Master thesis Eurailscout

‘Efficiency improvement in planning and scheduling of measurement trains’

Final report graduation thesis

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Colophon

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Preface

This report presents the results of my graduation thesis research at the company Eurailscout Inspection & Analysis. It represents the culmination of my studies in ‘Transport & Planning’ within the faculty Civil Engineering and Geosciences at Delft University of Technology in The Netherlands. Ten months of interesting research resulted in the study as presented in this document.

At this place I would like to mention some people who have helped me realizing this research. At first I would like to thank Eurailscout for offering me the possibility to conduct my master thesis there. Next I would like to mention the graduation committee who have helped me with useful feedback to improve the structure and content of this study. A special word of thanks goes to my supervisors at the university and at Eurailscout for their support and feedback during the writing of this thesis. They have helped me with constructive feedback, suggestions for (further) researches and with the necessary external contacts. Of course, I cannot forget my colleagues in the ‘bedrijfsbureau’ department at Eurailscout, especially the train planners. They provided me with the necessary information, answered many questions and gave me an interesting insight into the daily processes of railway operations. Furthermore, I would like to thank all my other colleagues, both at the office and on the measurement trains, for their interest in my research and the insight they gave me into their tasks.

Last but not least I would like to thank my parents, sister, family and friends for their continuous support not only during this master thesis, but during my studies at TU Delft.

Martin Sunter
April 2013

Summary

To guarantee the quality and safety level of railway networks, inspections of the tracks are carried out. Until a few decades ago most of the inspections were carried out by hand. However, a number of incidents and more stringent health and safety regulations made manual track inspections in the Netherlands almost impossible and measurement trains were introduced as a solution.

Eurailscout Inspection & Analysis is a measurement train operating company providing clients worldwide with data about the actual state of the tracks in the client's railway network. All sorts of data are collected with a fleet of inspection trains. Collected data range from rail wear (both external and internal) to the functioning of safety systems and from video-capturing to overhead wire wear. The rolling stock used for these measurements consists, among others, of geometry measuring, ultrasound and video-capturing trains (see front page for an overview of a large part of the rolling stock). Eurailscout analyzes the collected data and converts the raw data into a format that can be sent to the client. The data can be used to plan maintenance or determine track degradation over time. Recorded track videos are also used for the training of train drivers.

Problem description
Included in the latest contract between Eurailscout and ProRail is the condition that Eurailscout needs to improve its efficiency by a certain percentage annually. Eurailscout agreed with this condition in the light of the CO_2 emission reduction and their efficiency improvement. ProRail introduced this condition because the train traffic on the Dutch railway network is growing every year. In particular, the implementation of government plans to introduce 'PHS' (Programma Hoogfrequent Spoor, roughly translated: program high frequency train traffic) will result in railway lines being used far closer to their capacity, leaving less space for companies like Eurailscout. A complicating factor for Eurailscout is the specific requirements and limitations each inspection train has, such as maximum measurement speed, minimal turnaround times, fixed routing to inspect the planned tracks, etc. These requirements make the planning and scheduling of the measurement trains between the regular train traffic, a challenging exercise.

The main research question for this research is therefore:
How to establish an annual efficiency improvement in the planning and deployment of the Eurailscout measurement trains, given the limitations imposed by the measurement trains, the tracks and scheduling?

Efficiency is measured by ProRail in the number of deployment days Eurailscout needs to inspect the tracks as agreed in the contract. Internally Eurailscout measures their performance by the ratio of measured distance divided by the total driven distance in a measurement deployment (minimal ratio 0.0, maximal ratio 1.0). The expressions of efficiency are related: an increase in efficiency ratios as used by Eurailscout improves the daily production rate, reducing the number of required deployment days. Reason why both expressions are used in this research.

Not all trains are considered in this research, only the ones shown in Figure S1. These trains are selected from the total fleet, because they are the most important and most deployed in the Netherlands. The challenge facing both ultrasound inspection trains is their measurement speed of 60 km/h. The UFM120 is able to measure with speeds up to 110 km/h and is therefore easier to schedule between the regular train traffic. In addition, the UST96 needs a flat car for detection purposes. This flat car always needs to be at the rear of the train facing forward, which causes long turnaround times due to the fact that the measurement coach needs to reposition itself in relation the flat car for every journey.

The other Eurailscout measurement trains are not considered because they have too specific planning requirements.

Universal measurement train *UFM120*

Ultrasound measurement train *UST96*

Ultrasound measurement train *UST02*

Figure S1: Measurement trains considered in research

Literature study

A literature study revealed that few publicly available studies have been carried out on the planning of measurement trains. These studies contain little information about the methods used and most of time elaborate on the results achieved. Therefore similar problems were investigated. Creation of inspection paths covering all tracks to be inspected is comparable with the Chinese Postman Problem (CPP) which is a special variant of the well-known Travelling Salesman Problem. In the CPP the ‘postman’ needs to cover all streets in the most efficient manner possible (for example shortest distance or time). All sorts of solution techniques exist, ranging from the simple to the complicated but more or less all applied algorithms are based on branch-and-bound methods. Networks can be completely directed (all streets are one-way streets), undirected or mixed variants. Results of the studies seem promising and the network designs are used for the routing models developed for this research.

Planning processes

The inspection deployments for the trains under consideration are planned by Eurailscout’s planning department. Using software developed in-house (EB-ViCoP), Eurailscout planners determine the measurement train paths to cover the tracks to be inspected according to the contract signed with the client. Depending on the traffic volume and transported tonnages, tracks need to be measured with different frequencies. These frequencies are based on European legislation safeguarding the number of inspections required for a safe and reliable rail infrastructure.

Inspection paths are created heuristically, based on the contract, knowledge of the planners and experiences from previous runs. No automated routing method is used. The planners are planning on an empty network, free of other train traffic. With their knowledge and experiences from previous runs they try to take into account the other train traffic in the path creation process, for example by not choosing station platform tracks to change direction.

For the creation of measurement train timetables Eurailscout uses the services offered by an external party. A routing plan, containing the path the planners want the train to travel, is sent to an external party which uses it to determine the measurement train timetable. When the timetable creation process is finished the timetable is sent to Eurailscout. Next the planners convert the routing plan and timetable into a route book, containing the inspection path on track detail and color markings showing the track sections to be measured. This route book is sent to the train crew, dispatchers and other parties that need to be aware of the oncoming measurement train in the near future. Figure S2 presents this process schematically.

Current performance analysis

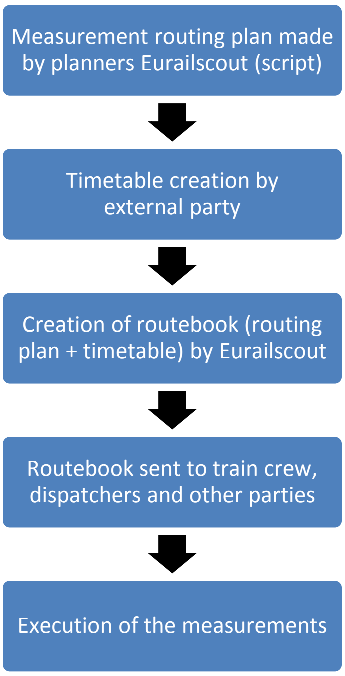


Figure S2: Planning and scheduling chain

An analysis of the current performance was made over the inspection deployments planned and realized in 2011 and in the first half of 2012. The analysis is based on the efficiency ratio used by Eurailscout internally: measured distance in a deployment divided by the total driven distance in the deployment. This ratio enables a comparison to be made between the planned and realized efficiency of specific trains and between the trains. It can be concluded from this analysis that the three trains under consideration – considering the highly utilized Dutch train network – show good efficiency ratios already. Comparing the efficiency ratios of the planned and realized inspection paths, train specific and between the trains, revealed that there are differences although they are in most cases not significant. In all cases the realized performance is marginally lower than the planned performance, caused by disturbances occurring in the execution of the measurements. The significant differences occurring when comparing the trains with each other can be explained by the way the trains are routed. Trains used to inspect many single track lines have lower efficiency ratios than trains mainly used to measure corridors, caused by the track layout: on a single track line the track is measured in one direction. On the way back, nothing has to be measured.

The efficiency ratios realized are lower for all trains than the planned ratios, due to disturbances occurring in the realization phase. The inclusion or exclusion of remeasurement deployments in which track sections are measured that could not be measured in the initial run, does not influence the results significantly. Although the differences in efficiency ratios are not substantial, the by the disturbances affected kilometers can be substantial. Reason why the causes for the disturbances are analyzed to search for possible improvements.

The Eurailscout planners keep detailed (train specific) lists of the missed track sections with the cause(s), responsible parties and the established contractual period in which these sections must be measured again. Using these lists the planners are able to plan the track section in subsequent runs for remeasuring. Analysis of these disturbance lists showed that causes for the deviations between planning and execution are diverse: from dispatchers assigning wrong paths to defects in the ‘sensitive’ measurement systems and from unforeseen circumstances such as signal failures to tracks being occupied by other trains. The same holds for the parties which the disturbances can be assigned to: from Eurailscout itself to dispatchers and from the external scheduling party to disturbances that cannot be assigned to any party (e.g. weather). In this analysis some improvements are identified. They are elaborated further on in this summary.

Routing models

Because the analysis of the current performance revealed that there are no significant differences between the planning and execution of the inspections, attention turned to further efficiency improvements in the way the trains are planned. Therefore two routing models were built in the mathematical programming software package MATLAB.

Several routing philosophies exist to create the inspection paths, such as measuring long lines (long continuous paths over multiple corridors with as few as possible direction changes), measuring corridors (inspection of one corridor at a time) or inspecting ‘yards first’ in which the yards at stations are inspected first before the remaining tracks are inspected. Each of these methods has its own advantages and disadvantages. Currently the trains are routed heuristically based on previous runs adapted with the knowledge of the planners and experiences from the previous runs. Resulting paths are most comparable with the routing philosophy ‘measuring long lines’ although the paths are also subject to influences from other routing philosophies. The routing philosophies ‘yards first’ and ‘corridor routing’ are studied because they are the most interesting for Eurailscout.

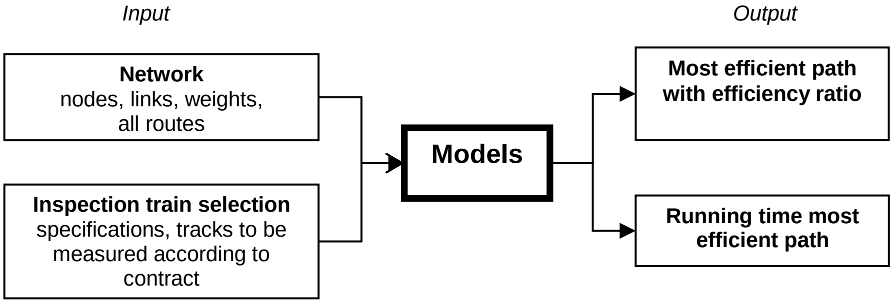


Figure S3: In- and output of the routing models

The purpose of the routing models is to determine whether a more systematic approach to the inspection train planning process will improve the efficiency ratios. Therefore, the output of the models needs to comprise the inspection path found, the efficiency ratio of this path and the required train running time, see Figure S3

Both routing models need a network to find the most efficient paths for the inspection trains under consideration. The line Utrecht Central station – Amsterdam Central station – Alkmaar (see Figure S4) is, in this case, used because of its dual character. It is a busy line with multiple parallel tracks between Utrecht and Zaandam but it also contains a ‘standard’ track layout of two parallel tracks between Zaandam and Alkmaar. The track layouts at Utrecht and Amsterdam are complex with many switches and platform tracks. Yet the track layout between Zaandam and Alkmaar is more simple with two tracks going in opposite directions and several turnouts to overtake tracks at (intermediate) stations.

