

The depot is the train storage facility on the UNSIJlijn. It is located between the stops P+R Westraven and Zuilenstein. The depot is not only used to add or remove trains from service, but near the entrance there is a separate track which trains can use to turn around. An overview of the tracks near the depot can be seen in Figure 6. The line between two circles is where the trains can turn around. Only one train can use this track at a time and it is a dead end. In the Figure the upper two tracks are used for regular traffic and the lowest one only for traffic which is turning or entering the depot. The track which in normal traffic is used for the direction Zuilenstein is used in both directions here. Traffic between the depot and Westraven first need to use the turning point, while traffic from Zuilenstein can directly enter the depot.

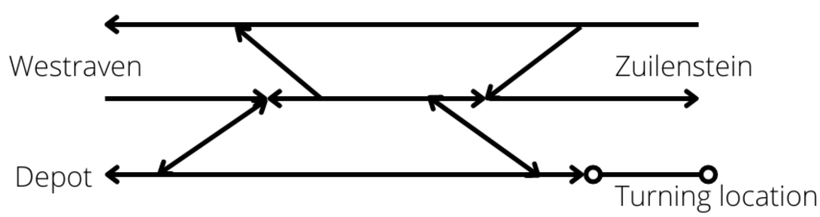

Figure 6: Overview of the track near the depot

2.6 Disruption Management Strategies

The traffic control of the Utrecht light rail system handles disruptions based on the severity of the incident. In the case that a train is fully stopped and can not continue for some time they will act in the following manner. Firstly they tell every affected train to stop as soon as possible. This instruction is spread by the traffic controller to the trams closest to the incident first and then spread out. If possible stopping the train is done at the next stop. The stops WKZ and Heidelberglaan are on a road shared with busses, so they try to not stop here. Notifying the trams is done verbally, so it will take time to instruct each tram individually. In the case of a long time disruption the trains can get recalled to the train depot or can be used to drive a new line. As previously mentioned all tram lines run from end point to end point. An end point is a stop with a track crossing, so the train can switch to the correct track for the return trip. This means that other stops like Vaartsche Rijn and Jaarbeursplein can also function as end points. This can only be done for the direction of the track crossing meaning that Nieuwegein Zuid to Jaarbeursplein is a possible line, but P+R Science Park to Jaarbeursplein is not. The one exception here is Vaartsche Rijn, it can be used as end point for both direction. This is however very rare since the disruption should be between Vaartsche Rijn en CS-Centrumzijde, which does not happen a lot. The track crossing at Vaartsche Rijn can be used to turn a train around. This creates multiple different possible routes and lines depending on the location of the incident and can be used to maximize service coverage even during major disruption. Passenger can also be referred to adjacent bus lines. The bus line 28 drives to the science park and either line 74 or 77 can be used to get to Nieuwegein. The people working at the offices of Qbuzz often have a bus driver's license and they can be instructed to drive busses to transfer passengers when there is a long delay on the light rail system.

3 The Simulation Model

In this chapter the digital version of the Utrecht light rail system will be described. This description will explain how the physical elements are represented and how they are connected. This chapter will also explain how train behavior is mimicked, how the timetable is set up, how passengers behave, how disruptions will be simulated, and how the performances is measured. In this chapter some assumptions will be made to simplify the simulation. These assumptions however will not have a big impact on the realisticness of this simulation.

3.1 System Representation

The digital model used in the simulation consists of a circular double-linked list of track elements. If the direction of a train is known the next track element can always be found. A track element is for example a stop, a track crossing, or an end point stop. Because the track elements are highly variable new behavior can easily be added with new track elements at the any desired location. There are special kinds of stops and track crossings. There is one track crossing, which is the split near Nieuwegein Stadscentrum that has its own rules. The split is also the only track element where two different track elements can be next.

The trains in the simulation are entities that hold information regarding the trip it is driving at that moment. This information entails the line number, its current location, which passengers are in the train, and the arrival/departures times for the important stops. Each train gets an unique ID for each trip it drives to efficiently investigate any scenario. In order to effectively guide trains through disruptions trains also have an instruction. This instruction is normally set to regular, but can be changed to redirect a train when needed.

3.2 Discrete Event Simulation

The simulation is build around the trains and the trains can either leave or arrive at track elements. The events in the simulation are based on those actions. There is a leave track element event and there is an arrive at track element event. Each event stores the following data: Time of event, train involved, track element involved, and if necessary which platform was included. An event is handled in three steps. The first step is to check whether the event is possible in respect to the constraints that hold for the involved track element. If the event is possible the second step adapts the system to all changes caused by this event. Finally in the third step if needed the next event is created. Arrive and Leave events for a single train always occur alternately. It is impossible to arrive somewhere if the train has not left the previous track element yet and vice versa. Because it is not possible to overtake on Utrecht light rail system, when arriving the order of the trains is checked. This needs to check out before the arrive event is possible to take place.

3.2.1 Arrive Event for Stops

In case a train arrives at a stop it checks whether the event can happen by checking the availability of the needed platform. After a train has left a platform it takes 40 seconds before the next train can enter it. This gap is required for safety reasons. If the platform is available the event can take place and the platform is set on occupied. If the stop is directly behind a track crossing the event can always take place, because the availability of the platform is checked before the crossing. The amount of passengers stepping in and out are determined (How this is done can be read in section 3.4 on passengers) and if the stop is used as an end point the direction of the train is reversed. Now the event finishes up by creating the next event. In this leave event we update the time at which it occurs by adding the dwelltime of the train to the time at which the arrive event occurred. The dwelltime will be determined by using a model described in the paper Rajbhandari et al. (2003). In this model the dwelltime is dependent on the amount of passenger getting in and getting out of the train and a fixed constant for opening/closing the doors. The function for dwelltime is as follows: $dt = a + b * P_{in} + c * P_{out}$. In this function P_{in}, P_{out} are the passengers getting in and out and a, b, and c are constants depending on the train system. In this simulation those constants will be set to 12.5, 0.22, and 0.13 respectively. Since this is a stochastic simulation this value will not be used directly. It will be used as an average to generate a value with a lognormal distribution as said to be realistic in Li et al. (2016).

If the stop is an end point the dwelltime will be determined differently. At end points the train will have to adhere to the timetable, so the dwelltime will be equal to the time of departure given by the timetable minus the arrival time. If this dwelltime is less than 3 minutes, it will be set to 3 minutes. This is because the train takes 3 minutes to turn around. If this happens the train will depart with a delay. When the departure time is given by the timetable the entire trip is planned. This means that the fixed departure times at CS-Centrumzijde and Nieuwegein Stadscentrum are also determined.

3.2.2 Arrive Event for Track Crossings

The check whether an Arrive Event can occur at a track crossing is the most complicated check. It is not only required to verify whether the crossing is available, but when a stop is directly behind the crossing there needs to be a platform available for the train. If there is no platform available the train would have to stand still on the crossing which would block all traffic. In the simulation a track crossing can have two stance, one for crossing tracks and one for staying on the same side. So in order to drive over a crossing, first the required stance needs to be determined. This is done by finding the platform the train wants to go to and planning a path. After this the availability of the track crossing is checked. If there is another train it could be possible for the incoming train to cross it at the same time. This can only happen if both trains drive parallel through the crossing. This can only happen if they drive in opposite direction and the required stance is straight for both of them. If this is not the case the last arriving train has to wait. If there are no trains using the crossing the assumption is made that if the previous train has used the crossing more than 5 seconds ago the track crossing has automatically been adapted to needed stance. If not the train will claim the track crossing and the time of the event will be delayed accordingly.

If all these checks are passed the event can finally be handled. The crossing is set on occupied and its stance is updated. The time of the event is also updated, so it always happens at least 5 seconds from the previous train leaving the crossing. And finally the event creates the next event where the train leaves the track crossing. It takes a train a constant 10 seconds to drive through the crossing. The arrive event for the split at Nieuwegein Stadscentrum works the same as the crossing, however the availability of a following up platform is not taken into account, because there is space behind the split to potentially stop. In the case a train is turning at the depot the turning platform needs to be available before the train can drive towards it.

3.2.3 Leave Event

The leave event for track crossings and most stops is relatively straight forward since there are almost no constraints on these events. In the events the track element is made available again for another tram, the travel time to the next destination is determined and an arrive event is planned accordingly. The only exceptions that would hinder this event is when a disruption event has told all trams to stop. At some stops the trains need to leave according to a timetable. When the leave event occurs it is checked whether the train is too late and this is recorded for performance measures.

A leave event is more complicated when the train leaves a stop which is directly followed by a track crossing. In that case it can only leave its stop if the crossing is available for use. For this the checks described in the previous section are used. If the track crossing is available the arrive event for the switch is scheduled directly after the leave event. In other words when leaving a stop that is immediately followed by a switch, we assume the travel time between those two is equal to zero. This is adjusted in the time it takes to drive through the track crossing.

3.2.4 Turning at the depot

When a train is instructed to turn at the depot between P+R Westraven and Zuilenstein it goes through a few specialized arrive and leave events. The first step is the arrival at the depot. In this event the availability of the turning platform is checked and whether the path to that platform is free. If this all checks out the train can drive to the turning platform and a leave event is planned for when it arrives there. This leave event does not mean that the train is leaving the depot, but is leaving the track crossing at the depot onto the platform. During this leave event the train is digitally turned around and

3 minutes later an arrive event is scheduled. This arrive event means that the train is ready to cross the track crossing again. If this is possible with in the regulations of the crossing it will drive through the crossing. Doing this will plan a leave event again at the depot. In this final leave event the train really leaves the depot and will drive back to P+R Westraven.

3.2.5 Unavailability of an Event

An important question to answer is what to do with events which do not pass the possibility check. In this case the event is skipped in the sense that no action is done and the train has to wait before the track element it could not enter. In the simulation the train is stored in a queue for the involved track element and its corresponding direction. This queue enacts the real life constraints of no overtaking and handles trains in order of arrival at track crossings. The assumption is that trains can be stored anywhere, except between a stop and a track crossing that are directly next to each other. This happens at end stops, Vaartsche Rijn, Jaarbeursplein, CS-Centrumzijde, and Nieuwegein Stadscentrum. Trains are in these cases always stored in the queue of the involved track crossing.

When a leave event has successfully been handled at a track element where this exception does not occur the queue is checked for waiting trains. If there is a waiting train, an arrive event at that track element is planned for the train. If this arrive event is now possible, the train can be removed from the waiting queue.

In the places with the exception all postponed events are stored at the track crossings. It is however possible that a train leaving CS-Centrumzijde away from its track crossing creates a space for a train waiting at the track crossing. This means that if a leave event has succesfully been handled at one of the stops from the exception, depending on the direction of the train from the completed event it might be needed to check the track crossing for a waiting train.

3.3 Timetable

In the future[1] trains will drive from P+R Science Park to IJsselstein Zuid and Nieuwegein Zuid. At the time of this research for this thesis a timetable for this new situation was not known yet, so a timetable had to be developed for this simulation. It is important to note that this timetable is determined based on the simulation and any performance measures can differ from real life. In this timetable all three lines (20,21, and 22) will have to share the track at a safe distance. Since the Uithoflijn is the most frequently used part of the track line 22 will be driven most. Starting from P+R Science Park where all lines start they will alternate as follows: 20, 22, 21, 22 and repeat. The plan is to have 20 trains per hour meaning that trains have to leave every three minutes. Since line 22 turns at CS-Centrumzijde there will be a train every six minutes

[1] At the start of this research trains did not drive between P+R Science Park and IJsselstein Zuid, however they started doing this during the concluding phases of the research.

between CS-Centrumzijde and the split in Nieuwegein, and from there on the headway between trains will be 12 minutes.

In order to maintain this headway the departure times for the end stops and the time stops are fixed. CS-Centrumzijde and Nieuwegein Stadscentrum are time stops. A time stop means that the train has to wait until its scheduled time before it can leave there. If it gets there later then the scheduled time it can leave when ready just like at all the other stops. The track can be divided into successive sections between the end stops and the time stops. The travel times for these sections can be seen in Table 1. This means that the a train leaving IJsselstein is expected to at Nieuwegein Stadscentrum approximately 13.1 minutes later, 20 minutes after that at CS-Centrumzijde and 17 minutes after that at P+R Science Park. Such a trip would take approximately 40 minutes excluding the dwell times at the time stops. When planning a trip these durations are slightly increased to give a margin of error. This means that fast trains will have to wait a bit longer at the time stops and slower trains will not be delayed as much.

Section	Travel time in minutes
Nieuwegein Zuid - Nieuwegein Stadscentrum	5.5
IJsselstein Zuid - Nieuwegein Stadscentrum	13.1
Nieuwegein Stadscentrum - CS-Centrumzijde	20.0
CS-Centrumzijde - P+R Science Park	17.0

Table 1: The travel times between successive time stops

3.3.1 Initialization

When the simulation is started the first trains need to be initialized. The first trains will be created at the major stations P+R Science Park, CS-Centrumzijde, IJsselstein Zuid, and Nieuwegein Zuid. Creating a trains means that in the simulation a new train appears at the needed location. In reality this train would have to drive to the location from one of the depots, but in the simulation the start is not important since only data is recorded around the disruption. The goal is to make a limited amount of trains drive the timetable as well as possible. The approach used in the simulation is to start sending trains at the correct interval from the end points and using CS-Centrumzijde to fill in large gaps. The trains departing from IJsselstein Zuid and Nieuwegein Zuid need to arrive with an interval of 6 minutes at Nieuwegein Stadscentrum. According to Table 1 the difference between those sections is approximately 7 minutes. The simulation starts with IJsselstein Zuid since that section is larger and will take longer to fill up with trains. So if t_0 is the starting time of the simulation in minutes and the train at IJsselstein Zuid departs at t_0, the train at Nieuwegein Zuid will depart at t_0+13. Every 12 minutes after the initial train the following trains will be created for both station. This happens until the trains coming from CS-Centrumzijde can fill those slots in the timetable and no new trains need to be created.

To fill the UNSIJlijn further trains are also spawned at CS-Centrumzijde in the direction away from P+R Science Park. Once again the first one will be towards IJsselstein and it will alternate after that. Since these trains do not have to take another line into account they can start driving at t_0 and can leave at an interval of 6 minutes as described in the time table. According to table 1 the first train will arrive at $t_0 + 33.1$ at IJsselstein Zuid and with the turnaround time of three minutes in mind it wont be able to make the fourth time slot there, which would be $t_0 + 36$. This means that at IJsselstein Zuid four trains will be created. The first train at Nieuwegein Zuid will arrive at $t_0 + 6 + 25.5$, where the 6 minutes is from departure interval. This means that the train will arrive on time for the third slot, $t_0 + 37$, so only two trains need to be spawned at Nieuwegein Zuid.

CS-Centrumzijde can stop creating those trains when the departure slots are filled with trains departed from P+R Science Park. If trains leave P+R Science Park at t_0 they will be at CS-Centrumzijde at $t_0 + 17$, on time for the fourth slot. Since this train contains passengers the gap between arrival and departure should not be too big, however in this case 1 minute is acceptable. Because trains leave alternately at CS-Centrumzijde and the first train went to IJsselstein Zuid, the first train departing from P+R Science Park should be going to Nieuwegein Zuid. After this first train every 3 minutes a train will depart according to the timetable. This will continue until trains from CS-Centrumzijde can fill in the timeslots.

From CS-Centrumzijde trains will also spawn in the direction of P+R Science Park. These trains will depart in an interval of 3 minutes starting at $t_0 + 1$ and will provide P+R Science Park with trains. Trains will be created at CS-Centrumzijde until provided for by other station. This happens sooner for line 22 than for the lines 21 and 22, because the trip for line 22 is shorter. This means that the first 6 trains are spawned at an interval of 3 minutes and after that the interval will be 6 minutes untill the first train from IJsselstein Zuid arrives. This happens at $t_0 + 33.1$ meaning that after the trains with an interval of 3 minutes and one last train with an interval of 6 minutes are spawned. This will results in 26 trains that together can drive the proposed timetable. An overview of all train creation can be found in table 2.