The network build for the models uses extracted data from EB-ViCoP (track layout, contract) and infrastructure maps provided by ProRail (distances). Nine maps split the line into smaller track sections, which are necessary to make calculations possible within a reasonable time-frame.

Figure S4: line used in MATLAB routing models

The complete network consists of two layers: layer one includes all links representing the tracks with their unique characteristics. Layer two only contains the positions where a measurement train can change direction (signals and buffer stops). On this second layer the actual routing by the models takes place (see Figure S5).

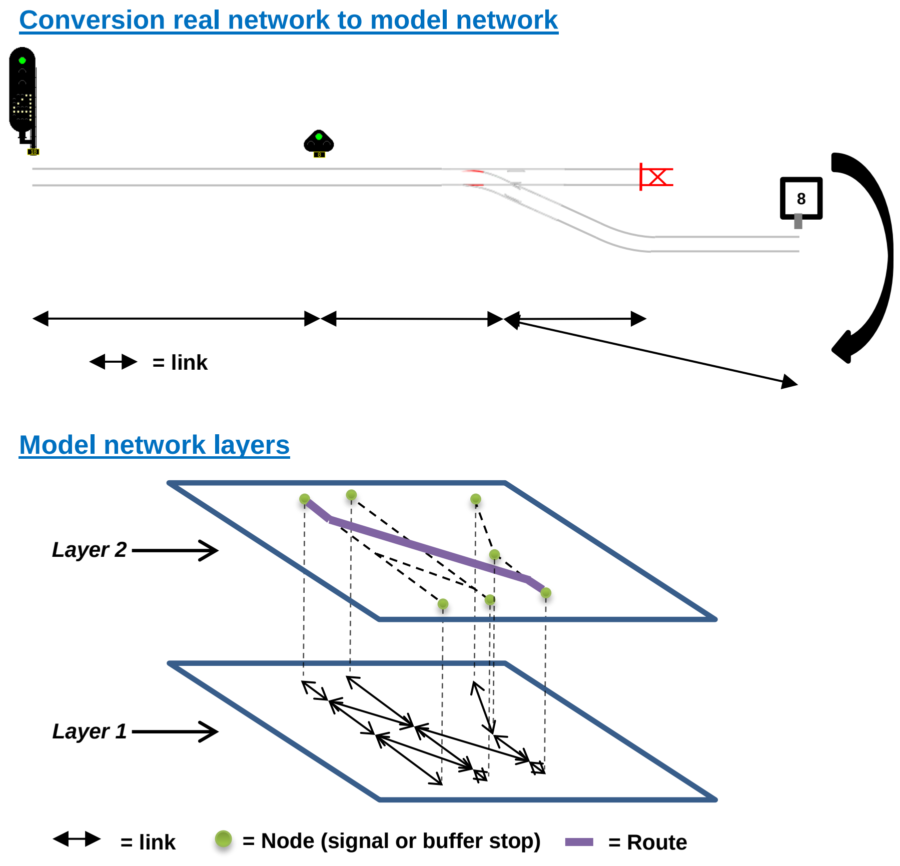


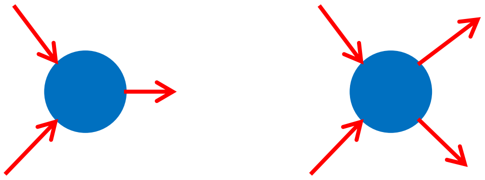
Figure S5: Network setup for routing models

The models also require additional input such as the inspection train for which the optimal path must be found. By selecting the train, the contractual tracks to be measured, as well as train characteristics such as maximum measurement speed and required turnaround times, are loaded.

Both models find an efficient path according to a routing philosophy. Model 1 uses the ‘yards first’ philosophy in which the inspection train covers a yard at a larger (intercity) station first, before continuing to the next station via an open track. The advantage of this method is that when the station is passed in a later run it does not matter which track is used. Model 2 routes the trains according to the philosophy of ‘corridor routing’: an inspection train first measures a corridor completely before continuing to the next corridor. The line considered in the models includes two corridors: Utrecht – Amsterdam and Amsterdam – Alkmaar. The advantage of this second method is that the routing is focused on one corridor at a time, decreasing the risk of missing track sections.

The primary assumptions and limitations of both models are that the network is free of other train traffic, optimization takes place on each map instead of over the whole line at once and that all tracks are undirected.

The path finding process starts with an assignment map, distilling a list of routes that need to be driven to measure the tracks that need to be inspected in the contract. Each of these routes may be travelled once, regardless the driving direction. All nodes in this list (representing signals and buffer stops) need to be even: they must be connected with an even number of routes to create a path, see Figure S6. Odd nodes are coupled together using a minimization process: the shortest paths connecting these odd nodes are selected, minimizing the overall distance to be driven. The routes in these paths are added to the list of routes to be driven.



Odd node:
2 ingoing routes
1 outgoing route

Even node:
2 ingoing routes
2 outgoing routes

If every route (red arrow) may be used once, the path through the odd node stops in the node the second time it is passed. There is no route available anymore to leave the node. When another outgoing route is added, this problem is solved and the path can continue (even node).

Figure S6: Explanation odd node problem

The final step in the path creation process is connecting all routes in the list into one path, which is done by an algorithm derived from an Euler tour creation process. In this process of coupling the selected routes into one path, the algorithm takes into account the driving direction on the current route when it chooses the next route in the path. Using this procedure the number of direction changes is minimalized reducing the required train running times. After completion of this last step the route is drawn on the map and the running time is estimated. The latter process is a straightforward method in which the track length is divided by the driven speed.

Calibration could only be done for the ‘yards first’ model at Amsterdam Central station. The trains under consideration are not planned using one of the studied routing philosophies, but the video-capturing trains use a ‘yards first’ method to inspect the tracks at Amsterdam Central station. Therefore calibration is done using a video-capturing train routebook. The result is that the path found by the model is 8% more efficient as the original path, but underestimates the train running time by approximately 10%. As a result, a supplement of 10% is added to the calculated train running times of the models, to compensate for accelerations/decelerations.

The outcomes of both models revealed that the theoretical mean efficiency ratio over the whole line is approximately 70% for the ‘yards first’ principle and approximately 67% for the ‘corridor’ principle, see Table S1. At large stations the theoretical efficiencies are the worst (approximately 40%); the best open track reaches 100% efficiency. One remarkable aspect is the inferior performance of the ‘yards first’ model on the yards compared with the ‘corridor routing’ model. The opposite is the case on the open tracks. The former can be explained by the larger number of transport kilometers required in the ‘yards first’ method to couple all tracks to be inspected at yard. The latter can be explained by the allowance to change direction on an open track in the ‘yards first’ model, saving transport kilometers in case of changing direction only at a station.

Table S1: Efficiency ratios reached in models

		'Yards first' model		'Corridor' model	
		Efficiency ratio		Efficiency ratio	
Map	Name	**UFM120**	**UST96 / UST02**	**UFM120**	**UST96 / UST02**
1	Utrecht	35.09%	39.87%	50.78%	48.67%
2	Utrecht-Amsterdam	84.41%	84.97%	73.60%	74.08%
3	Amsterdam	38.63%	49.12%	45.76%	50.75%
4	Amsterdam-Zaandam	58.03%	58.57%	58.03%	58.57%
5	Zaandam	56.97%	54.59%	67.86%	59.07%
6	Zaandam-Uitgeest	91.69%	91.69%	54.15%	54.15%
7	Uitgeest	49.22%	48.48%	79.17%	58.96%
8	Uitgeest-Alkmaar	100.00%	100.00%	100.00%	100.00%
9	Alkmaar	39.89%	73.52%	39.89%	73.52%
	Overall	70.61%	70.72%	67.17%	66.19%
	Corridor Utrecht-Amsterdam	-	-	68.35%	67.84%
	Corridor Amsterdam-Alkmaar	-	-	65.46%	63.90%

Regarding the estimated train running times, the 'corridor routing' model outperforms the 'yards first' model due to the lower number of direction changes required. A direction change costs at least 5 minutes which can be saved when reducing its occurrences. Estimated running times show that it is not possible to cover all inspection tracks on this line in one shift (assuming a maximum shift length of 10 hours).

Converting the outcomes into realistic situation will result in lower efficiency ratios and higher running times, due to other train traffic, lower number of possible routings and the impossibility of changing direction at every signal as is allowed in the models.

Efficiency improvement recommendations

To answer the main research question about how an annual efficiency improvement can be established, recommendations are made in two categories: recommendations studied and recommendations not studied in detail. In the former category suggestions are included that can be directly related to the current performance analysis or the developed models. The latter category contains suggestions that cannot be related to the analysis or models but are identified during this research. In the studied recommendations category, another division is made between the recommendations Eurailscout can initiate and those where Eurailscout is depending on other parties. The exact effects all recommendations could have are difficult to determine due to the complex processes in the railway operation environment.

In the studied recommendations category with suggestions Eurailscout can initiate, the routing philosophies as tested in the models can be applied. Compared with the current planned and realized mean efficiency ratios, the models' results improve the ratios by approximately 15% - 20%. The calibration showed an improvement of 8% to an actual path. It is therefore estimated that the model results improve the current mean efficiency ratios by 5%-10%. Furthermore, it is estimated that this recommendation saves 5% on deployments. Before implementation, further research is necessary to extend the model with, for example, track inspection frequencies. In addition, another overall model is needed to determine in which (optimal) sequence lines need to be measured.

Eurailscout line closures may help to guarantee track availability, especially now the Dutch railway network is utilized more intensively. Measuring with multiple trains at the same time combined with manual ultrasound inspections, increase the return on investment.

If Eurailscout can further improve the reliability of their high-tech but ‘sensitive’ measurement systems, mean efficiency ratio improvements of 2%-4% are possible. It will also save on the number of deployment days: an estimated 20% on remeasurement deployments.

In the second subcategory of improvements that have been studied (in which Eurailscout is depending on other parties), Eurailscout can, among other things, request priority over other trains. It will decrease the chance of deviations from planned inspection paths. Although the estimated effects on the efficiency ratios are small (0.1%-1.5%), the savings on deployment days can be substantial: an estimated 20% of remeasurement deployments.

Recommendations that have not been studied in detail were identified during execution of this research at the office, but cannot directly be related to the analysis of the current efficiency or developed models. In this category, improvements could be made by working in shifts, and thus coupling measurement deployments together. This saves on the number of required inspection runs. A requirement is to make the train crews able to operate on multiple inspection trains. A disadvantage of this recommendation is the increase in labor costs. Therefore a trade-off is necessary to determine whether the investment costs outweigh the benefits.

Increasing the number of parking locations (as shown in Figure S7) saves on transport time and kilometers back to the depot in Amersfoort. Currently in most cases the trains return to Amersfoort at the end of an inspection run because of the facilities there. If more parking locations can be used, a reduction in ‘transport’ movements can be established and the time saved can be used for measurements instead. To develop more of these parking locations is a request Eurailscout has to make at ProRail.