Stop	Time of train creation compared to t_0
IJsselstein Zuid	0, 12, 24, 36
Nieuwegein Zuid	13, 25
CS-Centrumzijde (UNSIJlijn)	1, 7, 13
CS-Centrumzijde (Uithoflijn)	1, 4, 7, 10, 13, 16, 19, 22, 25, 31
P+R Science Park	0, 3, 6, 9, 12, 15

Table 2: Train creations at time difference from t_0

3.4 Passengers

Passengers are created during arrive events at stops. Since trains drive at a low headway the assumption is made that passenger do not arrive at the station according to the timetable, but distributed over time. How the number of passengers is determined can be found in Section 4.2. Passengers do not 'know' which line the next train will drive. Passenger going to Nieuwegein-Zuid and IJsselstein-Zuid need different trains and both will not enter a train driving line 22. When a passenger is created, its destination is determined immediately. If the destination of the passenger can not be reached with a train the passenger will wait for next train. If the train at the stop is full, all passengers that do not fit anymore will have to wait until the next train. Since the destination for each passenger is know, the people getting out can be checked easily. In this method the starting point of the passenger is still known when arriving at its endpoint and more data can be retrieved.

Before new passengers are generated in an arrive event the waiting passengers are added to train. Passenger that could not enter a train, because it was either full or it did not match their destination, are stored in a queue. Each stop has their own queue where passengers for both directions are stored. This means that passenger that arrive first have a priority when entering the trains. It also means that stops with multiple platforms for the same direction have a single queue for both platforms. This means that in the simulation passengers can instantly switch between different platforms.

3.5 Performance Measures

3.5.1 Departure Graphs

A departure graph is a graph where the delay is shown for each fixed departure slot. An example of this can be seen in figure 17. On the x-axis the time is shown with vertical indentations to indicate each departure slot, which in this case are 3 minutes apart. On the y-axis the delay is shown in seconds. If there is a delay of more than 3 minutes the departure slot is not skipped. The graph is a collection from all departure graphs of 50 simulation iterations. A circle in the graph indicates that that delay has occurred at least once in those iteration. It does not provide information about how many times it has occurred. The blue points is the average delay for each departure slot. Since it is a stochastic simulation larger delays are normal, but the blue line indicates the overall performance best.

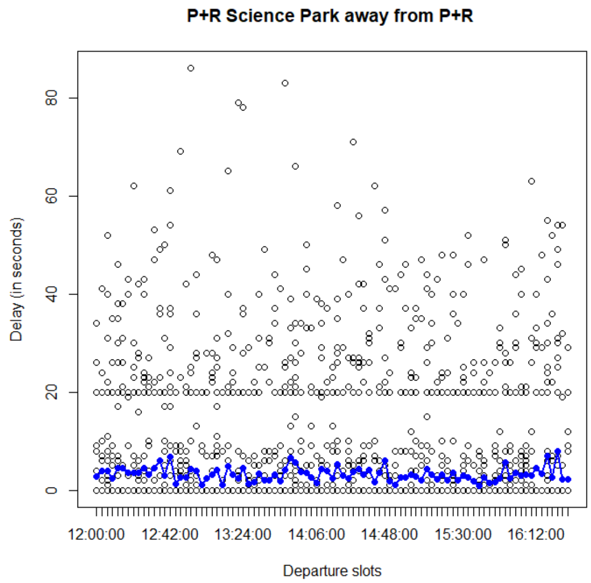

Figure 7: Departure Graph for P+R Science Park

3.5.2 Regularity

The metric used to find the performance of consecutive departures in a single simulation will be the regularity as defined in van Lieshout et al. (2021). In order to find the regularity first the departure are labeled in sequential order as $1, 2..., n$, where n is the number of departures. With sequential order the actual departures are used not the planned departures. Now d_i can be specified as departure i in seconds since the start of the simulation. With this the average interdeparture time, $\mathcal{H}$, can be determined with the following formula.

$$\mathcal{H} = \frac{1}{n-1}\sum_{i=1}^{n-1}(d_{i+1} - d_i)$$

Which can then be used for the regularity, $\mathcal{R}$, in the following function:

$$\mathcal{R} = 1 - \frac{1}{(n-1)\mathcal{H}}\sum_{i=1}^{n-1}|d_{i+1} - d_i - \mathcal{H}|$$

Note that this function is normalized which means that a regularity of 1 is the best possible result. The regularity will be calculated for each time- and end stop since the departures there are regulated. Aside from the regularity an overview will be given for the numbers of trains departing from each station. A perfect regularity means nothing if there no trains departing from that stop and for stops were only a few trains depart a small delay can have a large impact on the regularity.

3.6 Disruptions

3.6.1 Events

A disruption will be simulated by a fixed event which is set at the start of the simulation. In this event all information regarding the disruption can be stored e.g. duration, location, and involved tram/switches. According to the duration of the disruption an end disruption event is planned which restarts the system. When the disruption happens affected trains are given instructions on how to drive according to the location of the disruption and the current disruption strategy. These instruction are passed immediately. In reality this would take a while, but since the traffic controllers can choose which train to instruct first the assumption is made that the critical trains are informed on time for a similar effect. If a train has to stop due to the disruption the corresponding event is stored for when the disruption has passed. Now when the disruption is restarted those events can be rescheduled according to the disruption strategy.

3.6.2 Timetable

In case of a disruption the original timetable is maintained as much as possible. This means that for stops that are not affected by the disruption the same departure times will be used. When trains are turned earlier the departure times for those places are strict like the case at a normal end point. These departure times are set based on the travel time between the new turning point and the next time stop. In example when Vaartsche Rijn is picked as a new turning point, the departure times are based on the nearest time stop which is CS-Centrumzijde. If the departure time at CS-Centrumzijde in minutes would be t and the travel time between Vaartsche Rijn and CS-Centrumzijde is 3 minutes, the departure slots at Vaartsche Rijn would be at $t - 3.5$. The extra 30 seconds is a small buffer to decrease the number of delays. With this method the numbers in Table 3 are determined. After a disruption the goal is to restore to the original timetable as soon as possible. How this is done depends on the location, timing and the disruption strategy.

Section	difference between departure slots in minutes
P+R Westraven - CS-Centrumzijde	12.2
Vaartsche Rijn - CS-Centrumzijde	3.5

Table 3: Difference in departure times for the same train

3.6.3 Passengers

A disruption has minimal effect on the total passengers count. Passengers numbers are used to get an estimate on how a disruption strategy influences the amount of passengers that are not be able to reach their destination. Passengers are not aware that a disruption is happening and will arrive and enter a train just like in a normal situation. However when a train is forced to stop or has to turn earlier than normal, these passengers will not be able to reach their end goal. These passengers will have to get out of the train at that stop and are counted to find the number of affected passengers. These passengers are then assumed to take different transportation methods to their destination. Passengers that want to enter a train at a stop that is out of service are assumed to also find another method of transportation. Only passengers that arrive during the last 5 minutes of the disruption will wait until the disruption is over.

In an abstract way the number of affected passengers can be seen as the served region each of trains has during the disruption. When a lot of passengers are affected this means that it is probable that only a few stops are reached by the trains. Another possibility is that many passengers had the same destination which is now no longer in service. Passengers can be seen as an indication on how important the stop is and of course the total weight needs to be the lowest in order to have the optimal coverage.

4 Data Analysis

4.1 Travel Times

The travel times between stops is determined by analyzing data provided by Qbuzz. This data is based on real life occurrences on weekdays in the period January 2020 to March 2020. This data indicates when trains arrive and depart at stops. The travel times can be determined by taking the difference between the departure time from a stop and the arrival time at the consecutive stop. Doing this results in about 6000 different travel times for each section. This data however also contains all the extreme cases and wrongly measured data. In order to remove these extreme cases the top 3% quantile and the lowest 1% quantile is removed, approximately the 60 highest and 20 lowest travel times. The imbalance is because extreme values are much more rare on the low end of the data. A train always has to travel a minimum distance which cannot be skipped, so the minimal values have a limit. This cleaned data is used to find a distribution that accurately represents the data.

Since this data is based on the current situation there is no data available for the section between CS-Centrumzijde and Jaarbeursplein. At the moment no trains transport passengers between those stops. Travel times on this section will be based on the travel times on other similar sections with similar length. The section between CS-Centrumzijde and Jaarbeursplein does not contain any track crossings and only a small section intersects with roads. This means that we can assume it acts similarly as the other sections. A section which is a bit longer and a section a bit shorter will be chosen and the travel time will be interpolated from those values. A similar problem is between P+R Westraven and Zuilenstein. The depot lies in the middle of these stops and the travel times to the depot is not known. The distance on either side is known however and so the travel time between P+R Westraven and Zuilenstein is determined and then split according the correct proportions to find the travel time to the depot.

The problem with finding a fitting distribution is that there many different track sections and not all sections are the same. To give an example between stops Heidelberglaan and UMC Utrecht the train shares the road with busses. This results in a higher variety in travel times and potentially a different distribution than sections with no obstacles. The different track sections will be categorized and analyzed accordingly. The categories are sections without obstacles, sections with a track crossing, and lastly the sections where the train shares the road with busses. This analysis can be found in the next paragraphs. The conclusion from this analysis is that in all sections the travel time distribution is either a gamma distribution or a lognormal distribution. However a chi square test will for neither distribution result in an accepted hypothesis, so the decision will be based on eye sight. In the histogram from the sections with busses on the track the lognormal distribution seems to be a better fit than the gamma distribution and on the sections they seem to be almost equal. A lognormal distribution will thus be used to determine the travel times for all sections.

4.1.1 Sections with no Obstacles

The most sections do not have obstacles and are expected to be have balanced distribution. In Figure 8 the density plot is seen from travel times of the section between stops Wijkersloot and Nieuwegein Stadscentrum. The figure shows that either a lognormal or a gamma distribution would be the best fit. When looking at the Q-Q plots in Figures 9 and 10 it is seen that they are very similar. It is hard to identify the better candidate here.

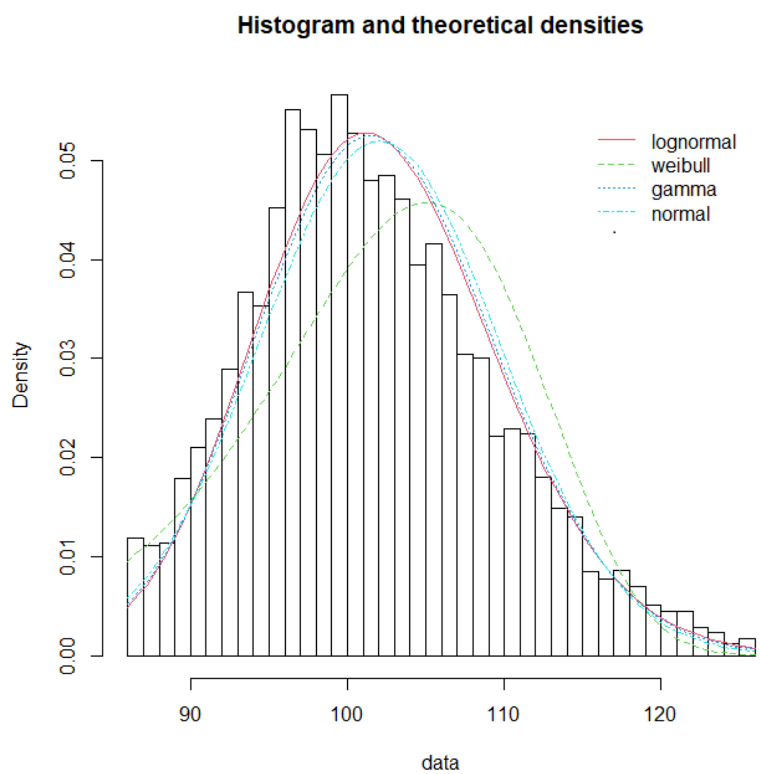

Figure 8: Density plot of travel times

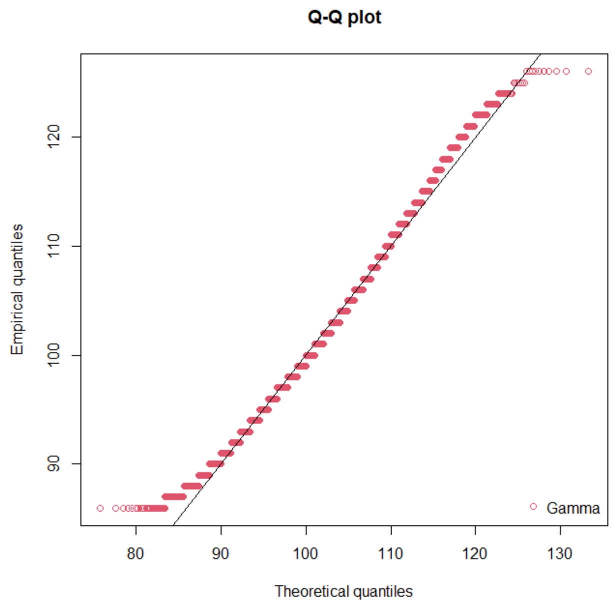

Figure 9: Q-Q Plot for the Gamma Distribution

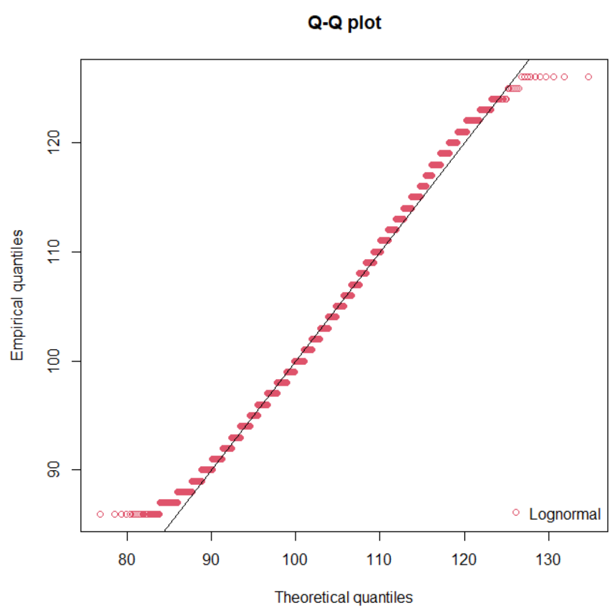

Figure 10: Q-Q plot for the Lognormal Distribution

4.1.2 Sections with a Track Crossings

The input data gives the travel time from stop to stop and does not take the track crossings into account. This means that potential waiting time at track crossing is included in the travel times retrieved from the data. However in the simulation model the travel time is determined without potential waiting. When unresolved this would the cause the simulation to have longer travel times at these sections. This is primarily seen in the busier sections at the Uithoflijn where the data has a high standard deviation. This is solved by cleaning the input data differently than done for the other sections. More long travel times are removed since these are more likely to be caused by the train having to wait and the standard deviation is lowered manually to a number that suits the corresponding section best.

In the sections with track crossings there are some special cases. In the section between P+R Westraven and Zuilenstein the depot is located, which is technically a track crossing. However since the travel time takes this already into account this section is not included here. The section between CS-Centrumzijde and Vaartsche Rijn has two track crossings, however the one located at Vaartsche Rijn is barely used it will also be seen as a section with only one track crossing.

The travel time distribution for this section can be seen in Figure 11. The first thing that stands out is that this peak is a lot wider than the peak in Figure 8. This is caused by the track crossing adding a lot of variety to the travel times. In this histogram it shows again that there is almost no distinction between the lognormal distribution and the gamma distribution and the same is the case in the q-q plots seen in Figures 12 and 13.