Figure S7: Eurailscout UFM120 and Strukton engine ‘Carin’ parked at Rotterdam CS

Combining all possible improvements results in a list of recommendations that could help Eurailscout increase their efficiency. Analysis of the estimated improvements that can be established by these recommendations showed that it is possible to decrease the annual deployments, at least in the first year. In subsequent years it becomes harder to improve further, due to the good current performance.

Conclusions and recommendations for further research

To answer the research question as to how annual efficiency improvements can be established in the planning and execution of the measurements by Eurailscout trains, efficiency improvements are possible in several ways and at several locations in the processes. The current efficiency of the measurements is good, making annual improvements difficult to realize. The recommendations presented may help to improve in at least the first year of application but then the gain will decrease in subsequent years. Both of the routing models that have been developed can be used as a basis to look at where further improvements can be sought or to route the inspection trains efficiently on closed lines.

Due to the complexity of the problem as studied, not all elements could be studied in as much detail as possible. In the current efficiency analysis, a more detailed study into the causes for disturbances may be necessary to, for example, determine whether disturbances which seem to have a cause in the realization phase are actually caused by a problem in the planning or scheduling phase.

Both routing models could be further improved by inserting track inspection frequencies or a better method to interconnect the odd nodes. Introducing an algorithm capable of assessing the complete line instead of the maps individually may further increase the results, but also require a substantially longer calculation time.

The effects of the efficiency improvement recommendations are roughly estimated due to the complex railway operation processes. Before implementation of the recommendations another study is necessary to determine the precise effects, the implementation costs involved and whether the benefits outweigh the costs.

Finally
Inspections of track and safety systems are and will remain extremely important for the safety level of rail transportation, especially with the growing demand in rail transport. Eurailscout provides their customers with details about the current state of their network. Efficient planning and execution of the inspections cause less hindrance to other rail traffic. This research helps Eurailscout to attain the targets they have set and to improve their efficiency on both the busy Dutch railway network and for other (international) customers on foreign railway networks.

Samenvatting

Inspecties van het spoor zijn nodig om de veiligheid en kwaliteit van het spoornetwerk te kunnen waarborgen. Tot een paar decennia geleden werden de meeste inspecties met de hand uitgevoerd. Een serie incidenten gecombineerd met strengere ARBO regelgeving, maken handmatig uitgevoerde metingen binnen in dienst zijnde sporen in Nederland nagenoeg onmogelijk. Als oplossing zijn meettreinen geïntroduceerd.

Eurailscout Inspection & Analysis is een internationaal opererend meettreinbedrijf dat klanten voorziet van gegevens over de actuele staat van hun spoorwegnetwerk. Allerlei soorten gegevens kunnen worden vastgelegd met de Eurailscout meettreinen: van railslijtage (zowel extern als intern) tot de werking van het treinbeveiligingssysteem en van videobeelden tot slijtage van de bovenleiding. Om deze metingen te kunnen uitvoeren bevat het materieelpark van Eurailscout onder andere geometrie meettreinen, ultrasoon inspectietreinen en videoschouwtreinen (zie de voorpagina voor een afbeelding van een groot deel van het materieelpark). Eurailscout analyseert de verzamelde ruwe meetdata en zet deze om in een formaat dat naar de klant gestuurd kan worden. Met deze gegevens kan onder andere het spooronderhoud worden gepland of de slijtagekarateristieken van het spoor over tijd worden bepaald. De vastgelegde videobeelden kunnen ook gebruikt worden voor het opleiden van machinisten.

Probleemstelling
Het meest recente contract tussen Eurailscout en ProRail bevat de voorwaarde dat Eurailscout zijn meetritefficiëntie jaarlijks moet verbeteren met een vastgesteld percentage. Eurailscout is hiermee akkoord gegaan met het oog op CO_2 uitstoot reductie en hun streven naar interne efficiëntie verbetering. ProRail heeft deze voorwaarde geïntroduceerd vanwege het groeiende treinverkeer op het Nederlandse spoorwegnet. Met name wanneer de plannen van de overheid om ‘PHS’ (Programma Hoogfrequent Spoor) te introduceren met als gevolg dat trajecten nog intensiever gebruikt zullen worden, zal er minder ruimte op het spoor beschikbaar zijn bedrijven als Eurailscout.

Extra moeilijkheidsgraad voor Eurailscout is dat de meettreinen specifieke planningskenmerken en benodigdheden hebben, zoals de maximale meetsnelheid, minimale keertijden en de noodzaak om specifiek die sporen te rijden die gepland zijn. Door deze kenmerken is het plannen en ontwerpen van de meettreindienstregelingen een uitdaging.

De hoofdonderzoeksvraag in dit masteronderzoek is daarom:
Hoe kan een jaarlijkse efficiency verbetering in de planning en uitvoering van metingen door Eurailscout meettreinen worden behaald, rekening houdend met de beperkingen van de treinen, het spoor en de treindienstregeling?

ProRail meet Eurailscouts efficiëntie in het aantal dagen dat Eurailscout nodig heeft om alle contractueel overeengekomen sporen te meten. Intern meet Eurailscout het eigen prestatieniveau aan de ratio van gemeten kilometers spoor in een inzet gedeeld door het totaal aantal gereden kilometers spoor in diezelfde inzet(minimale ratio 0.0, maximale ratio 1.0). Beide weergaven van efficiëntie zijn gerelateerd aan elkaar: een reductie van het efficiëntieratio gebruikt door Eurailscout, verhoogt de dagelijkse productie waardoor minder inzetdagen nodig zijn. Reden waarom in dit onderzoek beide weergaven zijn gebruikt.

Niet alle meettreinen zijn beschouwd in dit onderzoek. De treinen weergegeven in Afbeelding S1 zijn geselecteerd omdat zij de belangrijkste metingen uitvoeren en veel inzetten in Nederland hebben. Uitdaging van beide ultrasoontreinen is dat zij een meetsnelheid hebben van 60 km/u. De UFM120 kan meten met een snelheid van 110km/u en kan daardoor gemakkelijker tussen de gewone treinenloop in worden gepland.

Daarnaast heeft de UST96 een wagon nodig voor een goede detectie van de trein. Deze wagon moet altijd gekoppeld zijn aan de achterkant van de trein, kijkend in de rijrichting. Indien de trein moet keren, dient het meetrijtuig om de wagon heen te rijden, wat een lange keertijd tot gevolg heeft. De andere Eurailscout treinen blijven buiten beschouwing in dit onderzoek omdat zij té specifieke planningskenmerken hebben.

Universele meettrein *UFM120* (o.a. geometrie, bovenleiding) | Ultrasoon inspectietrein *UST96* *(o.a. interne spoorstaafdefecten)* | Ultrasoon inspectietrein *UST02* *(o.a. interne spoorstaafdefecten)*

Afbeelding S1: In dit onderzoek beschouwde meettreinen

Literatuurstudie

Uit de literatuurstudie is gebleken dat weinig openbaar onderzoek is verricht naar de planning van meettreinen. Gevonden studies bevatten geringe informatie over de gebruikte methoden, maar wijden vooral uit over de behaalde resultaten. Daarom is verder gezocht naar vergelijkbare studies. Het ontwerpen van een meettreinpad kan worden vergeleken met het ‘Chinese Postman Problem’ (CPP), wat een variant is op het bekende ‘Travelling Salesman Problem’. In een CPP moet een postbode alle straten af om post te bezorgen, in een route die zo min mogelijk kost (bijvoorbeeld in tijd of afstand) en zo min mogelijk straten twee keer doorkruist. Verschillende oplossingsmethoden bestaan, variërend van eenvoudig tot complex. Vrijwel alle algoritmes zijn echter gebaseerd op een ‘branch-and-bound’ technieken. De gebruikte netwerken kunnen volledig gericht zijn (alleen maar éénrichtingsstraten), ongericht of gemixte varianten. Uitkomsten van de studies zijn veelbelovend en de toegepaste netwerkontwerpen zijn gebruikt voor de routeringsmodellen ontwikkeld binnen dit onderzoek.

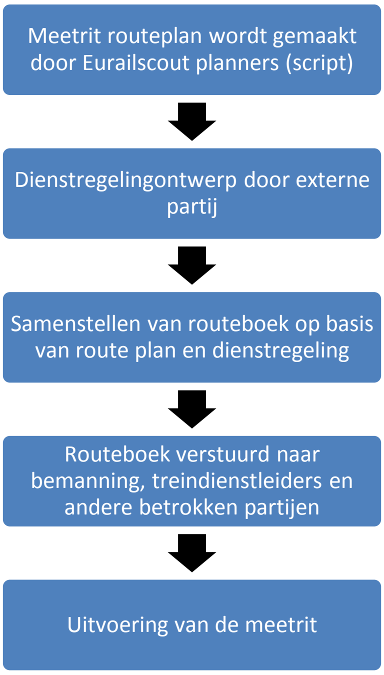
Huidige processen

De inspectieritten worden gepland door het bedrijfsbureau van Eurailscout. De planners maken gebruik van in huis ontwikkelde software (EB-ViCoP) om de meettrein paden te ontwerpen die alle sporen meten zoals afgesproken met de klant. De frequentie waarmee sporen worden gemeten is variabel, afhankelijk van de intensiteit van het treinverkeer en het getransporteerde tonnage over het desbetreffende stuk spoor. Europese normen bepalen de inspectiefrequenties en moeten zorgen voor een veilig en betrouwbaar spoor.

Momenteel worden de inspectieroutes heuristisch ontworpen gebaseerd op de contractafspraken, kennis van de planners en ervaringen uit eerdere ritten. Er is geen automatisch routeringssysteem. De ritten worden gepland op een netwerk vrij van ander treinverkeer, maar met hun kennis en ervaring proberen de planners wel alvast rekening te houden met het overige treinverkeer, bijvoorbeeld door de meettrein niet te laten keren op een perronspoor.

Voor het ontwerpen van meetritdienstregelingen maakt Eurailscout gebruik van een externe partij. Een routeontwerp bevat de route zoals de planners willen dat hij wordt gereden. De externe partij ontwerpt op basis van dit document een dienstregeling, die vervolgens naar de Eurailscout planners wordt verzonden. Zij maken van het routeontwerp en de dienstregeling een routeboek, waarin met kleurmarkering op spoorniveau staat aangegeven welke secties gemeten moeten worden.

Dit routeboek wordt vervolgens verstuurd naar de treinbemanning, treindienstleiders en andere partijen die op de hoogte dienen te zijn van de meetrit. Afbeelding S2 presenteert dit proces schematisch.



Afbeelding S2: Planning keten van een meetrit

Tijdens dit afstudeeronderzoek werd het oude planningssysteem ‘VPT’ (Vervoer Per Trein) zoals dat werd gebruikt door de externe partij om de dienstregeling te ontwerpen, vervangen door het nieuwe systeem ‘DONNA’. Efficiëntie verbetering voorstellen zijn in dit onderzoek echter nog gebaseerd op het oude VPT, omdat DONNA geleidelijk is ingevoerd en het nog enige tijd vergt voordat het volledig geïmplementeerd en operationeel is.

Huidige prestatieanalyse Eurailscout
Een analyse van de huidige prestatie van Eurailscout is uitgevoerd op de geplande en uitgevoerde inspectieritten in 2011 en de eerste helft van 2012. Deze analyse is gebaseerd op het efficiëntieratio zoals intern gebruikt bij Eurailscout: de gemeten afstand in een inzet gedeeld door de totaal gereden afstand in die inzet. Deze waarde maakt het mogelijk om de geplande en gerealiseerde prestaties treinspecifiek alsook tussen de treinen te vergelijken. Uit deze analyse kan de conclusie worden getrokken dat alle drie de beschouwde treinen al goede efficiëntieratio’s laten zien, gelet op het drukke Nederlandse spoorwegnet. Het vergelijken van de geplande efficiëntieratio’s met de gerealiseerde ratio’s, liet zien dat er een verschil is tussen beide (gerealiseerde ratio’s die lager zijn dan gepland) maar dat de verschillen in de meeste gevallen niet significant zijn.

De gerealiseerde efficiëntieratio’s zijn voor alle drie de meettreinen lager wat wordt veroorzaakt door verstoringen in de uitvoeringen van de metingen. Significante verschillen tussen de treinen onderling kunnen worden verklaard door de manier waarop de treinen worden ingezet. Treinen gebruikt om enkelsporige baanvakken te meten hebben een lagere efficiëntie dan de meettreinen ingezet op meersporige baanvakken. Op een enkelsporig baanvak kan immers alleen op de heenweg alles gemeten worden, op de weg terug hoeft er dan niets meer gemeten te worden.

De gerealiseerde efficiëntieratio’s zijn voor alle treinen lager dan de geplande ratio’s, veroorzaakt door verstoringen in de uitvoering van de metingen. Het wel of niet meetellen van her-metingsinzetten waarin stukken spoor die niet in de oorspronkelijke rit konden worden gemeten alsnog worden gemeten, beïnvloedt de resultaten niet significant. Hoewel de verschillen tussen planning en uitvoering niet substantieel zijn kunnen de door verstoringen beïnvloede afstanden substantieel zijn. Reden waarom verder onderzoek is gedaan naar de oorzaken van verstoringen.

Op de planningsafdeling van Eurailscout houdt men gedetailleerde (treinspecifieke) uitvallijsten bij waarin staat aangegeven welke stukken spoor zijn gemist, de oorzaak daarvan en de verantwoordelijke partij aangevuld met de contractuele termijn waarbinnen dit deel opnieuw gemeten dient te worden. Met behulp van deze lijsten kunnen de planners bepalen in welke meetritten gemiste stukken spoor kunnen worden herpland.

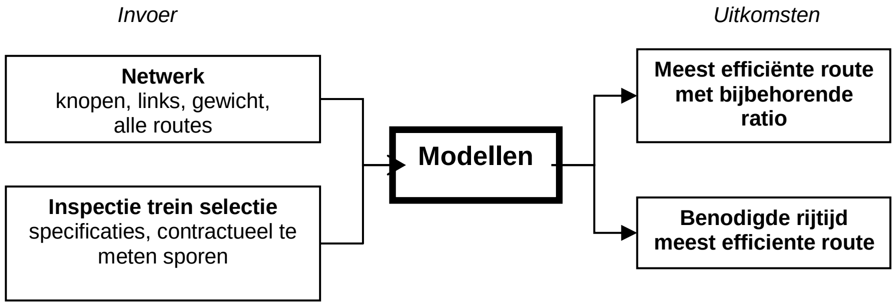
Uit analyse van deze lijsten blijkt dat de oorzaken van verstoringen divers zijn: van treindienstleiders die verkeerde rijwegen instellen tot storingen in de meetsystemen en van onvoorziene omstandigheden als seinstoringen tot sporen die bezet zijn door andere treinen. Hetzelfde geldt voor de verantwoordelijke partijen: van Eurailscout zelf tot treindienstleiders en van de externe dienstregeling ontwerpers tot verstoringen die niet aan een partij kunnen worden gekoppeld (zoals weersomstandigheden). In deze analyse zijn diverse mogelijke verbeteringen vastgesteld. Deze zullen verderop in de samenvatting worden toegelicht.

Routeringsmodellen

Omdat uit de analyse van de huidige efficiëntie bleek dat er geen significante verschillen bestaan tussen de planning en uitvoering, is hiernaar verder geen onderzoek verricht. Het onderzoek heeft zich in plaats daarvan gericht op efficiëntieverbeteringen in de manier waarop meetritroutes worden ontworpen. Hiervoor zijn twee routeringsmodellen ontwikkeld in het softwarepakket MATLAB.

Er bestaan verschillende routeringsfilosofieën waarmee inspectieroutes kunnen worden ontworpen. Voorbeelden zijn: ‘lange lijnen’ (lange continue routes over verschillende trajecten met zo min mogelijk keringen), het rijden van trajecten (het geheel meten van één traject voordat wordt verdergegaan met het volgende traject) of de ‘emplacementen eerst’ methode waarin een emplacement op een station volledig wordt gemeten voordat de meettrein verder rijdt naar het volgende station. Elke methode heeft zijn voor- en nadelen. Momenteel bepalen de planners door middel van heuristiek de meetroutes, daarbij gebruik makend van kennis en ervaringen van eerdere ritten. Gecreëerde routes kunnen het best worden vergeleken met de filosofie ‘meten van lange lijnen’, maar lokaal zijn ook invloeden van andere filosofieën terug te vinden. De routeringsfilosofieën ‘trajecten’ en ‘emplacementen eerst’ zijn bestudeerd in de ontwikkelde modellen omdat zij het meest interessant zijn voor Eurailscout.

Doel van de modellen is om vast te stellen of een meer systematische aanpak van het routeontwerpproces de efficiëntieratio’s kan verbeteren. Uitkomsten van de modellen moeten daarom de gereden route, de behaalde efficiëntie en de benodigde rijtijd bevatten, zie Afbeelding S3.



Afbeelding S3: Invoer en uitkomsten van de routeringsmodellen

Beide modellen hebben een netwerk nodig waarop de meest efficiënte (hoogste efficiëntieratio) route moet worden gevonden voor de geselecteerde meettrein. De lijn Utrecht Centraal station – Amsterdam Centraal station – Alkmaar (zie Afbeelding S4) is hiervoor gebruikt vanwege zijn tweezijdige karakter. Het is een druk lijn met meerdere parallelle sporen tussen Utrecht en Zaandam maar het bevat ook een standaard spoor layout met twee parallelle sporen tussen Zaandam en Alkmaar. Het spoorontwerp op de stations van Utrecht en Amsterdam is complex met vele wissels en perronsporen, in tegenstelling tot het traject tussen Zaandam en Alkmaar wat bestaat uit slechts twee sporen met enkele inhaalsporen op (tussenliggende) stations.

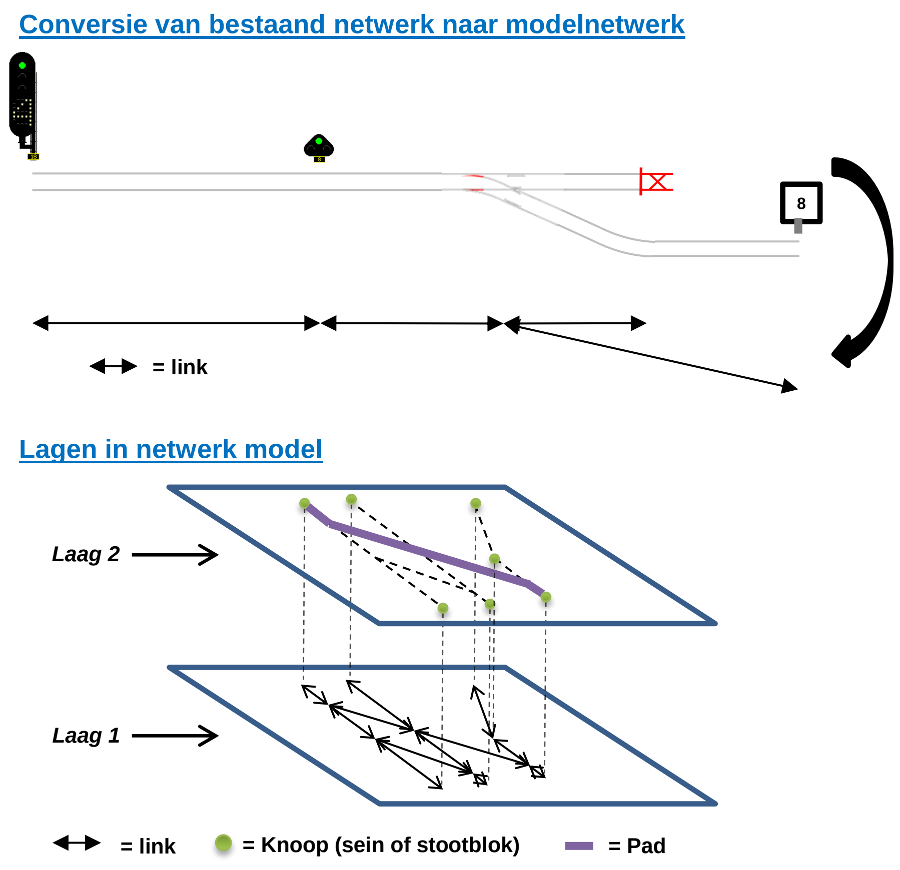
Afbeelding S4: Spoorlijn gebruikt in MATLAB routeringsmodellen

Het gebouwde spoornetwerk voor beide modellen gebruikt gegevens uit EB-ViCoP (spoorlay-out en contractueel te meten sporen) en infrastructuur tekeningen van ProRail (afstanden). De lijn is gesplitst in negen secties om berekeningen mogelijk te maken binnen acceptabele tijd. Het complete netwerk bestaat uit twee lagen: de eerste laag bevat links die spoorsecties met hun unieke kenmerken (max. snelheid, lengte, etc.) representeren. Laag twee bevat de posities van seinen en stootblokken: locaties waar een meettrein van richting kan veranderen (zie Afbeelding S5).

Andere invoer die de modellen nodig hebben is de selectie van een meettrein. Met het selecteren van een trein wordt het contract en de karakteristieken voor die trein in het model geladen.

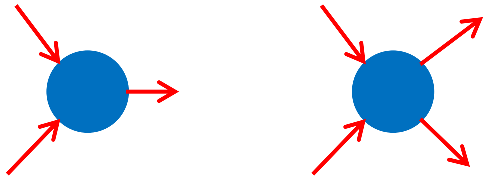
Beide modellen vinden een efficiënte route volgens een bepaalde routeringsfilosofie. Model 1 gebruikt de filosofie ‘emplacementen eerst’ waarin de inspectietrein eerst een emplacement van een station volledig meet alvorens via een baanvak verder te gaan naar een volgend emplacement. Voordeel van deze methode is dat wanneer in een latere rit het station gepasseerd moet worden, het niet uitmaakt welk spoor bereden wordt. Model 2 routeert de trein volgens de ‘traject’ routeringfilosofie: een inspectietrein meet eerst een traject volledig voordat verdergegaan wordt met een volgend traject. In het beschouwde netwerk bevinden zich twee trajecten: Utrecht – Amsterdam en Amsterdam – Alkmaar. Voordeel van deze filosofie is dat de metingen worden gefocust op één traject per keer waardoor het risico van het missen van spoorsecties afneemd.

Belangrijkste aannames en beperkingen in beide modellen zijn dat het netwerk vrij is van ander treinverkeer, optimalisatie per kaart plaatsvindt in plaats van over de gehele lijn ineens en dat alle sporen ongericht zijn (geen vaste rijrichting hebben). Gevolg is dat de uitkomsten puur theoretisch zijn.