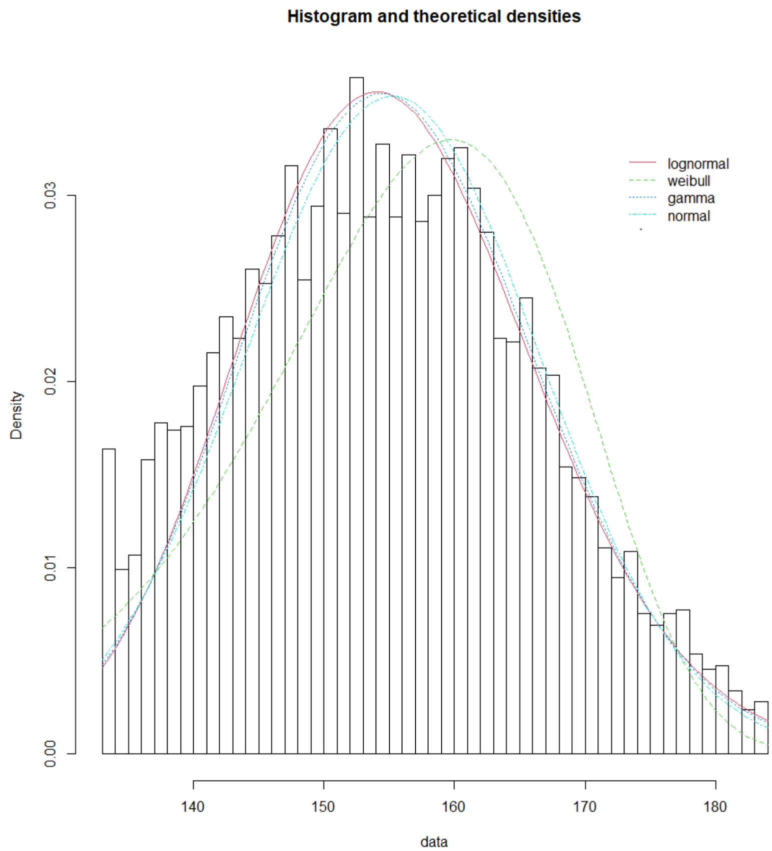

Figure 11: Density plot of travel times

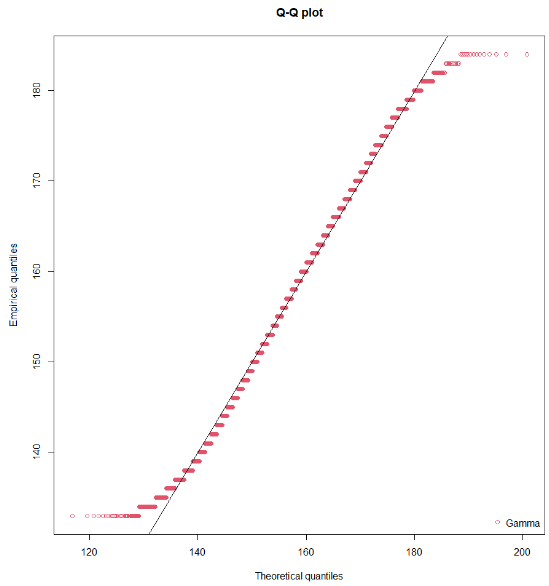

Figure 12: Q-Q Plot for the Gamma Distribution

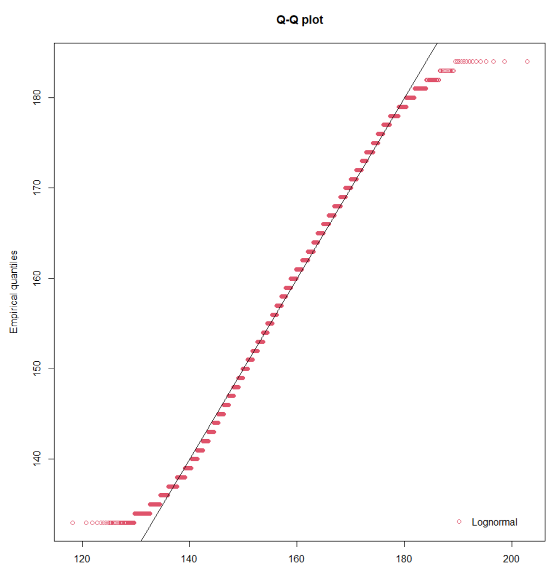

Figure 13: Q-Q Plot for the Lognormal Distribution

4.1.3 Sections shared with Busses

Sections where the track lies on a road which is also being used by busses can only be found at the Science Park in Utrecht. This happens at all the sections between stops Padualaan and WKZ. In Figure 14 the travel time distribution is shown for the section Heidelberglaan to UMC Utrecht. There is a peak for the travel times where the train did not get hindered, however there are many occasions where it did happen. This different shape of the distribution does not mean that a lognormal distribution does not hold here. According to the histogram it looks to even resemble the reality the best. The gamma distribution seems to be the closest competitor. The Q-Q plots for both distributions as seen in Figures 15 and 16 unfortunately give no further insights.

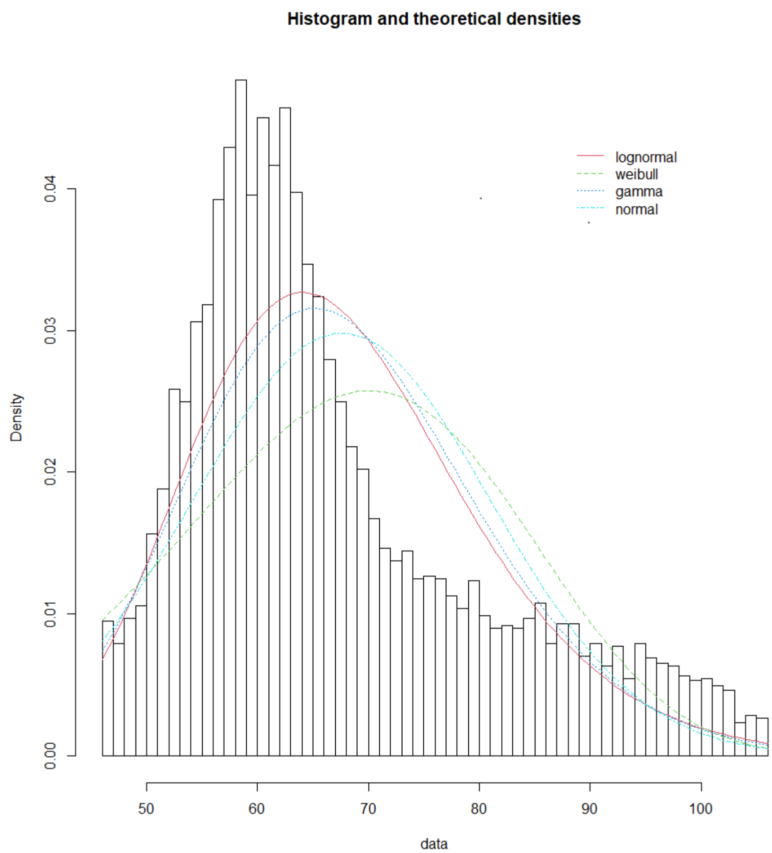

Figure 14: Density plot of travel times

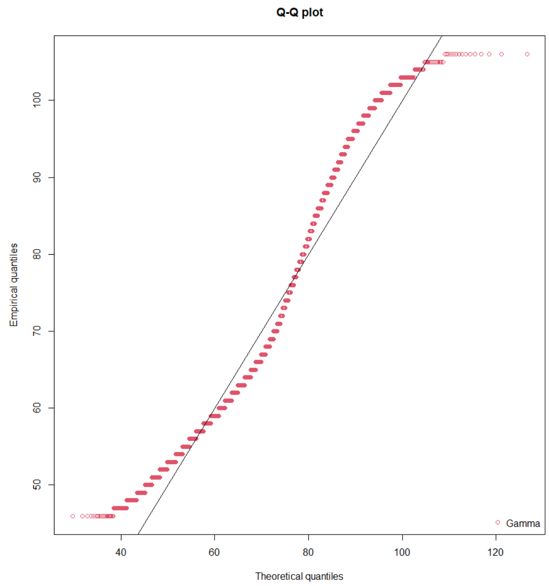

Figure 15: Q-Q Plot for the Gamma Distribution

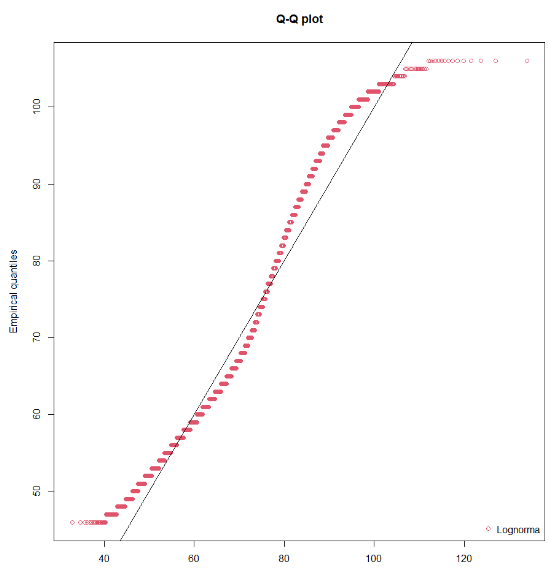

Figure 16: Q-Q Plot for the Lognormal Distribution

4.2 Passenger Numbers

The data on passengers is provided by Qbuzz and regards the period between January 2020 and March 2020. The data does not include weekends and is from before the Covid-19 pandemic. The data is based on origin-destination (OD) passengers. This means that for from each origin, S_O, to each possible destination, S_D there is a combination. In the data for each trip driven by a train the number of passengers r for each combination. The assumption is made that if an OD combination is not there, there are no passengers travelling between those stops. Since this data is given for each train it can be matched with the data used for determining the travel times to determine the passengers in each time frame. Passengers are divided into time slots of 30 minutes. This will mimic the passenger count fluctuations through out the day, in rush hours there will be more passengers and the direction of passengers will vary. In the end the data will contain 4 elements : $\{i, S_O, S_D, r\}$, where i is the time slot. This will allow the simulation to calculate for each time slot the total amount of people entering a train at S_O, R_{S_O} and the probability that one of those passengers leaves the train at S_D, P_{S_O,S_D}.

Since trains drive with a small headway, passenger will not arrive according to the train schedule. The assumption is made that passengers arrive equally distributed of time. Because of this passenger arrivals can be simulated with the use of a poisson distribution. Since passengers are generated when a train is at a stop, this stop will be S_O and so $R_{S_O}/30$ can be used as the arrival rate per minute. The destination of the generated can be determined at the same time, since the probability for all destinations is known.

5 The Experiments

In this study the normal situation (Scenario 0) and three different disruption scenarios will be analysed. The three disruption scenarios differ as much as possible from each other, but will all occur at the same time. A disruption will happen at 13:10 and it will take 30 minutes for it to be resolved. Depending on the scenario different strategies will be used to try to minimize the impact of the disruption. The approach of creating a disruption strategy is to first look at what is possible during the disruption. This is done by determining which lines can still be driven effectively and which stops will be used to turn earlier. For these lines and turning points a timetable will need to be constructed. In this simulation the timetable used will vary minimally from the regular timetable. This is done to make the transformation to and from the disrupted timetable smoother. The final decision is with which rolling stock this disrupted timetable is going to be executed. The availability of rolling stock varies for each disruption and will be the important part of a disruption strategy. In the disruption strategy there also needs to be a description of how to go back from the disrupted timetable to the regular timetable. This is also scenario depended.

5.1 Scenario 0 - Normal Timetable

In this first scenario a regular situation without any disruptions will be looked at. Knowing the timetable performance in a normal situation will help finding the effects of the disruptions. The normal situation will be analyzed for the time period after 12:00 and the regularity is calculated for the hour between 13:40 and 14:40. This is done because it is the same period in which the disruptions will be tested for the other scenarios.

5.1.1 Departure Graphs

Firstly the departure graphs will be analyzed. In Figure 17 the departure graph of P+R Science Park is shown for a regular timetable. With an average of only a few seconds delay this departure graph seems to work well. An interesting thing to note is the high frequency of delays of 20 seconds. This is caused by two things firstly that crossing a switch takes 10 seconds and secondly that both the departure interval and the turn around time are 3 minutes. If a train arrives while another train is using the train crossing. it will have to wait until that train is gone before crossing it himself. Assuming the departing train left exactly on time, this will make the arriving train arrive on P+R Science Park 20 seconds later than the previous train departed. If this arriving train has to be used for the next departure slot, which is 3 minutes after the previous departure and it still has to turn for 3 minutes it will have a 20 second delay. So if a train arrives between 1 and 10 seconds too late it will always result in a departure delay of 20 seconds.

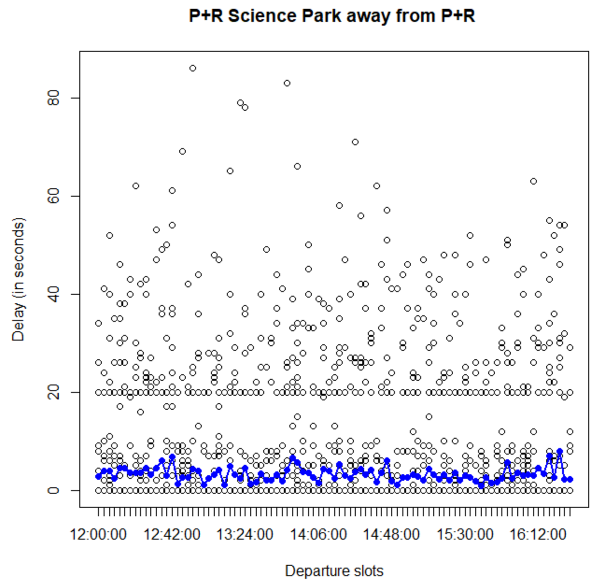

Figure 17: Departure Graph for P+R Science Park

In the departure graph for CS-Centrumzijde towards P+R Science park, as seen in Figure 18, another interesting effect can be seen. The average delays fluctuates clearly between a low and a higher delay. This is the result of two different kinds of departures at CS-Centrumzijde in the direction of P+R Science Park. There are departures that start the trip for line 22 and there departures that function as time stop for lines 20 and 21. Since line 20 and 21 have already driven a part of their trip they are more prone to delays, resulting in a higher average. In the Figures 19 to 23 the departure graphs for all other stops are given. These graphs do not show any unique behaviours, except for the higher departure intervals. This can be recognized by the larger distance between indentations on the x-axis.