Afbeelding S5: Netwerk setup in beide routeringsmodellen

Het routeringsproces start met een determinatiematrix, waarmee een lijst van paden die gereden moeten worden om de te meten sporen te rijden, gegenereerd wordt. Alle knopen in de geselecteerde paden moeten even zijn: elke knoop moet verbonden zijn met een even aantal paden om een route mogelijk te maken, zie Afbeelding S6.



Oneven knoop:
2 ingaande paden
1 uitgaand pad

Even knoop:
2 ingaande paden
2 uitgaande paden

Als elk pad (rode pijl) één keer mag worden gebruikt, stopt in het geval van de oneven knoop de route in de knop als deze voor de tweede keer wordt aangedaan. Er is geen uitgaand pad beschikbaar om de knoop te verlaten. Als een extra uitgaand pad wordt toegevoegd is dit probleem opgelost (even knoop)

Afbeelding S6: Toelichting oneven knopen probleem

Oneven knopen worden onderling verbonden door de kortste paden die deze knopen onderling verbinden, toe te voegen aan de eerder samengestelde lijst. De totaal te rijden afstand in het model wordt hiermee geminimaliseerd.

Laatste stap is het samenstellen van een route uit de lijst met paden, wat gebeurt met een algoritme afgeleid van het ‘Euler tour’ creatie proces. Dit algoritme houdt bij de keuze van het volgende pad uit de gegenereerde lijst, rekening met de rijrichting op het huidige pad. Hiermee wordt het aantal keringen geminimaliseerd zodat de benodigde rijtijden omlaag gaan. Nu de route is gecreëerd wordt deze getekend op de kaart en wordt de benodigde rijtijd bepaald. Het bepalen van de rijtijd gebeurt op eenvoudige wijze: de lengte van de spoorsectie wordt gedeeld door de maximaal snelheid van een meettrein.

Kalibratie kon alleen uitgevoerd worden voor het ‘emplacementen eerst’ model op Amsterdam Centraal station. De beschouwde treinen worden niet gepland volgens één van de bestudeerde routeringsmethoden, maar de videoschouwtreinen wél. Zij gebruiken een ‘emplacementen eerst’ methode om alle sporen op Amsterdam Centraal station te inspecteren. Resultaat van de kalibratie is dat het model een route creëert die circa 8% efficiënter is dan de bestaande route, maar de benodigde rijtijd onderschat met ongeveer 10%. Daarom worden de door de modellen berekende rijtijden vergroot met 10% om te corrigeren voor het optrekken en afremmen van de trein.

Resultaten van beide modellen laten zien dat de theoretische efficiëntie over de gehele lijn in het ‘emplacementen eerst’ model ongeveer 70% is en in het ‘traject routerings’ model ongeveer 67%, zie Tabel S1. Op grotere stations zijn de gerealiseerde efficiëntieratio’s het laagst (ongeveer 40%), de beste score wordt gehaald op een baanvak (100%). Opmerkelijk is de slechte prestatie van het ‘emplacementen eerst’ model op de emplacementen in vergelijking met het ‘traject’ routeringsmodel. Dit kan worden verklaard door het feit dat in het ‘emplacementen eerst’ model de trein meer transportkilometers moeten maken om alle te meten spoorsecties aan elkaar te koppelen.

Het tegengestelde is het geval op de baanvakken, wat wordt verklaard door het feit dat het in het ‘emplacementen eerst’ model is toegestaan om te keren op een baanvak. In het ‘traject’ routeringsmodel moet worden doorgereden naar het eerst volgende station om pas daar te keren, wat meer transport kilometers vergt en de efficiëntieratio’s naar beneden haalt.

Tabel S1: Gerealiseerde efficiëntieratio’s in routeringsmodellen

		‘Emplacementen eerst’ model		**‘Traject’ routeringmodel**	
		Efficiëntie ratio		Efficiëntie ratio	
Kaart	Naam	**UFM120**	**UST96 / UST02**	**UFM120**	**UST96 / UST02**
1	Utrecht	35.09%	39.87%	50.78%	48.67%
2	Utrecht-Amsterdam	84.41%	84.97%	73.60%	74.08%
3	Amsterdam	38.63%	49.12%	45.76%	50.75%
4	Amsterdam-Zaandam	58.03%	58.57%	58.03%	58.57%
5	Zaandam	56.97%	54.59%	67.86%	59.07%
6	Zaandam-Uitgeest	91.69%	91.69%	54.15%	54.15%
7	Uitgeest	49.22%	48.48%	79.17%	58.96%
8	Uitgeest-Alkmaar	100.00%	100.00%	100.00%	100.00%
9	Alkmaar	39.89%	73.52%	39.89%	73.52%
	Over gehele lijn	70.61%	70.72%	67.17%	66.19%
	Traject Utrecht-Amsterdam	-	-	68.35%	67.84%
	Traject Amsterdam-Alkmaar	-	-	65.46%	63.90%

Geschatte rijtijden in beide modellen laten zien dat het ‘traject’ routeringsmodel beter presteert dan het ‘emplacementen eerst’ model als gevolg van het lagere aantal benodigde keringen. Een kering kost minimaal 5 minuten die kunnen worden uitgespaard als het aantal keringen kan worden gereduceerd. De rijtijden laten zien dat het niet mogelijk is om alle te meten sporen te rijden in één shift (aannemende dat een shift maximaal 10 uur duurt). Omzetten van de uitkomsten naar de werkelijke situatie zal resulteren in lagere efficiëntie ratio’s en hogere rijtijden vanwege ander treinverkeer, minder paden die gereden kunnen worden en de onmogelijkheid om bij elk sein van richting te veranderen zoals wel is toegestaan in de modellen.

Efficiëntieverbetering aanbevelingen

Om de hoofdonderzoeksvraag (*Hoe kan een jaarlijkse efficiency verbetering in de planning en uitvoering van metingen door Eurailscout meettreinen worden behaald, rekening houdend met de beperkingen van de treinen, het spoor en de treindienstregeling?*) te beantwoorden zijn er aanbevelingen gedaan in twee categorieën: bestudeerde en niet in detail bestudeerde aanbevelingen. De eerste categorie bevat suggesties die direct gerelateerd zijn aan de huidige prestatieanalyse of de ontwikkelde modellen. In de tweede categorie zijn suggesties opgenomen die hieraan niet gerelateerd kunnen worden. Binnen de eerste categorie wordt verder onderscheid gemaakt in aanbevelingen die Eurailscout kan uitvoeren en aanbevelingen waarin zij qua uitvoering afhankelijk is van andere partijen. De exacte effecten die de aanbevelingen hebben zijn lastig te bepalen door de complexe samenhang van processen binnen de spoorwereld.

In de eerste categorie met bestudeerde aanbevelingen die Eurailscout kan uitvoeren wordt aanbevolen om (één van) de onderzochte routeringsmodellen te implementeren om het creëren van routes op een meer systematische manier te laten plaatsvinden. Vergelijkingen met de huidige gemiddelde geplande efficiëntieratio’s laten zien dat de modellen een verbetering realiseren van circa 15% - 20%. De kalibratie toont een winst van circa 8%. Geschat is dat implementatie 5%-10% verbetering in de efficiëntieratio’s teweeg brengt en circa 5% op de inzetdagen zal besparen. Voordat de modellen worden geïmplementeerd in het planningsproces, is verder onderzoek nodig waarin het model wordt uitgebreid met bijvoorbeeld de meetfrequenties van sporen. Ook is een ander model nodig dat bepaalt in welke volgorde lijnen gemeten moeten worden.

‘Eurailscout buitendienststellingen’ kunnen helpen om de beschikbaarheid van sporen voor metingen te garanderen, zeker nu het Nederlandse spoorwegnet steeds intensiever gebruikt wordt. Door met meerdere meettreinen en/of de ultrasoon handmeetploegen gebruik te maken van dezelfde buitendienststellingen wordt het resultaat van de investering in deze verbetering vergroot.

De meetsystemen aan boord van de treinen zijn hightech maar ook gevoelig voor storingen. Als Eurailscout de betrouwbaarheid van deze systemen verder kan verbeteren, kan een efficiëntiewinst van 2%-4% worden behaald. Daarnaast bespaart dit circa 20% van de hermetinginzetten.

In de tweede subcategorie van bestudeerde aanbevelingen (waarin Eurailscout afhankelijk is van andere partijen) kan Eurailscout bij ProRail voorrang aanvragen over andere treinen. Tot nu toe heeft het overige treinverkeer waardoor stukken te meten spoor gemist worden. Hoewel de effecten op de efficiëntieratio’s klein zijn (0.5%-1.5%), zullen de besparingen op inzetten substantieel zijn: circa 20% van de hermetinginzetten komt hiermee te vervallen.

Niet in detail bestudeerde aanbevelingen zijn vastgesteld gedurende het onderzoek uitgevoerd op kantoor. Een aanbeveling in deze categorie is bijvoorbeeld het werken in shifts door meetritten aan elkaar te koppelen, wat inzetdagen zal uitsparen. Voorwaarde hierbij is wel dat de treinbemanning op meerdere meettreinen kan werken. Een nadeel is dat dit voorstel meer arbeidskosten met zich meebrengt. Hierom is een economische afweging nodig om vast te stellen of de investeringen opwegen tegen de te verwachten opbrengsten.

Het vergroten van het aantal stallingslocaties (zie bijvoorbeeld Afbeelding S7) waar de meettreinen kunnen staan na hun dienst is een andere optie. Hiermee zal het aantal transport ritten terug naar Amersfoort en de benodigde tijd daarvoor, afnemen. Momenteel keren de meettreinen meestal terug naar de thuisbasis Amersfoort vanwege de faciliteiten die daar op het emplacement aanwezig zijn. De tijd die bespaard wordt door niet terug te rijden naar Amersfoort kan worden besteed aan het uitvoeren van metingen.

Afbeelding S7: Eurailscout UFM120 en Strukton loc 'Carin' geparkeerd op station Rotterdam CS

Alle aanbevelingen samen kunnen Eurailscout helpen om de efficiëntie te verhogen. Uit analyse van de geschatte effecten die de genoemde aanbevelingen zullen hebben, blijkt dat het mogelijk is om de efficiëntie te verbeteren.

Conclusies en aanbevelingen voor verder onderzoek

Antwoord op de onderzoeksvraag hoe een jaarlijkse efficiëntieverbetering in de planning en uitvoering van de metingen door Eurailscout treinen kan worden bereikt, is dat verbeteringen op diverse manieren en op verschillende locaties in de processen mogelijk zijn. De huidige prestaties van de meettreinen zijn al goed wat het lastig zal maken om jaarlijks verder te verbeteren met een vast percentage. De gepresenteerde aanbevelingen kunnen helpen daadwerkelijk progressie te boeken, in ieder geval in het eerste jaar dat de verbeteringen worden toegepast. Echter de behaalde progressie zal per jaar afnemen. Beide ontwikkelde routeringsmodellen kunnen hierbij dienen als basis waarvandaan verdere verbeteringen ontwikkeld kunnen worden of ze kunnen worden gebruikt om de treinen te routeren op buitendienst gestelde sporen.

Vanwege de complexiteit van het onderzochte probleem en het grote aantal factoren dat van invloed is op het probleem, konden niet alle onderdelen even goed worden onderzocht als wenselijk. Voor meer inzicht in de exacte oorzaken van verstoringen is het nodig een meer gedetailleerd onderzoek te verrichten, bijvoorbeeld om vast te stellen of verstoringen die een oorzaak lijken te hebben in de realisatiefase, eigenlijk worden veroorzaakt door problemen in de planning of dienstregeling ontwerpfase.

Beide routeringsmodellen kunnen verder worden verbeterd door het toevoegen van de spoorinspectiefrequenties of door het verder verbeteren van de methode om oneven knopen aan elkaar te koppelen. Het ontwikkelen van een algoritme dat de gehele lijn in één keer beschouwd in plaats van per kaart kan de behaalde resultaten verder verbeteren. Nadeel is wel dat dit nadelige gevolgen heeft voor de berekeningstijd.

De effecten van de gepresenteerde aanbevelingen zijn grof geschat vanwege de complexe samenhangende processen in de spoorwereld. Voordat de aanbevelingen worden uitgevoerd is nadere studie noodzakelijk om de exacte effecten vast te stellen. Ook moet beoordeeld worden of de investeringen opwegen tegen de te behalen efficiëntie winst.

Tot slot

Inspecties van het spoor en het spoorbeveiligingssysteem zijn en blijven van groot belang voor een veilig spoornetwerk, zeker met de verdere groei in het railtransport. Eurailscout voorziet haar klanten van gedetailleerde informatie over de huidige staat van het spoor in hun netwerk. Efficiënt meten van dit netwerk zorgt voor zo min mogelijk hinder voor het overige treinverkeer. Dit onderzoek helpt Eurailscout in het vinden van verbeteringen in de efficiëntie van de metingen en het behalen van de gestelde doelen. Dit geldt voor zowel het druk bereden Nederlandse spoorwegnet als voor spoornetten van buitenlandse klanten.

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1 Introduction

To guarantee the quality and safety level of a railway network, inspections of the track (especially superstructure) are necessary. These inspections include measurements on track geometry, internal rail defects, running surface defects, overhead wire/rail wear and measurements on the functioning of railway safety systems.

Until a few decades ago track inspections were carried out by hand. A crew of workman executed the inspections alongside or in the tracks which were most of time still in service. Due to a number of incidents related to workmen working in and alongside the tracks, more stringent rules in the field of health and safety regulations and the increasing train traffic, manual track inspections became impossible. Over the years 2000 till 2010 the number of track maintenance personnel injured in the Netherlands reduced from seven to one [1], among others the result of the more stringent health and safety regulations. As a solution for the inability to measure tracks manually, measurement trains were introduced. The Dutch national railway company NS (Nederlandse Spoorwegen) already used for several years two measurement trains: an ultrasound inspection train and a train for monitoring the safety system ATB.

1.1 Eurailscout Inspection & Analysis

In 2000 the company Eurailscout Inspection & Analysis was founded. It originated from the NS-measurement department and two contractors. Eurailscout Inspection & Analysis b.v. provides inspections with its own fleet of measurement and inspection trains on the Dutch railway network on authority of the infrastructure provider ProRail. Furthermore measurements are executed on behalf of KeyRail (Betuweroute) and Infraspeed (HSL). Apart from the Netherlands, Eurailscout has other European countries in its work field. The company has two offices: the main office in Amersfoort the Netherlands where contract development, train and personnel (re)scheduling, measurement run preparation and data analysis take place. In the second office in Berlin, Germany the technical development department is housed.

Services

In an inspection run data about the driven track are collected. Among others these data consists of track geometry measurements, (internal) rail defects, rail/overhead wire wear and (high resolution) video capturing. To execute all these measurements Eurailscout possesses several dedicated inspection trains. Most of the rolling stock is diesel powered to make working on non-electrified tracks or foreign countries with different overhead wire voltages, possible. Table 1 presents data about Eurailscouts current rolling stock, while Figure 1 shows a picture of a large part of the rolling stock.

Apart from trains, Eurailscout has a team of employees that use hand-held ultrasound equipment. This team checks the points/faults found by the ultrasound inspection trains more precisely and assess the severity of the rail damage. Furthermore they perform ultrasound measurements on switches and rails on constructions like bridges. At these locations the ultrasound inspection train cannot measure with sufficient accuracy due to technical limitations.

Table 1: Data of rolling stock Eurailscout

Measurement train type	In service	Abbreviation	Measurements	Max. speed [km/h] (measuring/transport)
Universal	3	UFM	among others track geometry, rail/overhead wire wear, gauge	110/120
Ultrasound	2	UST	(internal) rail defects	65/100
Video capturing	3	VST	video capturing (top view of rail and fastening, front view in wide angle)	100/100 (VST-05: 80/80)
Overhead wire	2	ODT, UMR	including wear, alignment, tension of overhead wire	100/100
Switch inspection and measuring	2	SIM	switch alignment, visual inspection (video) of frog and switch blades	100/100
Dutch safety system (ATB,GSMR)	1*	BRT 'Jules'	functioning of ATB (Dutch rail safety system) and GSMR (Dutch rail communication system)	85/140
European rail safety system ERTMS	1*	BRT 'Jim'	functioning of ERTMS on tracks where installed	140/140

* Electrical train that can only drive in The Netherlands due to catenary voltage limitations.

Figure 1: Large part of the current rolling stock of Eurailscout

The data collected by both the measurement/inspection trains and the manually performed inspections are analyzed by Eurailscouts Data Processing Center (DPC). DPC analyzes the data collected and transforms the raw data into a format that can be sent to the customer(s). With these data the customer is able to determine whether immediate track replacement is necessary or replacement in the long term track maintenance schedule can be planned. The collected data is also used for determination of track degradation over time and for training of train drivers. For the latter the recordings of the front view camera mounted on the video capturing trains can be used. These cameras record the sighting a train driver has.

In appendix A1 an organogram of the company Eurailscout is included.

1.2 Problem on hand

With signing the latest contract between Eurailscout and the Dutch railway network provider ProRail, a new contractual period started in which Eurailscout performs all kinds of track inspections as agreed with ProRail.

Figure 2: ProRail (source: www.prorail.nl)

One of the terms as requested by ProRail is that Eurailscout has to increase its efficiency every year with 10%, starting 2014. Eurailscout agreed with this term in view of CO_2 emission reduction and efficiency improvement. In the new contract an exact definition of efficiency is not provided. ProRail expresses the efficiency performance of Eurailscout in the contractually established deployment days they pay to Eurailscout. The amount of days paid by ProRail consists of the actual needed measurement days plus some spare days. In the new contract ProRail cuts this number of days by 10% every year. For example: in 2013 120 days (110 needed for measurements and 10 spare days) are paid to Eurailscout. In 2014 only (120-10%=) 108 days are paid, in 2015 (108-10%=) 97 days, etc. Each additional day needed for the measurements is at costs of Eurailscout.

Internally Eurailscout measures its performance among others on the ratio of measured kilometers over the total driven kilometers. A ratio value of 1.0 represents 100% efficiency (all the driven kilometers were measured), a value of 0.0 represents ‘zero’ efficiency or transport only (no measurements were executed in the driven kilometers). This expression of efficiency is directly related to the efficiency expression as used by ProRail: a reduction of the transport kilometers implying a higher efficiency ratio and allows to increase the production rate, helps to save on the number of deployment days required.

ProRail introduced this contractual provision because the already highly utilized Dutch railway network will become more and more utilized in the coming years. Especially with the government plans to introduce a high-frequency rail service meaning every hour six intercity and six local trains at a railway line (‘Programma Hoogfrequent Spoor’, PHS), the railway network will be utilized far closer to its capacity [2]. This implies that the number of slots available for freight train operators but also for maintenance companies and companies like Eurailscout, will decrease.

Additional problem for Eurailscout is that the available slots in the timetable have to fulfill specific requirements. Each of the inspection trains has its own requirements/limitations like maximum measurement speed, fixed routing to inspect tracks that need to be inspected, the need for specific signal aspects, minimal turnaround times, setup and breakdown times of the measurements, etc. These requirements make the scheduling of the measurement trains even more difficult and a conflict free execution of the total timetable harder to accomplish.

Another difficulty for Eurailscout is the time period in which track sections that could not be measured in the initial run, have to be remeasured. For each measurement system of each train, the contract with ProRail prescribes a time period in which missed track sections have to be remeasured. For most measurement systems this period is four weeks, starting at the initial run. A fine/bonus rule is included to motivate Eurailscout to finish measurements on time.

1.3 Research questions

For this master thesis research the problem as described in paragraph 1.2 is converted into the following main research question:

> *How to establish an annual 10% efficiency improvement after the year 2013 in the planning and deployment of the Eurailscout measurement trains, given the limitations imposed by the measurement trains, the tracks and scheduling?*

To answer this question several sub-questions have to be answered first. These sub questions, divided over several categories are:

Contract

- Which measurement/inspection frequencies are used?
- According to which standards does ProRail determine the track measurement frequencies?

Current planning Eurailscout

- How are inspections planned at the moment?
- How are the routes of the measurement trains currently determined?
- What is the current efficiency in the planning by Eurailscout?
- How does Eurailscout determine which track is measured when?
- What are the parties involved in the planning process (stakeholders)?
- What are limitations in the planning process that have to be dealt with?

Literature

- Is there any scientific literature on this topic available?

  If there is:

  - Which researches were executed?
  - Which methods were used?
  - What are the results of these researches?
  - Can the in literature applied methods contribute to this research?

  If there is not:

  - Are there in other (transportation) fields researches executed that can contribute to this research?
  - What methods are used in these researches?
  - What are the results of these researches?

Theoretical possibilities

- What efficiency is theoretically possible in a situation with track and vehicle limitations but without any other rail traffic?

Theoretical possibilities versus practice

- How does the current efficiency relate to the theoretical possibilities?
- What are causes for differences?
- Which involved party is responsible for which differences?

Improvement suggestions

- What improvements can be indicated?
- Are the improvements applicable in reality?
- What effect on the efficiency can each improvement suggestion establish?
- Which improvement suggestions can be marked as solution for the efficiency improvement problem?

Implementation within Eurailscout/Dagplan/Lokaal Plan

- How can these solutions be implemented in the current planning procedures within Eurailscout and/or Dagplan and/or Lokaal Plan?
- What are consequences when these solutions are implemented?

These questions will be answered throughout the text. To answer the main research question the efficiency expression as used by ProRail (the number of deployment days needed to measure all contractual established tracks) is required. Because it is directly related to the efficiency expression as used internally by Eurailscout, both expressions of efficiency are used in the analyses and recommendations.

In this research the following inspection trains are considered:

Universal measurement train *UFM120*

Ultrasound measurement train *UST96*

Ultrasound measurement train *UST02*

These trains are chosen out of the total rolling stock park currently active in the Netherlands, because they are the most important for Eurailscout regarding the inspections in the Netherlands. The UFM120 measuring coach is an inspection train performing multiple measurements in one passage using multiple (most of time over 10) systems at the same time. Because the measurement speed is approximately 100km/h this train can ‘easily’ be scheduled in the railway timetable.

Both ultrasound measurement trains are chosen because they have many deployments in The Netherlands. They are limited to a maximum speed of 60km/h during measurements. Consequently they form a ‘driving blockade’ in the execution of the railway timetable. In addition the UST96 needs a flat car for safety system detection purposes. This flat car always needs to be coupled at the rear of the train facing forward. A change of direction requires the measurement coach to drive around the flat car which takes a lot of extra turnaround time compared to the UFM120 and UST02. Additionally this change of direction movement is only possible at locations where the measuring coach itself can drive around the flat car (minimal two parallel tracks connected with switches needed).