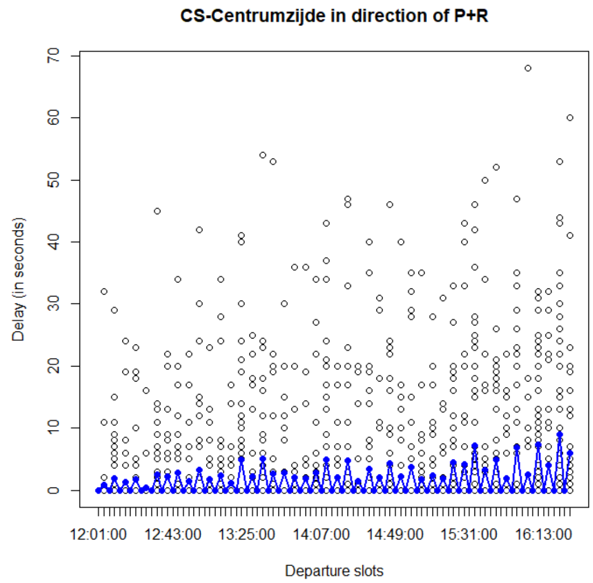

Figure 18: Departure Graph for CS-Centrumzijde towards P+R Science Park

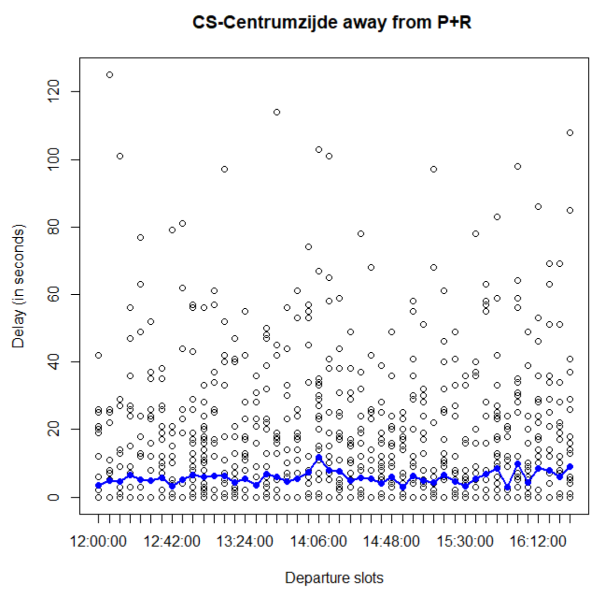

Figure 19: Departure Graph for CS-Centrumzijde away from P+R Science Park

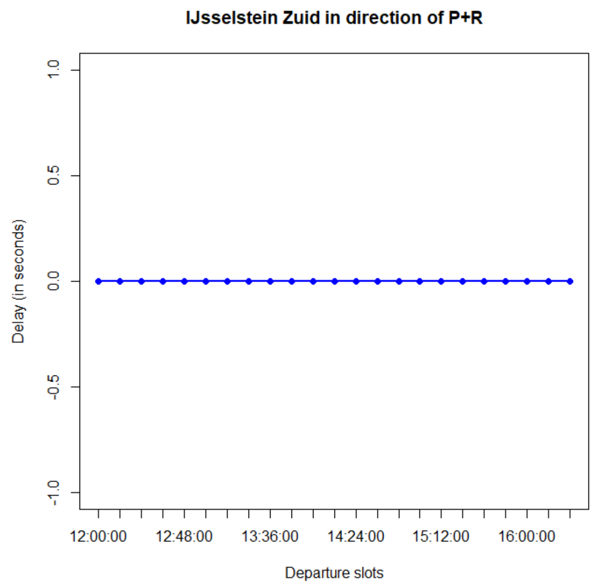

Figure 20: Departure Graph for IJsselstein Zuid

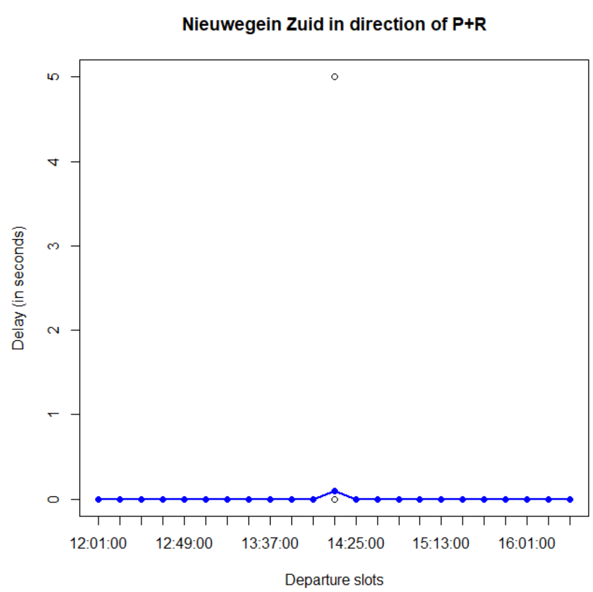

Figure 21: Departure Graph for Nieuwegein Zuid

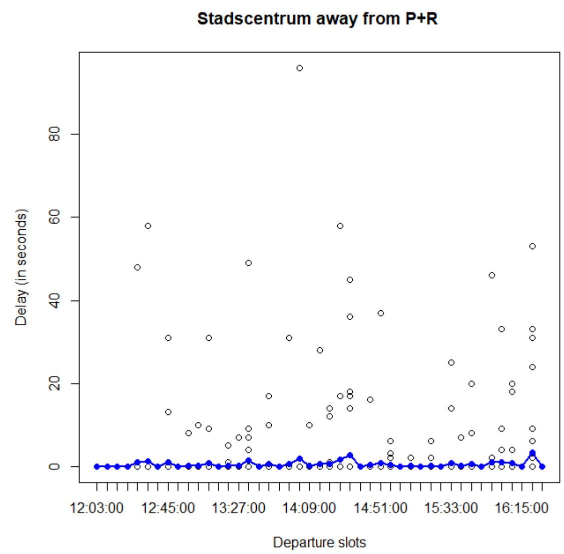

Figure 22: Departure Graph for Nieuwegein Stadscentrum away from P+R Science Park

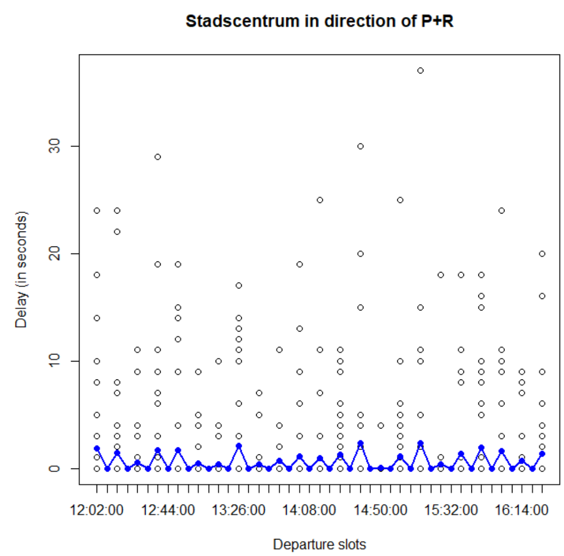

Figure 23: Departure Graph for Nieuwegein Stadscentrum away from P+R Science Park

5.1.2 Regularity

In a regular situation the regularities, as seen in Table 4, seem to be close to perfect, however there are a few exceptions. The worst performing stops are P+R Science Park and CS-Centrumzijde away from P+R Science Park. P+R Science Park performs the worst, because the delays are influenced by the track crossing they are longer than they would have been at other stops. These delays are likely to propagate to CS-Centrumzijde away from P+R Science Park. The regularity can sometimes also be recognized in the corresponding departure graph. For example for IJsselstein Zuid, which has a perfect regularity, there are no delays in the departure graph as seen in Figure 20. These regularities below are measured for the hour after the disruptions are resolved in the disruptions scenarios. These regularities are similar to the regularities of the hour before the disruption since there is no big difference in terms of passengers between the time periods 12:10-13:10 and 13:40-14:40. The regularities below can thus also be seen as a base value before any of the disruptions happen.

	Minimum	Maximum	Average
P+R Science Park	0.9296	0.9985	0.9655
Nieuwegein Zuid	1	1	1
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.9276	1	0.9723
CS-Centrumzijde[b]	0.9471	1	0.9808
Nieuwegein Stadscentrum[a]	0.9511	1	0.9962
Nieuwegein Stadscentrum[b]	0.9850	1	0.9979

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 4: Departure Regularities for a Non-disrupted Timetable

In Table 5 the number of departing trains can be seen for each important stop. These departing trains are divided into intervals in which the disruptions will take place later on. The regularity is based on the departures in the intervals 13:40 to 14:10 and 14:10 to 14:40. In Table 5 a regular consistent timetable is represented. One thing to note is that at Nieuwegein Zuid and IJsselstein Zuid it alternates between 3 and 2 trains each half hour. This is the effect of a departure interval of 12 minutes. Adding two adjacent columns together will give the total number of trains departing per hour from that stop.

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	10	10	10
Nieuwegein Zuid	2	3	2	3
IJsselstein Zuid	2	3	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	10	10	10
Nieuwegein Stadscentrum[a]	5	5	5	5
Nieuwegein Stadscentrum[b]	5	5	5	5

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 5: Number of trains departed in the corresponding interval

5.2 Scenario 1 - Using Vaartsche Rijn

In this scenario a disruption at the stop Heidelberglaan on the Uithoflijn will be analysed. This is an interesting disruption to analyse not only because it is on the busiest sections of the light rail system, but also because many disruptions happen here in real life. The stop Heidelberglaan lies in in the center of Utrecht Science Park where there is a lot of other traffic. The track lies on a road which is also being used by busses and it is crossed regularly by pedestrians. This makes this location very accident-prone. So what happens if the track at Heidelberglaan gets blocked in both directions for 30 minutes?

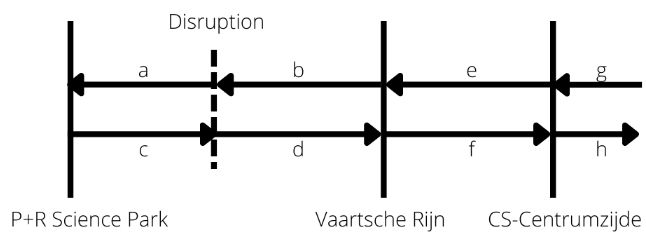

Figure 24: Overview of Scenario 1

5.2.1 Consequences

In Figure 24 an overview of this scenario is given. The vertical dotted line is the location of the disruption and the vertical full lines are stops where trains can turn. The horizontal arrows indicate the track and the direction of traffic. These labelled track section are affected differently by the disruption.

The disruption in scenario 1 prevents any traffic between P+R Science Park and Vaartsche Rijn. Since this leaves only two stops available for line 22, line 22 will not be driven during this disruption. The disruption strategy will have to determine what to do with trains driving this line. The UNSIJlijn is not hindered and can still be used for lines 20 and 21. These lines can however not turn anymore at P+R Science Park and will have to turn earlier at Vaartsche Rijn. Since the regular timetable will be adhered as much as possible the departure times at Vaartsche Rijn will be set with regards to the departure slots at CS-Centrumzijde. The travel time between the two stops is approximately 3 minutes. The departure slots at Vaartsche Rijn will be set 3.5 minutes before the train has to leave at CS-Centrumzijde. This will give a small margin of delay for the train. This will be the disrupted timetable.

In order to realize this disrupted timetable the available trains need be determined. The trains located in sections a, b, and c are cut off from the available track and can not be used anymore. This is because a and c are boxed in by the disruption and there is no location where b can turn in order to return to Vaartsche Rijn. The trains in b and c will have to stop. This can either be as soon as possible or as close to the disruption as possible. The trains in a can also choose to stop as soon as possible, but since they have passenger in them they will continue their trip to P+R Science Park and wait in the depot until the disruption is over.

The first trains eligible to be used for the departure slots at Vaartsche Rijn are the trains in d and e. These are followed by trains from g will be used. At the start of the disruption Vaartsche Rijn can not handle to use trains of both d and e, since there are simply more trains than needed for the timetable. In the disruption strategy a choice has to be made for which section to use, but both have their advantages.

5.2.2 The Start of the Disruption

According to the previous section there are three choices that will have to be made. What to do with lines driving line 22 in sections d, e, and f? What to with trains in sections b and c? And which trains will be used to fill the first time slots at Vaartsche Rijn?

Since the trains for line 22 are no longer used, they need to be stored somewhere, so they do not block the other lines. An option would be to store them in the depot near P+R Westraven, but this is too far for a disruption of 30 minutes. This leaves two places for the trains to go to which are the platforms at CS-Centrumzijde meant for turning trains and they can go to section b. The former is the best solution, since storing the trains at a turning point prepares them for a new trip when the disruption is over. However there is only space for two trains at CS-Centrumzijde, meaning that only the last two trains arriving from d and f can be stored there and the others have to enter section b. It is possible for trains from line 22 in section g to turn at Vaartsche Rijn and then enter CS-Centrumzijde. However this comes with two problems, firstly using only the trains from d and f is enough to fill CS-Centrumzijde and secondly turning too many trains at Vaartsche Rijn overcrowds the stops causing a waiting time before the station. There is a possibility that the last train in d is driving line 22. In this case this train could potentially stop in section d without blocking any trains. This train however is filled with passengers which then would not reach their destination. To help these passengers this train will not stop in d and finish its trip towards CS-Centrumzijde.

The trains in b and c are more different than it seems. Section c is the least complicated of the two, since it is a relatively short section there will only be one or two trains there at the moment of disruption. And for those it is best to keep their distance to make the restart easier, so these trains stop at their next stop. The section b is more complicated. Not only because there are more trains, but as discussed in the previous section there are more trains incoming. Trains that drove line 22 and maybe some trains from e will also go onto section b. In order to create space for those incoming trains all trains will continue as far as possible onto section b. Their last stop for passengers will be De Kromme Rijn from where it will join the train queue waiting for Padualaan.

The different disruption strategies that will be tested are based on the choice whether to use trains from section d or e for the first couple trains. The advantages of choosing trains from section d is that they do not need to turn and are filled with passengers already going in that direction. If section d was not used these trains would have to stop and all those passengers would be stranded. However stopping these trains is an advantage for when the disruption is over. This would cause the trains to be more equally divided over the system, so a restart would run more smoothly. The disadvantage of not choosing e is that the first few trains then have to continue onto section b. There are already stopped trains in b and adding even more causes an imbalance that will impact the restart. To summarize choosing d prioritizes the moment of disruption, while choosing e benefits the restart after the disruption. Choosing section d will from now on be referred to as strategy 1 and choosing section e will be strategy 2.

5.2.3 Coming Back from the Disruption after Strategy 1

When the disruption is over the aim is to get back to the original timetable as quickly as possible while missing no departure slots. Since strategy 1 was used at the beginning of the disruption the following problems need to be resolved. Section d is empty, there is a queue in section b before Padualaan, and the trains at CS-Centrumzijde and in the depot at P+R Science Park need to be reintroduced.

In section d there are no trains since they have all been used for the disrupted timetable. This means that if trains are no longer turned around at Vaartsche Rijn immediately after the disruption there could be a big gap between sequential trains. This gap is filled by turning the first train after the disruption at Vaartsche Rijn. Because there is a queue of trains in section b, this train will not be needed there and can thus be used to spread out the trains. This only hinders the passenger in that trains, which can not enter their destination now. In Figure 25 the effects can be seen clearly. the red line is the start of the disruption and the green line is the end. In this situation no extra trains are turned at Vaartsche Rijn only the ones already at the station finish their turn. There is a clear distinction between the two cases. The points on the top right are all from situations where there were no trains at Vaartsche Rijn at the end of the disruption and so no extra train was send. These huge delay will stay there if there is no further action. However if there was a train at Vaartsche Rijn which turned the timetable could be followed almost perfectly.

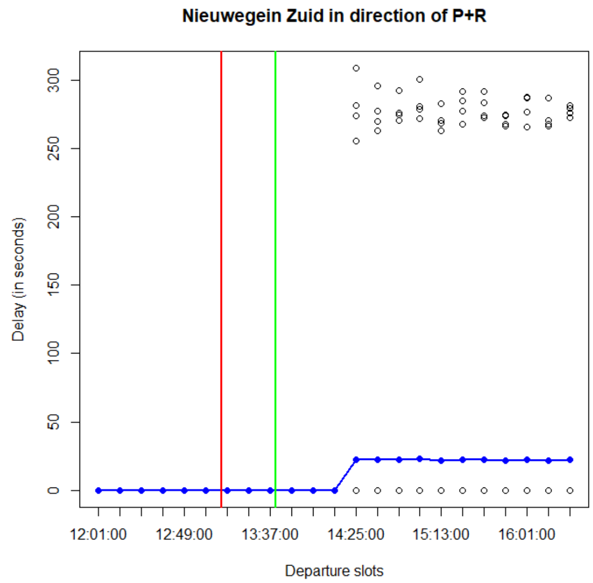

Figure 25: Departure graph for Nieuwegein Zuid

The trains in section *c* will be rescheduled to a new line and can depart immediately after the disruption is over. The assumption is made that the headway stays constant and small deviations will be corrected at the time stop CS-Centrumzijde. The line they will drive will depend on the last train that is turned around at Vaartsche Rijn, in order to keep the line pattern between trains. However the first train will always be a line 20 or line 21 since those are needed sooner. The line 22 can be skipped since there are enough trains waiting at CS-Centrumzijde.

The first train to depart from CS-Centrumzijde can not start immediately after the disruption is over. In Figure 26 it is shown that the number of trains in section *b* is very high at the end of the disruption. Section *b* is too crowded and sending trains there will only result in more delays. The first train will depart in the time slot that is just before the arrival of the first line 22 train arriving from section *c*. This however means that it will take longer to restart traffic between CS-Centrumzijde and P+R Science Park. This will be approximately 6 minutes after the first train from UNSIJlijn arrives that will not turn at Vaartsche Rijn.