The video capturing trains are left out of consideration in this research because they are owned and driven by Eurailscout but planned and scheduled directly by ProRail. Both BRT safety system control trains are also left out of consideration because these trains demand too specific planning requirements to include them in the research.

For the Eurailscout trains different terminology is used: ‘inspection trains’ and ‘measurement trains’. Both terms are used interchangeably throughout the text, but mean the same.

1.4 Reading guide

The main research question as stated in paragraph 1.3 is answered by answering all sub questions mentioned in the same paragraph. Throughout the chapters of this research the sub questions are answered. It starts in chapter 2 with a scientific literature study to find researches about similar problems and the applied solutions. Before analyses starts, it is necessary to present an overview of the current processes. Chapter 3 maps the processes within Eurailscout and other parties involved in the measurement planning and execution chain. Next chapter 4 discusses the current performance of the track inspections by the Eurailscout trains under consideration. Also problems occurring in the execution are identified and analyzed.

New routing methods are tested in developed MATLAB models. Chapter 5 discusses the purpose, limitations, setup and functioning of the models. Furthermore the algorithms used, the results obtained and the conclusions that can be drawn from these results are presented in this chapter. Based on the analyses in chapter 4 and the model results in chapter 5, recommendations for efficiency improvements are presented in chapter 6.

Conclusions on the study and recommendations for further research are presented in chapter 7. References used are listed in chapter 8, followed by an English-Dutch vocabulary in chapter 9. The appendixes contain additional information and data.

2 Literature review

Part of this research is a literature study to search for scientific publications about the planning of measurement/inspection trains. In this chapter an overview of the literature found is given complemented with the relation of the papers to this thesis and the possible application of described methods and results.

2.1 Search elements

At first the key search elements have to be defined. The problem under consideration in this master thesis is about efficient planning of measurement/inspection trains. One part of this problem is routing the trains as efficient as possible through a railway network, the other part is about scheduling these trains into the timetable. To determine the most efficient routing method for each of the trains under consideration, a model will be built to analyze the different routing methods. To make the model work, several elements are necessary. At first a network is needed to simulate the train movements. Next characteristics of the trains are necessary (for example maximum speed during measurements/transport, minimal turnaround times, continuous working hours/distances, etcetera). Also different types of routing methods are needed as input. Then the best model setup needs to be determined to maximize the performance (optimal solution) within limited calculation time (target: maximal two hours of calculation time). Output of the model has to be information about the optimal path found, the number of double crossings of track sections and the time needed to drive the route.

In the scientific literature information has been searched about measurement/inspection train scheduling and researches that can help to build the inspection train routing models.

2.2 Literature

Because of the specific subject not much literature about the measurement train scheduling problem can be found. Peng et al. [3] studied periodical rail inspection scheduling (by road-rail vehicles) applied on (part of) the North American rail network. Proposed is a vehicle routing model with multiple types of constraints like periodicity (frequency of measurements), non-simultaneously constraints (no two measurement vehicles at the same time on the same track segment) and time window constraints. The inspections are modeled as tasks that have to be assigned to crews and vehicles. In the model a network is used containing only directed arcs. A Greedy algorithm first searches for an initial optimal solution in a short time horizon. Next a specific algorithm is used to further optimize the solution performing a local search around the previous found solution by changing/adding/swapping of tasks and crews. If not all constraints are met, the time horizon will be extended to search again for an optimal solution. Case studies show that their method performed better than the manual scheduling done by planners, both on short and long term planning.

Morales et al. [4] studied optimal routing of geometry cars in North America. They used a branch-and-bound technique for solving the routing problem with frequency and track restriction constraints. The network consists of nodes and arcs with track constraints like maximum curvature, maximum speed and allowed driving direction. Furthermore they assume that both start and end point are given as input. Because this document is not a paper but a presentation given at an annual meeting, it does not provide details about the exact algorithm. What can be distilled is that the algorithm is based on a branch-and-bound technique and can solve a network consisting of 70 nodes with 252 links to optimality within 12 hours. It achieved a reduction of 40% in the repositioning miles.

For this thesis several items from the previous two papers can be extracted. From the paper of Peng et al. [3] the setup and usage of the network can be used. Their model is quite complicated and extensive in comparison with the targets set in this research. Periodicity constraints, non-simultaneously constraints and time window constraints are examples that will not be used in the model in this research. The routing method Morales et al. [4] presented, fits the purpose of the model to be built well. The general approach can be used without the frequency constraints, because the model to be built is about finding one optimal path for an inspection train using a certain routing method.

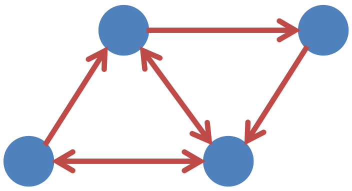

Figure 3: Example network consisting of 4 nodes connected with 3 arcs and 2 edges[1]

In literature several studies were executed to similar routing problems. An example is the Chinese Postman Problem (CPP), which is a special variant of the Traveling Salesman Problem (TSP). In a TSP a salesman has to visit several cities in a cost efficient route. A CPP is about finding a least cost route covering all arcs, edges and nodes in a network at least once[1]. See Figure 3. Real life examples of CPP are routes made by a postman delivering post, city garbage collection or street sweepers.

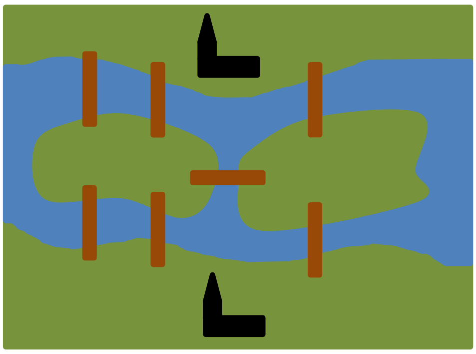

Figure 4: Seven bridges of Königsberg

One of the first and most well-known routing problems related to the Chinese Postman Problem is the Königsberg seven bridges problem. Goal is to cross all bridges exactly once in a continuous path (see Figure 4). Euler showed already in the year 1736 that this problem has no solution, that is, there is no continuous path possible where all bridges are crossed exactly once. One bridge always need to be crossed twice to make this possible.

In the scientific literature many studies about solving CPP routings are available. One of the first studies on methods for solving CPP was executed by Edmonds and Johnson [5]. Their solution method consists of two parts. First step is to check in the network under consideration whether the nodes are incident to an even number of links. Where necessary links are inserted, which is done by a specific algorithm making the network symmetrical (meaning every node has an equal number of inflowing and outflowing links). In the symmetrical network Euler tours are searched for. An Euler tour is a tour over a network consisting of nodes and edges where every edge is covered exactly once. The algorithm to do this starts by creating a path from the starting point (also the end point), which not necessarily covers all links. Secondly at nodes incident to links not included in the path, the original path is cut and a new path over the first excluded links is inserted. Repeating this procedure several times until all links are covered results in an Euler tour. The added links are the links that have to be covered twice. This solution technique is only applicable to an undirected or completely directed network.

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[1] Link: segment with unique characteristics connecting two nodes; for example a track section with a speed limit of 40km/h between two signals
Arcs: links with a fixed travel direction (directed link)
Edges: links with no fixed travel direction (undirected link)
Nodes: center points interconnected with arcs or edges representing for example stations

For mixed networks an extension on the mentioned CPP solution technique is also proposed by the authors. Mixed networks are composed of directed and undirected links (respectively arcs and edges). In the previous solution algorithm a rule is inserted that first uses all edges when arriving at a node (if available) and as soon as they are all used once then arcs are used. The paper presents details about the used methods but no test results are provided to prove the functioning of this method.

Minieka [6] studied especially the CPP for mixed networks (mixed CPP or MCPP). In his paper the author propose an integer linear programming method for solving the CPP. In this method the undirected arcs are assumed to have a direction, to create a symmetric graph. From there on the method applies least cost searching paths for solving the problem. No results are presented in which the functioning and proof of the method is shown. In the same paper the author also reviews the Windy Postman Problem (WPP). This problem is comparable with the CPP but now some links have a preferred direction. When looking to the original postman problem the WPP can be explained as follows: a postman prefers downhill over uphill sections or tailwind over headwind in his route. The approach for solving the WPP is the same as for the CPP but here the edges (undirected links) have different costs in both travelling directions such that the ‘least costly’ direction is always preferred over the other.

In the paper of Christofides et al. [7] an optimal method for MCPP is presented. First the authors refer to a research of Papadimitriou [8] who shows that the general MCCP is NP-Complete. Christofides et al. present an exact solution algorithm based on a branch-and-bound technique with Lagrangean relaxations of constraints to create lower bounds. Upper bounds are based on the heuristic as presented by Minieka [6]. Branching is executed on the edge-variables. Computational results provided in the paper show that this technique can completely solve problems up to 50 vertices, 66 arcs and 39 edges within 500 seconds.

Eiselt et al. [9] give an overview of studies applied on the (mixed) Chinese Postman Problem. They combine multiple methods of published studies into a general solution method. First they make a network Eularian (circular) by making a graph directed (all links having a fixed driving direction). Next a branch-and-cut method is applied. This method can solve instances to optimality.

As referred to by Pearn and Chou [10] in their paper, Frederickson [11] added steps to the solution procedure of Edmonds and Johnson [5] to make the network even again. Both methods combined are known as ‘Mixed-1’. In an earlier paper Pearn and Liu [12] proposed extra steps to remove artificial edges and arcs in the Mixed-1 method to improve the solution. This is known as ‘modified Mixed-1’. Now Pearn and Chou [10] propose the ‘improved Mixed-1’ procedure, consisting of extra steps to reduce the number of arcs and edges. Numerical results show significantly improvements in the results obtained.

For solving the Windy Postman Problem (WPP) as introduced by Minieka [6] several methods exist. Guan [13] developed an algorithm transforming a WPP into an undirected CPP, which in turn is solved by the method of Edmonds and Johnson [5]. Pearn and Li [14] added some additional steps to improve the algorithms performance. These steps comprise the decomposition of a graph into several subcycles. All optimal routes of the subcycles together form a postman tour. By repeating this procedure several times, the best postman tour can be selected. Another – approximation – solution method presented by Guan [13] is the reverse Win’s algorithm, based on the algorithm proposed by Win (as referred to by the authors: [15]). It consists of two phases. First directions are assigned to edges, new arcs are added and a minimal-cost flow algorithm is applied to find desired flows. Second phase is applying minimal-cost matching. Based on experiments with the two procedures the authors find out that both methods improve the original procedures by about 4%. Furthermore the reversed Win’s algorithm found 176 best solutions out of 240 problems.

The CPP and WPP can contribute to the problem on hand in this master thesis. In essence the routing of the Eurailscout measurement trains is a Chinese Postman Problem. In a network the measurement trains have to cover all (at least the contractual required) arcs in the most efficient way: as few as possible double crossings. The problem in this thesis can therefore be modeled as a CPP. In the rail network tracks can have preferred driving directions which can be modeled as a WPP. Based on the described papers about (M)CPP and WPP the generalized approach is to make networks even and to solve the problem using branch-and-bound techniques. Especially the paper of Christofides et al. [7] is comparable with the problem on hand in this research. As stated they use a mixed network which is solved using a branch-and-bound algorithm with upper and lower bounds created using Lagrangean relaxation of constraints.