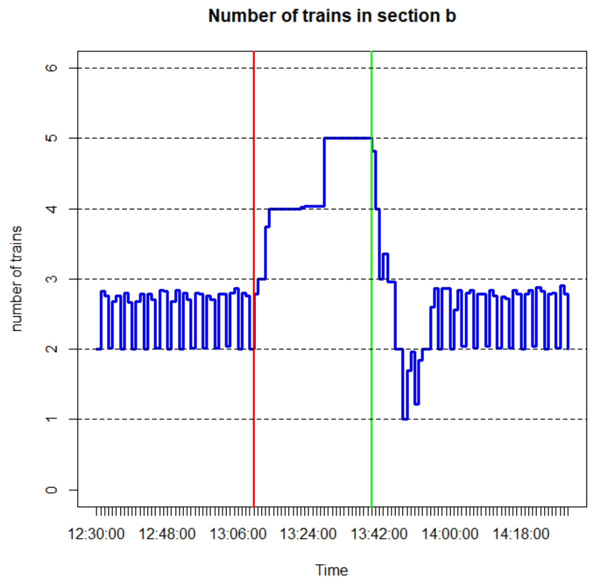

Figure 26: Average number of trains in section b

The instructions for the trains in the depot of P+R Science Park and the trains in the queue of section b are codependent. The trains in the depot will be depart from P+R Science Park according to the regular timetable. It is possible for the first trains of the queue to arrive at P+R Science Park before the last train from the depot has departed. This can put a big strain on that infrastructure, so the trains in b can not all leave quickly after each other. For the trains leaving Padualaan there will be a forced headway of 3 minutes in order to put less stress on the section near P+R Science Park. This stress does not completely disappear with this solution. The simulation showed that trains arriving at P+R Science Park will have to wait approximately 1 minute before it can enter the station because all platforms are taken. These waiting times before trains can enter the stop P+R Science Park can be seen in Figure 29. This gives a perfect departure graph as seen in Figure 27, but waiting trains is not preferable. Since the end of a disruption is predictable for Qbuzz, they can also choose to let a train depart earlier than the end of the disruption. The disadvantage here is that trains coming out of c will drive with a low headway, but the advantage is that it will stop the clutter at P+R Science park. The same effect could also be achieved by keeping one train in the depot, however this will result in many small delays on other points of the system. In Figure 28 the effect can be seen of letting a train depart earlier. In the beginning there is a possibility of a big delay, but after half an hour it will balance out. This big delay does not affect the other stations and trains do not have to wait to enter the station. With this solution trains do not longer need to wait before entering

P+R Science Park, this can be seen in Figure 30. Only the queue arriving from b has a small waiting time in some situations.

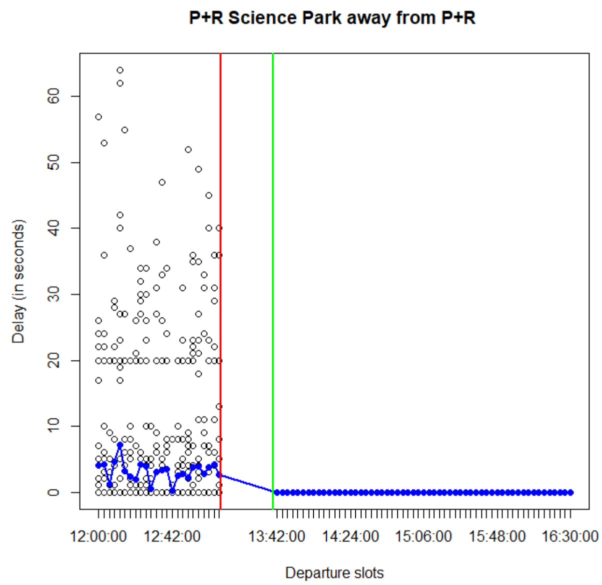

Figure 27: Departure graph at P+R Science with No actions

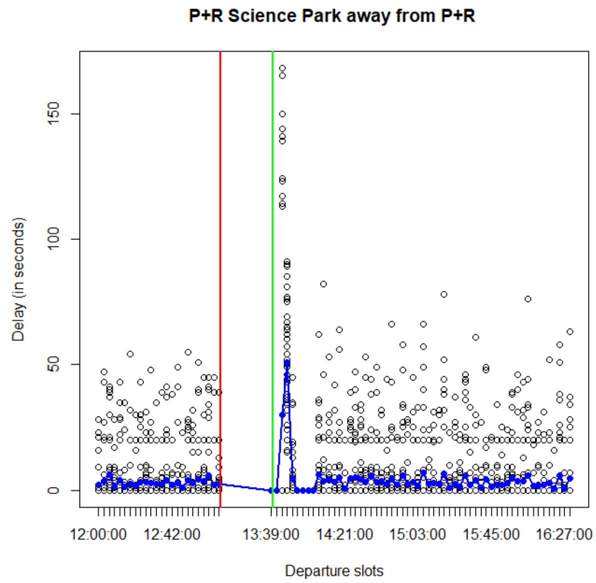

Figure 28: Departure graph at P+R Science with Train departure during disruption

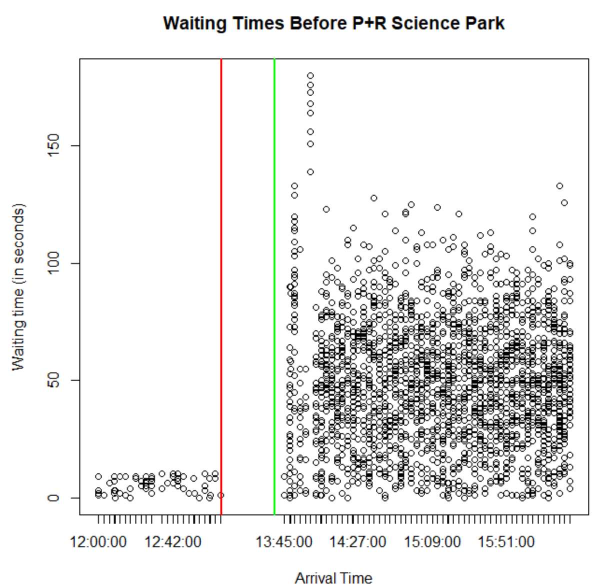

Figure 29: Waiting time before entering P+R Science Park with No actions

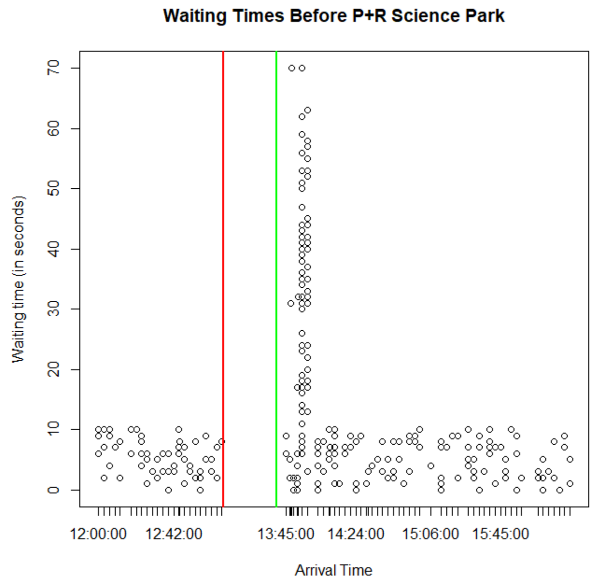

Figure 30: Waiting time before entering P+R Science Park with Train departure during disruption

According to the departure graphs this disruption strategy seems to work rather well, except for the delays for the trains from section *b*. In the simulation this method affects on average 423 passengers.These passengers were not able to reach their destination, because their train either had to stop at an earlier stop or was turned around at Vaartsche Rijn while they wanted to go further. A disadvantage of this method is that trains start departing from CS-Centrumzijde later meaning that there is a longer period of no traffic between CS-Centrumzijde and P+R Science Park. This is however only 6 minutes, which might be short enough to allow it.

5.2.4 The Start of the Disruption for Strategy 2

When using strategy 2 there are a few details to make clear. At the moment of disruption trains in section *d* will have to stop at the their next stop. It is however possible that their next stop is Vaartsche Rijn, these trains have no place to stop and will continue their trip after Vaartsche Rijn. It is likely that no trains from either line 20 or line 21 will arrive at Vaartsche Rijn after the disruption. So the question is where to get the train for the first departure slot? The obvious answer is of course from section *e*, but what if there are no trains in *e*. In this situation the first train to depart from CS-Centrumzijde, the next train to reach Vaartsche Rijn, will always turn at Vaartsche Rijn in order to fill the first time slot. The original line of this train is not taken into account. There are two problems to note on this extreme case and its solution. The first minor problem is that there are now even less trains in section e for the restart, which has to be handled when the disruption is over. The second problem is that it is impossible for this train to make the departure slot. The trains has to drive to Vaartsche Rijn and has to turn which all takes between 5 and 6 minutes. As seen in 31 this causes many delays in the first departure slot. The lag of trains at Vaartsche Rijn in this scenario can in some cases also lead to further delays later on. This however does not happen as often as the delay for the first slot.

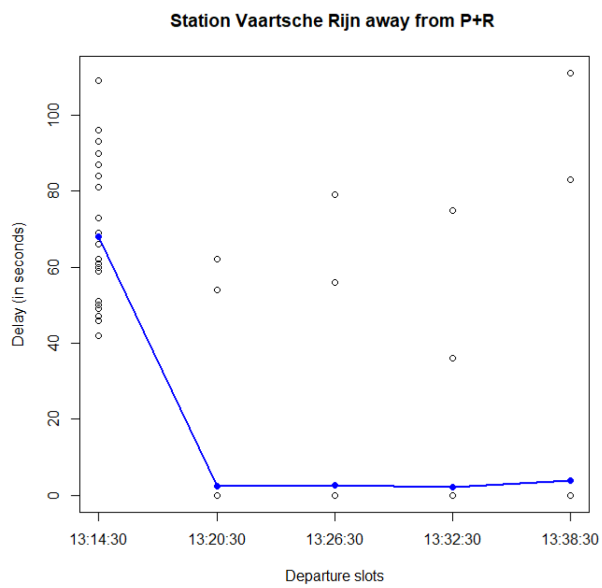

Figure 31: Departure graph for Vaartsche Rijn

5.2.5 Coming Back from the Disruption after Strategy 2

If strategy 2 is used to the pick the first trains to depart at Vaartsche Rijn after the disruption some of the same issues will be there as with strategy 1. These issues can vary in how many trains are involved. The two largest differences are that the queue in section b is shorter and that there are trains in section d. Both of these differences have an impact on how the end of the disruption should be handled. Firstly the trains stopped at CS-Centrumzijde need to be rescheduled sooner than done in strategy 1. This is because trains from d will arrive sooner than the trains from c did and because there are now less trains queued in section b so new trains are needed for P+R Science Park. Secondly the turning of trains at Vaartsche Rijn needs to be planned differently for when the disruption ends. And lastly the small amount of trains in section b can cause other issues.

When the disruption is over the trains in section d will continue their trip.

This will will provide trains for Vaartsche Rijn shortly after the disruption is over. Continuing to turn trains at Vaartsche Rijn will not be necessary and since section b does not have many trains they will be needed there. The question is where exactly will this line be drawn. Since the end of the disruption can be predicted, it is possible to stop instructing trains to turn earlier. It is likely to assume that the first trains from section d arrive approximately 4 minutes after the end of the disruption at Vaartsche Rijn. Since trains depart at a 6 minute interval at Vaartsche Rijn any time slot later than the end of the disruption does not require a turned train, but can be picked up by a train from d. This can also be seen Figure 31 above where the fixed departures end at 13:38:30, which is 90 seconds before the disruption ends. This however assumes that there is a train at the stop Stadion Galgenwaard, but that can some times not be the case. This results in the delays seen in the Figure 32 and in a single rare occasion also in Figure 33.

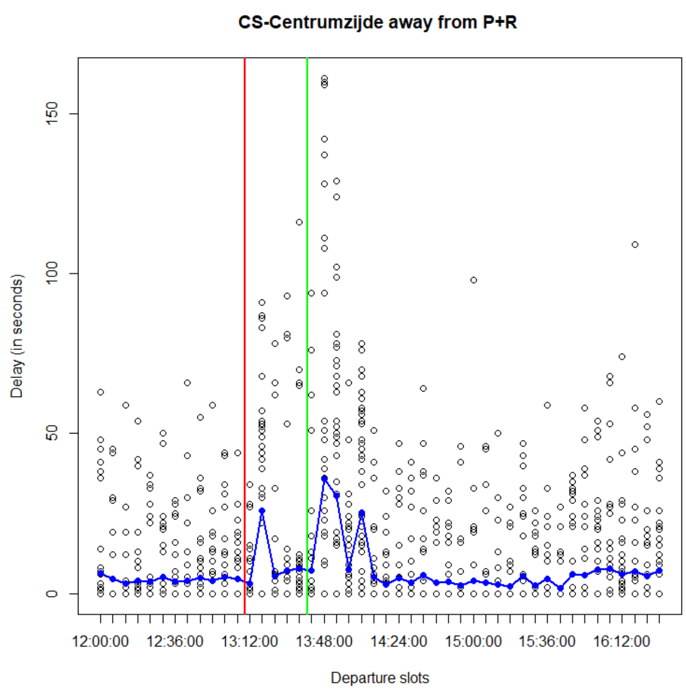

Figure 32: Away from P+R

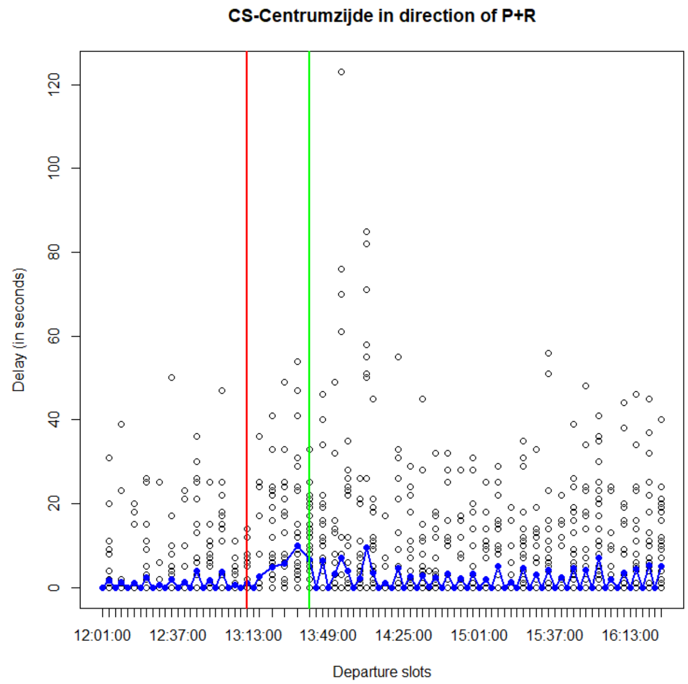

Figure 33: Towards from P+R

These delays are a one time occurrence and do not have a big impact on other trains in the timetable. They could potentially be solved by making trains turn at Vaartsche Rijn anyway after the disruption is over, but there already are only a few trains in *b* so this would cause a delay at P+R Science Park. Allowing these larger delays at CS-Centrumzijde will benefit the timetable in the long run.

The amount of trains in section *b* can vary depending on the situation when the disruption started. This can be seen in Figure 34. The average number of trains waiting in section *b* during the disruption is somewhere between 3 and 4. Since this number is based on 50 iterations it shows that there is no definitive number of trains in *b*. This average seems to be closer to 3 trains in section *b* meaning that that situation occurs more often. This uncertainty affects the departures at P+R Science Park. If there are not enough trains in *b*, not all the departure slots can be filled on time. In strategy 1 the first departure at P+R Science Park was just before the end of the disruption. Whether this can be done in this new situation is dependable on the amount of trains in *b*. If there are less than four trains in *b* and the first departure is early, there will not be enough trains for the later departures, or they will leave with delays. However if there are four or more trains in *b* and the train does not depart earlier the same issue arises as seen in Figure 27. Where all trains leave on time but have to wait before they can enter P+R Science Park, which is undesirable since the passenger then also have to wait. Because of these consequences the first departure slot at P+R Science Park is depended on the amount of trains in section b when the disruption ends. If there are four or more trains in section b the first departure slot is before the end of the disruption and otherwise it is after the end of the disruption. The resulting departures can be seen in Figure 35. Similar as with strategy 1 the first trains from b do not arrive on time for their time slots, but after those initial trains are passed the timetable is maintained almost perfectly.

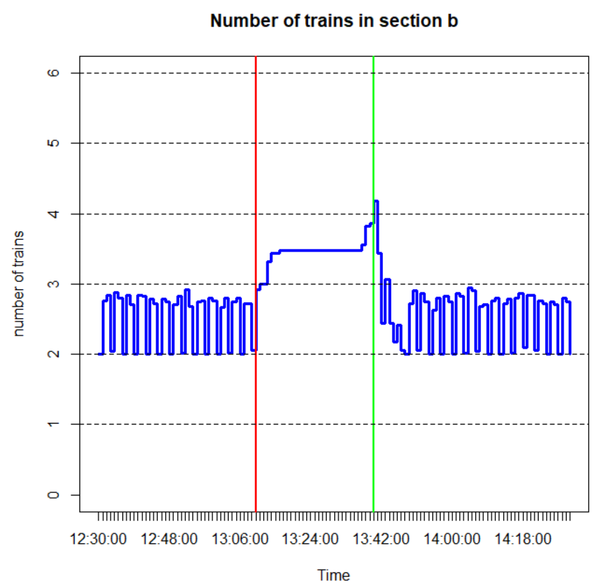

Figure 34: Average number of trains in section b

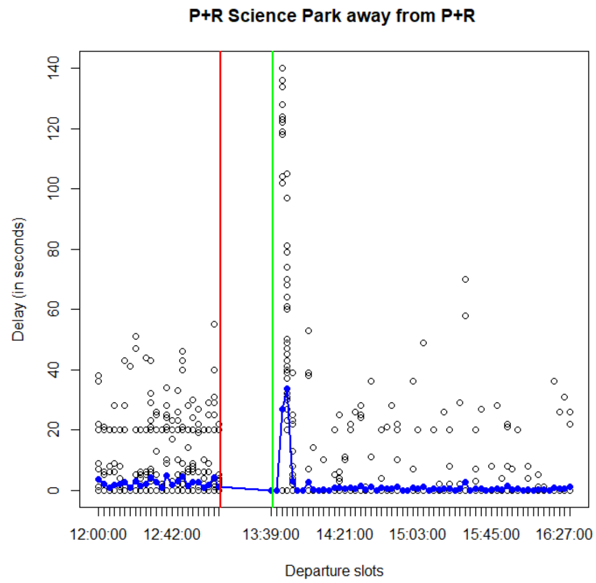

Figure 35: Departure graph for P+R Science Park

Strategy 2 is a suitable strategy in this kind of disruption. During this disruption 370 passengers were not able to reach their end destination. The disadvantage of strategy 2 is the large amount of variety in the starting situation. Depending on where are trains and where there are no trains the strategy has to be adjusted. At the moment of the disruption a traffic controller would have to make this decisions, which is something that is not preferable. The transition needs to be easier and precise. The benefit of strategy 2 was supposed to be that the trains in d would make for an easier transition back to the regular timetable. The delays in Figure 32 show that this has a small effect. The uncertainty of where the trains there are in d makes this strategy difficult.

5.2.6 Results

In Table 6 the regularity is given for strategy 1. These regularities below are measured for the hour after the disruptions is resolved. It is clear to see where the disruption happened. P+R Science Park and CS-Centrumzijde perform worse than the stops away from the disruption. Their regularity is heavily impacted by the delays shortly after the disruption. Where CS-Centrumzijde has a low regularity all around it is possible for P+R Science Park to get a good result. It will depend on the timing of the trains from section d. In Table 7 the effects of strategy can be seen. The single train departing from P+R Science Park during the disruption to make space for the trains form section d, the one train departing regulated from Vaartsche Rijn after the disruption, and the postponed start of departures from CS-Centrumzijde after the disruption is over.

	Minimum	Maximum	Average
P+R Science Park	0.8645	0.9983	0.9354
Nieuwegein Zuid	1	1	1
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.9806	1	0.9980
CS-Centrumzijde[b]	0.8608	0.9140	0.8975
Nieuwegein Stadscentrum[a]	0.9944	1	0.9998
Nieuwegein Stadscentrum[b]	0.9800	1	0.9962

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 6: Departure Regularities with an optimal Strategy 1 disruption strategy

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	1	10	10
Nieuwegein Zuid	2	3	2	3
IJsselstein Zuid	2	3	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	7	9	10
Nieuwegein Stadscentrum[a]	5	5	5	5
Nieuwegein Stadscentrum[b]	5	5	5	5
Vaartsche Rijn	0	4	1	0

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 7: Number of trains departed during the interval with Strategy 1

Strategy 2 performs less well in terms of regularity as seen in Table 8. It is not only that the average regularities are lower, but there is also a big gap between the maximum and minimum values. This gap is caused by the uncertainty's that comes with this strategy. These uncertainty's can also be recognised in Table 9. The average of 0.7 trains departing from P+R Science Park during the disruption is the result of the choice that has to be made.

	Minimum	Maximum	Average
P+R Science Park	0.8650	1	0.9587
Nieuwegein Zuid	1	1	1
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.8506	1	0.9480
CS-Centrumzijde[b]	0.8742	0.9995	0.9714
Nieuwegein Stadscentrum[a]	0.9244	1	0.9797
Nieuwegein Stadscentrum[b]	0.9811	1	0.9963

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 8: Departure Regularities with an optimal Strategy 2 disruption strategy

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	0.7	10	10
Nieuwegein Zuid	2	3	2	3
IJsselstein Zuid	2	3	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	6	10	10
Nieuwegein Stadscentrum[a]	5	5	5	5
Nieuwegein Stadscentrum[b]	5	5	5	5
Vaartsche Rijn	0	5	0	0

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 9: Number of trains departed during the interval with Strategy 2

Although Strategy 2 affects less passengers, 370 against 423, and in Strategy 1 it will take a bit longer for traffic to restart at CS-Centrumzijde towards P+R Science Park it seems that strategy 1 is the better strategy. In terms of regularity it performs better and more consistently making the schedule more reliable. Strategy 1 is also less complicated than strategy 2. In the case of a disruption the traffic controllers want to be able to act quickly and do not have time to sort out all the details. In strategy 2 with all the possibilities this can sometimes be needed making strategy 1 the overall better practice.

5.3 Scenario 2 - Turning at the Depot

In the second scenario a disruption on the UNSIJlijn side of the system will be simulated. This disruption will be between the depot and the split at Nieuwegein Stadscentrum. The resulting disrupted system is very similar to what could have occured in the old system and it will be interesting to see how well this scenario works in the new system. In this scenario the depot is located close to the disruption, it is interesting to see which possibilities that will add to this scenario. The disruption will be at the stop Wijkersloot, disrupting in both directions.

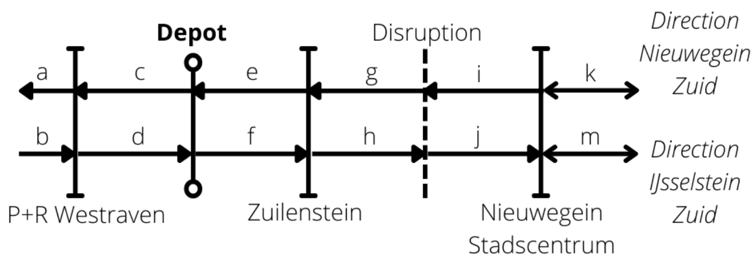

Figure 36: Overview of Scenario 2

5.3.1 Consequences

An overview of the scenario can be seen in Figure 36. The depot is indicated by the line with circles on both ends and regular stops are indicated with a line with a perpendicular smaller line on both ends. Direction going to and coming from Nieuwegein Zuid and IJsselstein Zuid are indicated by the double headed arrows k and m. An important thing to note is that trains can turn at the depot, but they can not turn at the split at Nieuwegein Stadscentrum. Since this disruption is on the UNSIJlijn trains driving line 22 are not affected and can continue as planned. Trains driving lines 20 and 21 however can not reach their end goals and need to turn earlier. They can either turn at the depot or CS-Centrumzijde. The latter will not be used since this will put a big portion of the system out of service.

This means that only the trains in sections a, b, c, d, e, and g are available for the disrupted schedule. Trains in f, h, and i have to stop immediately, because they can not turn and their path is blocked by the disruption. The interesting aspect comes in the sections j, k, and m. These trains are cut off from the rest of the system, but have a large section still available to use in a disruption strategy. Trains in k and m driving towards the disruption will have to stop somewhere since they can not reach their end goal anymore. The question is where this is going to be. Trains driving in k and m away from the disruption can still reach their end goals. However Nieuwegein Zuid and IJsselstein Zuid do not have a depot at the end, like P+R Science Park. This means that if too many trains finish their trip they can not all be stored at the end points and some might have to leave again on a trip which they can not finish. The same holds for trains in section j, however trains in j can decide to not follow its original plan to prepare for a restart. Section m is larger than section k and sending more trains that way at the restart can be beneficial.

5.3.2 The Start of the Disruption

When this disruption starts the trains in f, h and i get the instruction to stop as soon as possible since there is no place for them to go. Trains in b and d get the instruction to turn at the depot so they can be used for new lines between P+R Science Park and P+R Westraven. This is however very time sensitive. In certain cases it is impossible for the trains turning at the depot to be on time for the first departure slot. This can be seen in the Figures 37 and 38. In Figure 38 the disruption starts 7 minutes earlier and suddenly the transition is very rough. This could maybe be solved by skipping the first departure slot, which works for P+R Westraven but removes a very much needed train from other places. This can however be anticipated and when this train should have arrived at P+R Science Park a train from the depot there could be used to fill in the space.

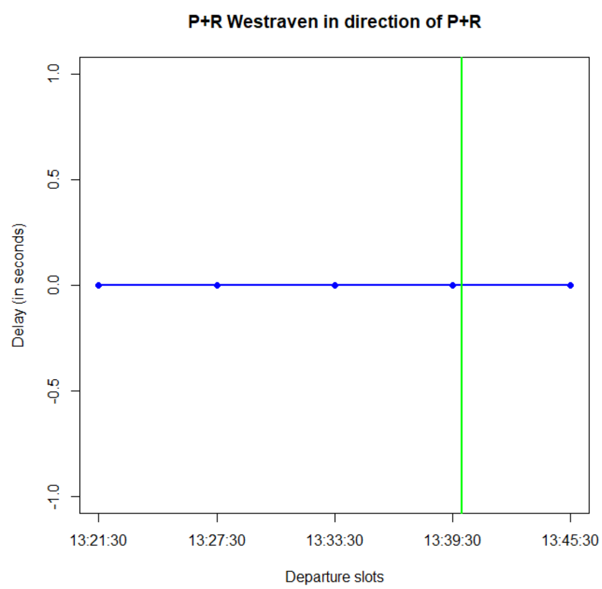

Figure 37: Departure graph for Westraven after a disruption at 13:10:00

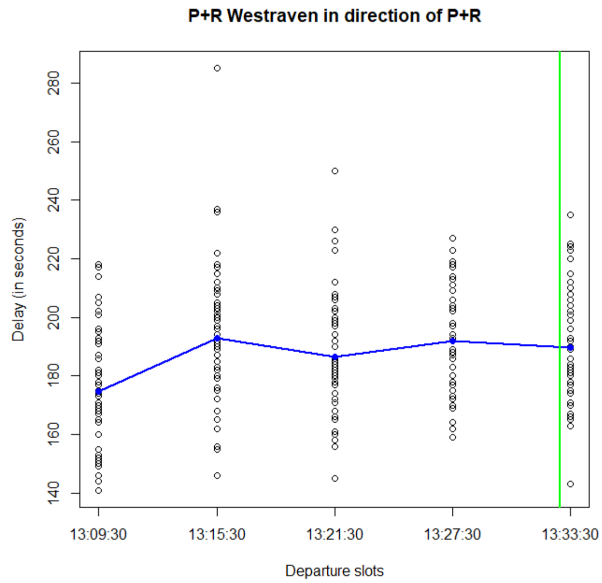

Figure 38: Departure graph for Westraven after a disruption at 13:03:00

The variability of the disruption strategy lies in the sections j, k, and m. Those trains are cut off from the rest of the system and need a place to be stationed until the end of the disruption. This can be at the next stop they encounter, but this will have an impact on all passengers in the train who now have to get out. However the severity of this is debatable. For trains travelling away from the disruption there are only a few stops left and for trains driving towards the disruption the difference in stops is also relatively small. This means that a minimal amount of extra passengers will be affected if the trains are stopped earlier. Another possibility is too stall the trains at the corresponding end points and traffic going away from the disruption will be stopped at the last stop before the split at Nieuwegein. If the latter strategy is chosen the exact position of the trains that will stop at the end points needs to be specified. Since only two trains will fit at the platforms and since m is a large section there is a possibility that there more than two trains going to IJsselstein-Zuid. Traffic going in the other direction will stop at the last stop before the split at Nieuwegein. If this stop is taken it will form a queue for the stop, but these queues will be small if not nonexistent since the sections are relatively short. In that case they will stop before the end stop having not turned yet. Stopping them immediately will from now be referred to as strategy 1 and letting the trains continue until the end of their section will be strategy 2.

5.3.3 Coming Back from the Disruption after Strategy 1

With strategy 1 all trains in the affected sections were stopped at their next stop. This would have preserved the approximate headway between the trains. With the restart the strategy is to let all trains continue their trip. The trip of the trains will be rescheduled to new departure slots. These departure slots, mainly the ones at Nieuwegein Stadscentrum, will restore the headway for all trains coming from k and m. Trains departing from Nieuwegein Zuid and IJsselstein Zuid will depart according the first slot after the disruption. After the end of the disruption no trains will be turned around at the depot anymore. If a train is turning the moment a disruption ends it will finish its turn. Cancelling a turn is hard to do in the depot and will cost so much time that it is never worth it.

According to Figure 39 this seems to work well. Over 50 iterations the average delay stays low at CS-Centrumzijde towards P+R Science Park. There is however one iteration with a huge delay shortly after the disruption. This delay has no big impact on the rest of the system. As to be seen in Figure 40 the departures are not impacted a lot by this disruption. Just the extreme cases occur sometimes, but again do not have a big impact. On the other side of the disruption everything runs smoothly. In Figure 41 the restarted flow of traffic can be seen which come in with no large delays. The one thing to note is that the second departure slot is not used since this one corresponds to a departure slot at Nieuwegein Zuid during the disruption. This 'missing' trains does not have an impact on the rest of the system. Overall this seems to be a good method if the start of the disruption can be handled smoothly. 642 passengers were affected during this operation.

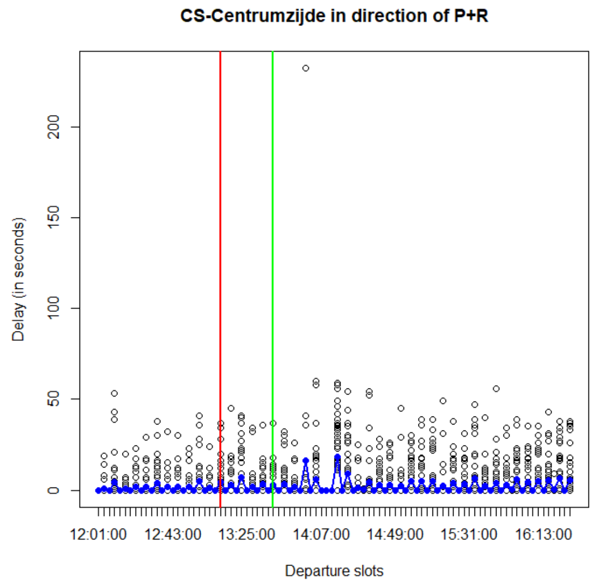

Figure 39: Departure graph for CS Centrumzijde towards P+R Science Park

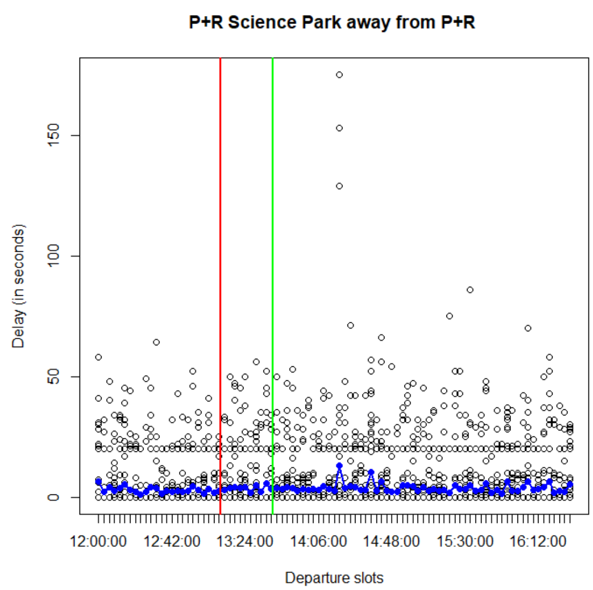

Figure 40: Departure graph for P+R Science Park

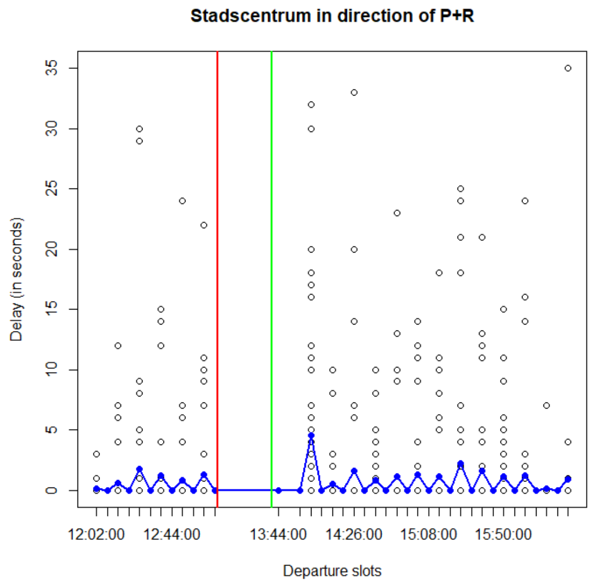

Figure 41: Departure graph for Nieuwegein Stadscentrum Towards P+R Science Park

5.3.4 Coming Back from the Disruption after Strategy 2

The situation at the end of the disruption is that there are trains stopped at/waiting for Nieuwegein Zuid and IJsselstein Zuid. There are trains stopped at/waiting for the stops Merwestein and St. Anthoniusziekenhuis. And there are trains surrounding the disruption. The latter one is the easiest since they can just depart when the disruption is over and continue their trip. It might be interesting to note the number of trains between the disruption and the split at Nieuwegein, because this might influence the headway to the first train departing from the Split at Nieuwegein. However since trains do not immediately appear at the split after the disruption, the headway will be always be large enough to not have to take it into account.

The trains at the end stops, Nieuwegein Zuid and IJsselstein Zuid, can both go back to their original schedule. The first departure slot here will be the first slot after the disruption. This is under the assumption that the other trains waiting near the split would in a normal situation have filled those slots. This means that after the disruption the end points go relatively back to their normal situation.

The trains at Merwestein and St. Anthoniusziekenhuis will be rescheduled according to departure slots at Nieuwegein Stadscentrum. This will be done alternatively between the stations starting with St. Anthoniusziekenhuis. St. Anthoniusziekenhuis has the most trains waiting since it is part of the largest section. Having the most trains means that they need to be handled first to prevent an imbalance. These trains will depart in a 6 minutes interval. If in the situation there are two trains at St. Anthoniusziekenhuis and 0 at Merwestein, those two trains will depart at a twelve minute interval as usual on that line.

Below the three resulting departure graphs are shown. These graphs are very similar to the ones resulting from strategy 1. This means that the best performing strategy needs to be determined according to other metrics.

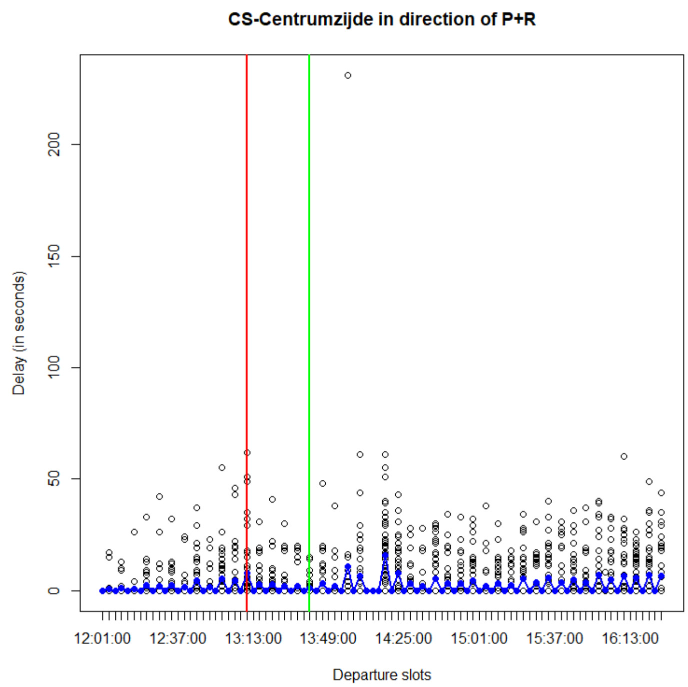

Figure 42: Departure Graph for CS Centrumzijde towards P+R

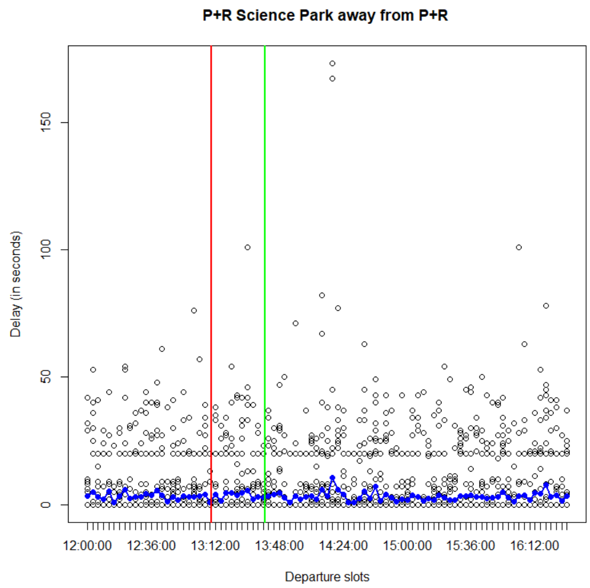

Figure 43: Departure Graph for P+R Science Park

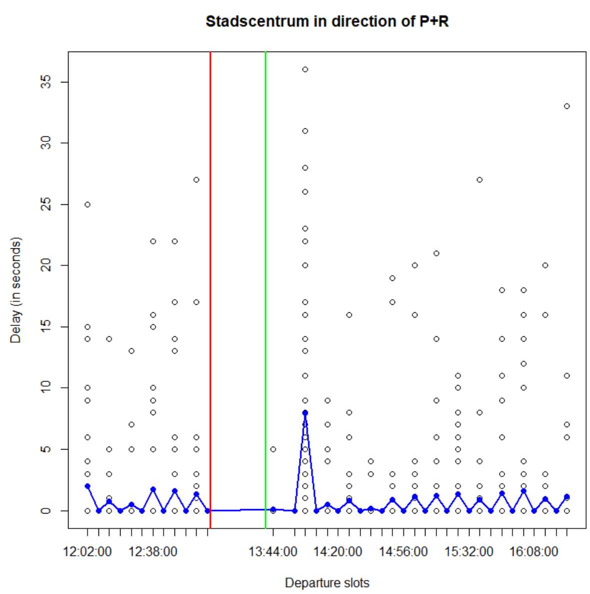

Figure 44: Departure Graph for Nieuwegein Stadscentrum towards P+R

5.3.5 Results

In Table 10 the regularities are shown for the hour after the disruption. The minimum and maximum value can vary quite an amount in some cases. This is the result of situation where trains just passed a point or were just delayed enough to cause problems. In comparison to the regular regularities, shown in Table 4, this situation does not perform a lot worse on average and just like in a regular situation it can reach the best regularity value, however the minimum values are much worse. An exceptional low value is seen for Nieuwegein Stadscentrum towards P+R Science Park. This is the result of skipping one departure slot shortly after the disruption. This can be seen in the Figure 41 and most clearly in Table 11, where in the interval 13:40 to 14:10 only four trains depart compared to the normal five. In these results the disruption is not taken into account meaning that some regularities might be better here than they really were. In Table 11 it is shown that during the disruption interval that are places were no trains leave at all.

	Minimum	Maximum	Average
P+R Science Park	0.8634	0.9963	0.9578
Nieuwegein Zuid	1	1	1
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.8999	1	0.9705
CS-Centrumzijde[b]	0.8799	1	0.9733
Nieuwegein Stadscentrum[a]	0.9772	1	0.9979
Nieuwegein Stadscentrum[b]	0.8056	0.8080	0.8057

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 10: Departure Regularities in the hour after the disruption from Strategy 1

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	10	10	10
Nieuwegein Zuid	2	0	2	3
IJsselstein Zuid	2	0	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	10	10	10
Nieuwegein Stadscentrum[a]	5	0	5	5
Nieuwegein Stadscentrum[b]	5	0	4	5

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 11: Number of trains departed during the interval with Strategy 1

The results for strategy 2 can be seen in Tables 12 and 13. These results are very similar to the ones for if Strategy 1. There are only small differences, but these can be pointed to the stochastic nature of the simulation. To identify the best of the two strategies other factors need to be investigated. Strategy 1 affects 642 passengers and strategy 2 affects 592 passengers. Strategy 2 performs better here since the trains drive further at the start of the disruption. In terms of complication there are no big preferences since they are both not very complicated. The moment a restart occurs after strategy 1 the trains are more equally distributed over the system, which means that on average all stops will be serviced earlier. There are advantages to both strategies and the best strategy can not be pointed out with a confident certainty.

	Minimum	Maximum	Average
P+R Science Park	0.8807	1	0.9653
Nieuwegein Zuid	1	1	1
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.8954	0.9995	0.9647
CS-Centrumzijde[b]	0.8635	1	0.9720
Nieuwegein Stadscentrum[a]	0.9778	1	0.9978
Nieuwegein Stadscentrum[b]	0.8056	0.8080	0.8056

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 12: Departure Regularities in the hour after the disruption from Strategy 2

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	10	10	10
Nieuwegein Zuid	2	0	2	3
IJsselstein Zuid	2	0	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	10	10	10
Nieuwegein Stadscentrum[a]	5	0	5	5
Nieuwegein Stadscentrum[b]	5	0	4	5

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 13: Number of trains departed during the interval with Strategy 2

5.4 Scenario 3 - IJsselstein Zuid Unreachable

In the third scenario the disruption will be located in the section between IJsselstein Zuid and the split near Nieuwegein Stadscentrum. In contrast to scenario 2 this disruption will not affect line 20 going to Nieuwegein Zuid. This gives the possibility of using different instructions for lines 20 and 21. The disruption will be at the stop Clinckhoeff, which lies approximately in the middle between the split at Nieuwegein Stadscentrum and IJsselstein Zuid.

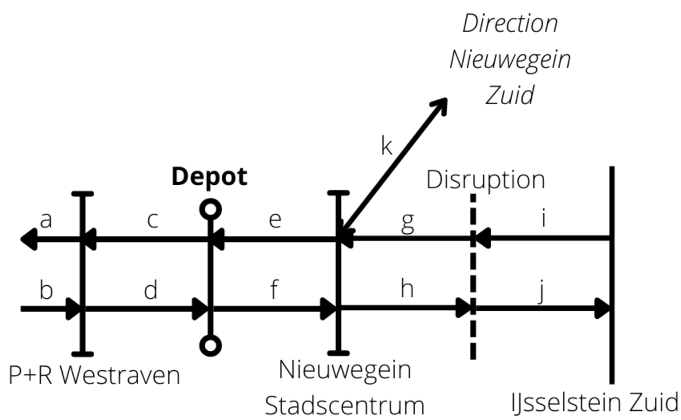

Figure 45: Overview of Scenario 3

5.4.1 Consequences

An overview of this can be seen in Figure 45. This disruption only has an effect on line 21 to IJsselstein Zuid. Line 20 and 22 do not use the disrupted section. This means that this disruption has a direct effect on trains in sections i, j, and h. In these sections the trains have to stop since they are cut off from the rest of the system. Trains in section j can choose to finish their trip and continue to IJsselstein Zuid. Trains heading towards IJsselstein Zuid in the sections between b and f have a choice to make. They can neither finish their trip to IJsselstein Zuid nor can they stop immediately since that would hinder the trains from line 20. There are three potential options namely they can turn trains at the depot, they can go to Nieuwegein Zuid, and they can drive onto section h and stop there. This latter option is however very inefficient since there would be too many trains in h. In this scenario directing trains with line 21 to Nieuwegein Zuid will be strategy 1 and turning them at the depot will be strategy 2.

5.4.2 The Start of the Disruption

At the start of the disruption the trains in the sections h, i, and j do not need a complicated strategy. In these sections trains drive with a headway of 12 minutes. Because of this, it is likely that there is only 1 train per section and the impact of a strategy would be minimal. These trains will continue as far as possible and stop at the end stop or near the disruption. Trains waiting to depart from IJsselstein Zuid will not depart until after the disruption. The disruption has no effect on trains in the sections a, c, e, g, and k. These trains can continue as planned. The same holds for trains driving line 20 in the sections b, d, and f. Trains from line 21 in the sections b, d, and f will behave like strategy 1 or 2, however with strategy 2 trains in section f can not turn at the depot anymore. In this case these trains will continue onto section h.

When the disruption starts trains from line 21 can still continue from sections e and g. Since these two together make for a relatively long track section it might take a while before the last train arrives at the depot. If strategy 2 is chosen and the first trains start turning at the Depot immediately after the disruption these two trains could hinder each other. So depending on the location of the last train coming from g and the arrival of the first train at the depot, it might be necessary to let the latter train continue driving onto h. In the disruption tested here this is always required. Since trains with line 21 arrive on a 12 minutes interval and the first departure slot is filled with a regular train only two trains actually turn at the depot.

The luxury of having too many trains does not occur with strategy 1. The falling out of the trains from i and the ones departing from IJsselstein Zuid causes a departure slot at Nieuwegein Stadscentrum to not be filled. This can be seen in Figure 46 where a departure slot around 13:30 is skipped. This gap can not be filled, because it takes too long for the first trains to reach Nieuwegein Zuid and turn there. However the fact that one train less will reach CS-Centrumzijde is not a problem, since CS-Centrumzijde can still fill all their departure slots as seen in Figure 47. It can do this, because CS-Centrumzijde has a small buffer. The platforms that are used for turning trains driving line 22 are occupied more often than not, which means that there are always two trains there. In Figure 48 the total number of trains at those two platforms are shown. This number falls down approximately 20 minutes after the departure slot at Nieuwegein Stadscentrum when the extra train is used to fill in the gap. Ofcourse the punctuality of that second train needs to be good in order to make this slot, which is not always the case. That is why there is a small delay peak at the corresponding time in Figure 47.

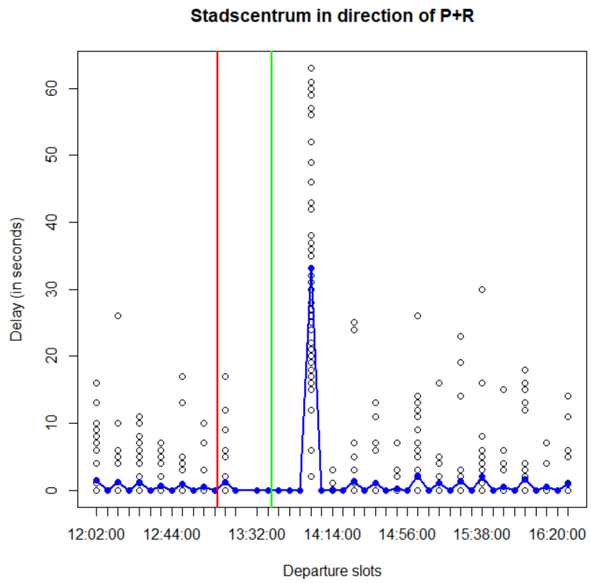

Figure 46: Departure Graph for Nieuwegein Stadscentrum Towards P+R Science Park

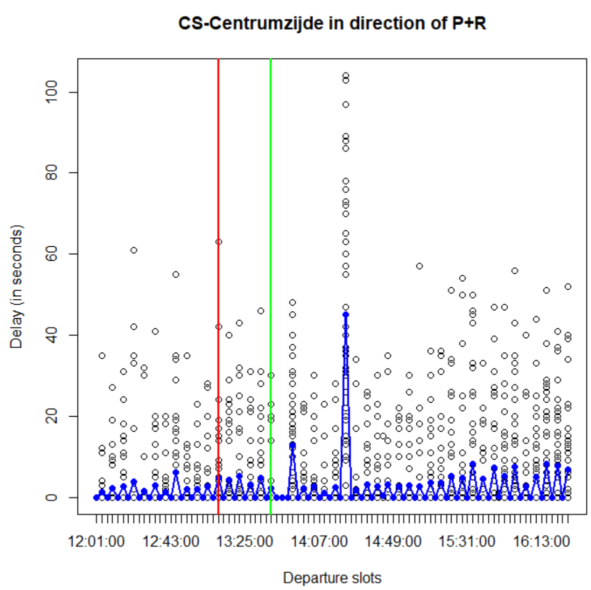

Figure 47: Departure Graph for CS-Centrumzijde Towards P+R Science Park

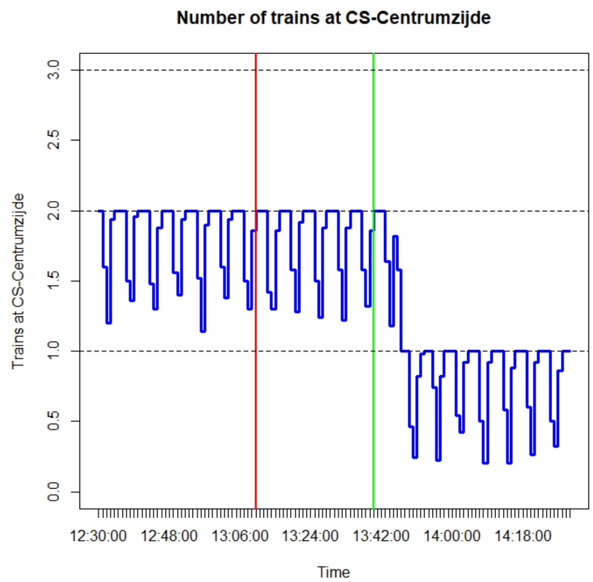

Figure 48: Number of Trains at CS-Centrumzijde

5.4.3 Coming Back from the Disruption with Strategy 1

When the disruption is over both strategies have similar ways of getting back to the normal timetable. For both strategies the trains in sections h and i will continue their trip. In this scenario the planning for the first train from i is very tight. After it starts up again it can not make its departure slot at split which influences the punctuality for CS-Centrumzijde aswell. This can be seen in Figures 47 and 46 from the previous subsection. The large peaks just after the disruption ended are caused by this. This same situation occurs for strategy 2.

The deviation with the timetable for trains in h are not relevant since it wont encounter any trains before reaching IJsselstein Zuid. At IJsselstein Zuid a new trip starts and the trains timetable will be adjusted. The first departure slot filled after the disruption at IJsselstein Zuid is the first one available. In extreme case where the disruption starts just before a departure slot and/or ends just after one it is better to take the departure slot just before the end of the disruption.

After the disruption the departure slots at Nieuwegein Zuid need to go back to an interval of 12 minutes. Immediately after the disruption trains from line 21 will no longer go to Nieuwegein Zuid. Which means there are not enough trains to maintain the 6 minutes interval. The interval however can not change at the same time the disruption is over. This is because there might still be trains from line 21 going to Nieuwegein Zuid and because the departures need to align with the regular timetable. The way to solve both these issues is to change the interval after a train at Nieuwegein Zuid is scheduled for a departure slot that would have been in the regular timetable. In this way it guarantees that the normal timetable is driven and that there are no trains from line 21 coming to Nieuwegein Zuid anymore. The latter is the case because trains planned according to the regular timetable at Nieuwegein Zuid are always trains from line 20 and because the travel time between the split and Nieuwegein Zuid is less than the headway between trains. If a train arrives at Nieuwegein Zuid after the disruption and is planned normally, this means that are no trains from line 21 behind it since it either has not arrived at the split yet or it has already been sent to IJsselstein Zuid. The transition between a 12 and a 6 minute interval can be seen in Figure 49. Note that after the disruption has ended one more train leaves with a 6 minute headway and that if the middle two departures are removed from the cluster of 5 it would be a regular schedule. These two departures are from rerouted line 21 trains.

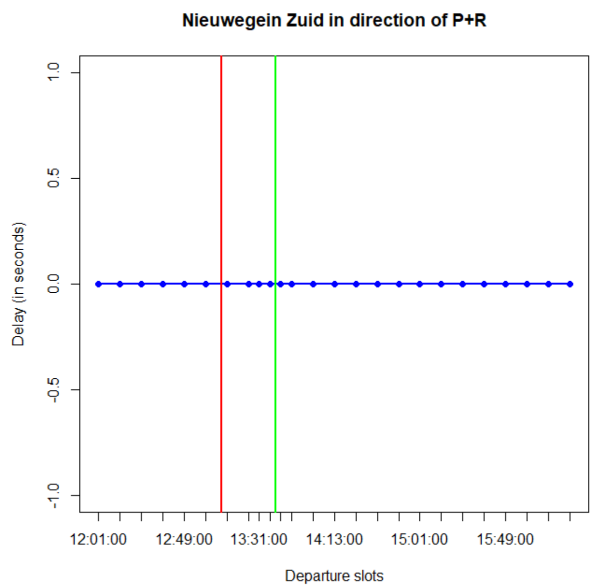

Figure 49: Departure Graph for Nieuwegein Zuid

There seem to be no major setbacks to this disruption strategy, except for the delay coming from the first train to depart from i. This delay however also occurs with strategy 2, so not a big disadvantage for this strategy. Another consequence of this strategy is that the average amount of trains at CS-Centrumzijde decreases. This however does not influence the punctuality at CS-Centrumzijde, since no big difference can be seen in Figure 47. This strategy affects 213 passengers.

5.4.4 Coming Back from the Disruption with Strategy 2

When using strategy 2 the recovery from the disruption is similar to strategy 1 for trains in sections i, h, and the trains stationed at IJsselstein Zuid. Trains coming from i still can not make their departure slot at Nieuwegein stadscentrum and consequentially CS-Centrumzijde. The first train from section i is interesting in a different way though. After the disruption it takes a while before this train reaches P+R Westraven. This means that if trains stop turning at the depot early there will be a gap that is not filled. At the start of disruption the first train does not always turn at the depot combining this with turning one more train after the disruption results in the departure graph shown in Figure 50. Because of the 12 minute interval and the skipping of some departure slots only two trains turn at the depot when using this strategy.

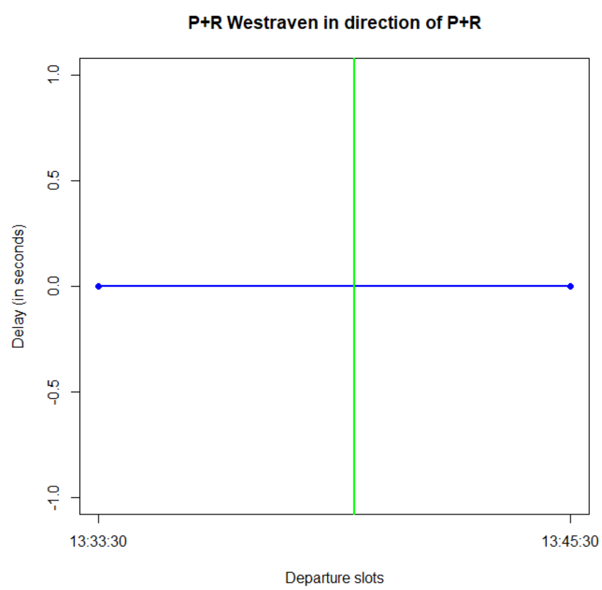

Figure 50: Departure graph for P+R Westraven

A difference with strategy 1 is that there are more departure slots at Nieuwegein Stadscentrum not filled. This can be seen in Figure 51 where there are larger gaps between some points. These gaps are filled by the two trains that turned around at the depot. In regards to punctuality strategy 2 seems to work well since there are no major new delays. The problem with strategy 2 is however that short turning the trains at P+R Westraven might have a negative consequence on the passengers in those trains. With strategy 2 on average 271 passengers can not reach their destination, which is more than strategy 1. The difference with strategy 1 comes from the trains with a destination in section f. With strategy 2 these passengers will have to switch trains at P+R Westraven in order to reach their destination.

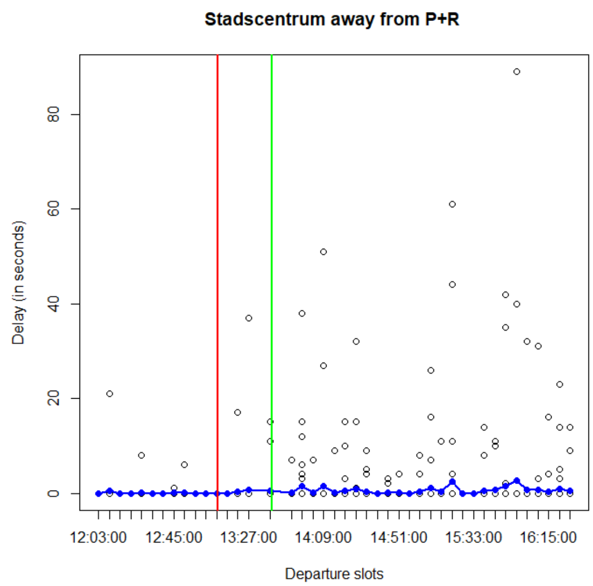

Figure 51: Departure Graph for Nieuwegein Stadscentrum

5.4.5 Results

The departure regularity for strategy 1 are shown in Table 14. The first thing to note is the consistent regularity of 0.7333 at Nieuwegein Zuid. The regularity is measured in the hour after the disruption and when the disruption has just ended Nieuwegein Zuid is still driving on a 6 minute interval and will only later switch back to a 12 minutes interval. Despite the regularity not being equal to 1, there are no delays at Nieuwegein Zuid as seen in Figure 49. At IJsselstein Zuid all regularities are 1 meaning that in this scenario there are always enough trains to depart according to the timetable. The last interesting thing to see is that for CS-Centrumzijde and Nieuwegein Stadscentrum travel in the direction of P+R Science Park seems to perform worse according to the average regularity. This is caused by the first train from i, which has trouble making its first departure slot. In Table 15 the increase of departures at Nieuwegein Zuid and the lack of departures at IJsselstein Zuid can be seen. The departure slot that could not be filled at the start of the disruption since a trains was stopped in section i results that only 4 trains departed from Nieuwegein Stadscentrum towards P+R Science Park.

	Minimum	Maximum	Average
P+R Science Park	0.9286	0.9968	0.9619
Nieuwegein Zuid	0.7333	0.7333	0.7333
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.9344	1	0.9686
CS-Centrumzijde[b]	0.9238	0.9931	0.9600
Nieuwegein Stadscentrum[a]	0.9406	1	0.9954
Nieuwegein Stadscentrum[b]	0.9628	0.9989	0.9803

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 14: Departure Regularities after the disruption from Strategy 1

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	10	10	10
Nieuwegein Zuid	2	4	3	3
IJsselstein Zuid	2	0	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	10	10	10
Nieuwegein Stadscentrum[a]	5	5	5	5
Nieuwegein Stadscentrum[b]	5	4	5	5

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 15: Number of trains departed during the interval with Strategy 1

In the regularities for strategy 2 seen in Figure 16 Nieuwegein Zuid is no longer much lower than the others. However this role is now set for departures in both directions from Nieuwegein Stadscentrum, this is caused by similar reasons. Just after the disruption the slots are yet filled, because there is still one more train turning at the depot. On average these regularities seem to perform similarly to the ones from strategy 1. The effect of the strategy can be seen in Table 17 where there are now trains departing according to schedule and a decreased amount of trains at Nieuwegein Stadscentrum.

	Minimum	Maximum	Average
P+R Science Park	0.9042	0.9927	0.9628
Nieuwegein Zuid	1	1	1
IJsselstein Zuid	1	1	1
CS-Centrumzijde[a]	0.9150	0.9972	0.9690
CS-Centrumzijde[b]	0.9047	0.9938	0.9571
Nieuwegein Stadscentrum[a]	0.8161	0.8289	0.8222
Nieuwegein Stadscentrum[b]	0.7895	0.8065	0.8045

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 16: Departure Regularities in the hour after the disruption from Strategy 2

	12:40 - 13:10	13:10 - 13:40	13:40 - 14:10	14:10 - 14:40
P+R Science Park	10	10	10	10
Nieuwegein Zuid	2	3	2	3
IJsselstein Zuid	2	0	2	3
CS-Centrumzijde[a]	5	5	5	5
CS-Centrumzijde[b]	10	10	10	10
Nieuwegein Stadscentrum[a]	5	4	4	5
Nieuwegein Stadscentrum[b]	5	3	4	5
P+R Westraven	0	1	1	0

[a] Departures away from P+R Science Park
[b] Departures towards P+R Science Park

Table 17: Number of trains departed during the interval with Strategy 2

When comparing the two strategies strategy 1 seems to win the contest. Not only does it affect less passengers, 213 to 271, but it is also less complicated. Redirecting trains over the short section that leads to Nieuwegein Zuid does affect the timetable by a lot. Continuing trains also maintains the availability in sections e ad f which benefits the passengers. In a scenario where the disruption was in the branch to Nieuwegein Zuid and the branch to IJsselstein Zuid was clear this same result is not guaranteed. Since the IJsselstein Zuid branch is over twice as long this would result in different numbers. It would take a lot longer for diverted trains to get in the system. In this scenario it is likely that using the depot as turning point would be the optimal strategy.

6 Conclusion

The aim of this project was to determine disruption management strategies for the Utrecht light rail system. A disruption management strategy should be easy to implement in order to create a smooth transition into the disrupted state and back into the regular state afterwards. When creating a disruption strategy the passengers should also be kept in mind in order to minimize the effect on them. In this thesis an optimal disruption strategy is determined for three different disruption scenarios.

The Utrecht light rail system has very limited turn possibilities and does not allow overtaking. This restricts the possibilities for disruption strategies a lot. In the three scenarios there were only two viable strategy to try out that had a chance of being useful. In scenario 1 and 3 this strategy was for trains still in use during the disruption and for scenario 2 the strategy determined where trains were stopped during the disruption. There was no decisive difference in the performance between the strategies for scenario 2, but there were performance differences between the strategies for scenario 1 and for scenario 3. This seems to point out that it is more important to focus on the trains that are still active during the disruption. The options for these trains are more valuable to invest in.

The three scenarios were picked, because they differ on traffic interval. In scenario 1 affected traffic drives on a 3 minute interval, in scenario 2 on a 6 minute interval, and in scenario 3 on a 12 minute interval. The higher number of affected trains in scenario 1 creates issues that need to be resolved. They group up and specified instructions are needed to resolve this. In scenario 3 this does not happen since trains are so far apart grouping up after the disruption is rare. Increasing traffic in the light rail system will mean that more complex disruption strategies are needed.

The strategies applied on the three scenarios were created with the goal to keep as much as possible of the system in use. According to the departure data for all scenarios enough trains can always depart from the unaffected stops. The regularities for these stops is also not very different than in a regular situation. This means that with an optimal disruption strategy the rest of the system can be utilized like in a normal situation.

7 Discussion

Although the results seem to say that an optimal disruption strategy can almost nullify the effects on the rest of the system this might not always be the case. In the experimentation the disruptions always happened at the same time and had the same duration. In reality a disruption can occur at anytime and there are different types of disruptions with varying length. It is possible that the strategies described in this thesis perform less well in a different situation. The scenarios have a fixed location and a disruption somewhere else might also affect the performance of a strategy.

In the simulation a timetable is used that is constructed based on simulation data. This means that the timetable is based on the travel times between end/time stops as seen in test runs of the simulation. Although the simulation is based on reality it is possible that this timetable is subjected to overfitting. The disruption strategies can also be specific to this timetable and perform worse when other timetables are in use. This timetable does not take into account the driver planning. In practice drivers need to breaks and can not work the entire day. This planning is not included in the simulation and might have an effect as well. Overall this thesis does not provide strict strategies that should be directly used in real life, but provides an insight into problems and the possibilities that come with determining disruption management strategies.

Continuation of this research could build on the previously mentioned points. Firstly an approach to making a general disruption management strategy that can manage a large variety of different disruptions can be investigated more. Secondly incorporating the drivers into the simulation will add more realistic value into the simulation and will add another complication to the disruption strategy. And lastly an interesting research could be done into what could have been if there were more turn possibilities in the Utrecht light rail system. For example trying to find potential spots for extra track crossings, so that frequent disruptions can be handled with maximum efficiency.

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