Because the routing possibilities of trains on mainlines (only two or four tracks connected with some switches) is limited compared to the routing possibilities in stations (multiple tracks connected with many switches offering many possible routes), it can be useful to search for methods of routing trains in stations. The following three papers present methods to do so.

Zwaneveld et al. [16] propose a branch-and-cut approach for routing trains through stations. The problem is modeled as an integer linear program problem (ILP) which is solved to optimality using a CPLEX solver. To be able to solve the problem, they split operational processes into arriving, departing and shunting to for example a parking area. The CPLEX solver executes the procedure of initialization, preprocessing in which the size of the problem is reduced, formulation of the ILP of the routing problem and finally applying the branch-and-bound technique. This procedure is tested on three different size stations in The Netherlands. Due to the applied preprocessing techniques the problem instances could be solved within reasonable time to optimality.

Kroon et al. [18] showed in their paper that it is not necessary to include all routing possibilities at railway stations in the decision process to assign a certain group of trains to feasible paths. Furthermore the authors show that decreasing routing possibilities of trains from 3 options to 2 options makes solving the problem more likely and reduces computation time.

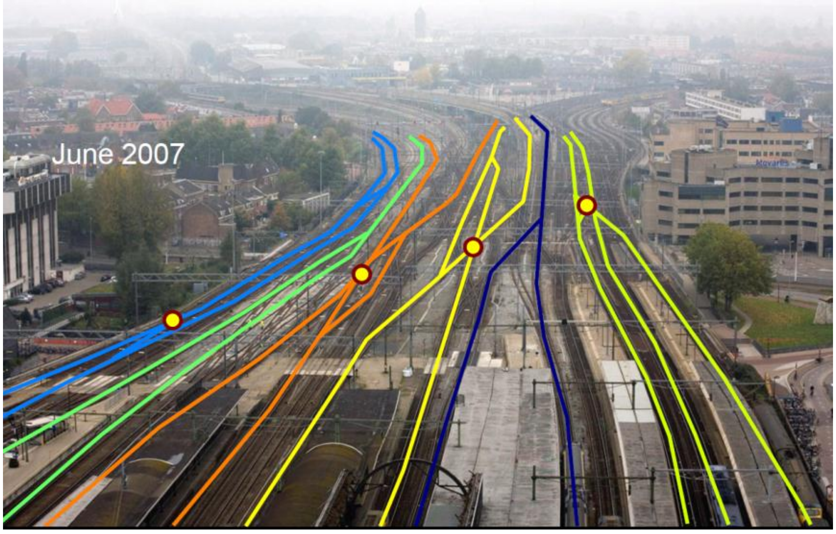


Figure 5: Example of possible paths at Utrecht Central station (Source: [17])

Carey [19] studied the same problem of routing trains in an efficient way through railway stations. He proposes a solution method in which the trains are offered a choice of platforms and tracks. The mathematical problem is solved by splitting up the original problem in smaller, mathematical easier to solve, sub problems. Routing of trains is done one by one using a branch-and-bound algorithm with upper and lower bounds to reduce the search space. Furthermore they apply mathematical algorithms simulating the actions of dispatchers. The total solution algorithm first assigns a path to the first train in the timetable (the timetable is not fixed, only the sequence is). Next the subsequent trains are routed. This procedure is continued until all trains are routed once. If necessary for a more optimal solution, trains can iteratively be rerouted.

The arriving and departure times of the trains can be changed for optimality but within time boundaries to shorten computation times. Results on a numerical example with 10 trains, 10 nodes and 28 undirected links, gave short computation times. However no comparison is given to which the computation time can be measured.

The three researches introduce methods for routing and scheduling trains through railways stations. In all three studies the authors study routing and scheduling of trains in an hourly repeating timetable. The techniques applied in the papers of Zwaneveld et al. [16] and Kroon et al. [18] are useful for routing the inspection trains through railway stations. Although the movements of these trains are not comparable to ordinary trains, the methods presented can offer starting points for extending these methods to suite the inspection trains. The proposed path determination is based on a branch-and-cut approach with upper and lower bounds, limiting the initial routing possibilities.

As stated in paragraph 2.1, part of the inspection train planning problem is scheduling these trains into the (existing) timetable. The following papers investigated the scheduling of additional trains.

For the scheduling of extra (freight) trains on a railway network, Cacchiani et al. [20] executed a study on this subject. The network is filled with passenger trains running according to a presumed fixed timetable. In their study, the authors take into account a whole railway network assuming it is allowed to reroute freight trains over parallel routes between their start and destination point. Objective in this study is to fulfill the freight train running request of a freight operator with as few as possible changes to it and preventing hindrance for passenger train services. Their network consists of nodes, edges and arcs. Timetables are given as nodes in a specific order with their corresponding arrival and departure times. For freight trains a similar type of timetables is used:

- fixed starting and destination nodes
- a list of intermediate nodes that can but not necessarily have to be visited
- a desired departure time at the starting node

Only the departure time is given because for freight trains an exact arrival time is less essential unlike passenger trains. The difference between the requested freight train timetable and the actual timetable is expressed as profit. A positive difference – shorter actual timetable – is a profit for the freight train operator, a negative difference is a cost for the operator. Constraints are track capacity related. The problem is converted into an Integer Linear Program (ILP) with the objective of maximizing the total profit of a timetable respecting the track capacity constraints. The problem is solved with relaxation of the track capacity constraints. Result is an heuristic algorithm able to solve this problem.

Burdett and Kozan [21] investigated techniques for inserting additional trains into an existing timetable. Scheduling of these extra trains must be done in such a way that disruptions to other existing services is prevented or at least minimized. The authors use three phases ranging from a fixed existing timetable (phase 1) to a free existing timetable (phase 3). Phase 2 selectively takes scheduled trains for fixed or free to change. Additional trains are preferably inserted in the first phase, but they can also be inserted in phases two and three. Now the problem is solved with a job shop method and uses disjunctive graphs. Numerical results show that building a complete timetable from scratch applying time window constraints, proved to be very effective.

Compared with adding the inspection trains into the timetable, the elaborated papers present methods for adding extra trains into a timetable but with constraints that do not or at least partly apply to the inspection trains. In the planning of these trains it is for example not allowed to reroute the measurement train during measurements unless there are no other options are left. However the methods applied may help to develop a method for scheduling the measurement trains into the timetable minimizing the hindrance for already scheduled trains. Although the model in this thesis will not include other trains and therefore will not include a timetable, the above presented papers can help in finding theoretical solutions to increase the efficiency of the inspection trains.

2.3 Remarks about the literature study

Due to the fact that the process of planning and routing inspection trains is a specific subject, not much literature about this topic was found. However from the literature collected it may be concluded that the best way to setup the inspection train routing method evaluation model is:

1. Network: no specific form needed. Undirected, directed or mixed networks are all solvable however the complexity increases accordingly.
2. Solution method: most papers assessed used some kind of branch-and-bound technique for path searching. To limit the search space and calculation time, upper and lower bounds are applied. The results achieved give a promising outlook for the methods used.

Besides information about the methods for the model to be built in this thesis, the literature also gave some information about methods that can be used in scheduling additional trains into an existing timetable. Although this topic is not used in the model to be built, it provides some ideas for generating solutions and recommendations for efficiency improvements in the planning of the measurement trains.

3 Current processes

To make efficiency improvement recommendations, first the current planning process has to be mapped. This chapter describes the current planning process and the involved parties with their respective roles/responsibilities. In appendixes A2 and A3 the planning process is captured in a graphical representation.

3.1 Eurailscout

As described in chapter 1 Eurailscout works on authority of the Dutch railway infrastructure manager ProRail. ProRail determines the tracks to be measured, the measurement frequencies and the type of measurements to be performed. All these requirements are stated in the contract. Based on these data Eurailscout determines a schedule for their trains and personnel.

ProRail requests tracks to be inspected with a certain frequency. This frequency is based on the amount of trains using a track and the total tonnage transported over the track. Using European standards ProRail determines the track inspection frequencies for each measurement system. For the trains under consideration in this thesis, these track inspection frequencies range from 2x/year to 6x/year. ProRail automatically meets the European rail safety legislation by using these European standards for track inspection. Possibly the European standards are too strict for the Dutch situation, implying higher inspection frequencies then necessary. Developing standards based on the Dutch situation falls out of this research scope, but could have a positive effect on the inspection efficiency for Eurailscout.

Before the current contract was signed, Eurailscout checked the inspection request on illogical situations with respect to the inspection frequency. An example of an illogical situations is a case were similar used tracks (both in number of trains and tonnage) have to be measured with different frequencies, see Figure 6.

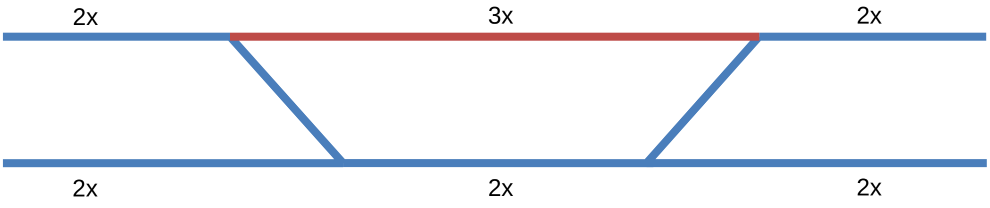


Figure 6: Fictive example of illogical situation occurring in inspection request by ProRail

The cause for such an illogical inspection frequency, lays in the determination process ProRail uses to select the tracks to be inspected. At the moment ProRail uses the data of the previous contract and updates these to the new contract specifications. Problem for Eurailscout in this situation is that the inspection frequencies on the tracks may not match: in the case of Figure 6 2x/year means every six months an inspection, while 3x/year means every four months an inspection. The first and last inspection of the track with frequency 3x/year can be combined with the inspections of the tracks with frequency 2x/year. Consequently the train needs to return 1x to inspect only the track with frequency 3x/year for the third time. Any illogical situation that arose in the concept contract was discussed with ProRail. Improvements were made to solve the problem(s) arising before signing the definitive contract.

Each of the measurement trains has its own specific requirements for its train path. Requirements like track specific routing, the maximum speed and the need for particular signal aspects (for rail safety system (ATB) checks), make the scheduling of the Eurailscout trains a difficult exercise.

Figure 7: EB-ViCoP

To make routing plans for the inspection trains, Eurailscout currently uses their own developed planning software: EB-ViCoP. The name EB-ViCoP is a contraction of the Dutch words “Efficiënt Beheren, Visualiseren, Controleren en Plannen” (Efficiently Manage, Visualize, Check and Plan). Basis of this software is a database containing the track layouts of all countries Eurailscout is active and the contracts as agreed with their clients. In a graphical interface EB-ViCoP shows the tracks to be measured with their respective inspection frequencies on schematized maps of the railway network. Using these data the Eurailscout planners have a good overview of the tracks to be measured and the paths they can make.

A year in advance the planning department of Eurailscout makes a complete routing plan (‘annual plan’) for the coming year according to the contracts with all their (Dutch) customers. Included in this plan are, among others, all detailed (track specific) paths of each inspection train for a whole year. These paths are determined by the Eurailscout planners based on the contractual requirements, knowledge of the planners and experiences from previous inspection runs. At the moment no automated routing tool is used, all paths are constructed manually. The ‘annual plan’ is created using EB-ViCoP and is necessary for requesting track capacity. Furthermore it is used to show the customers the developed plans fulfill the contractual requirements (paths covering the tracks to be inspected). A few months after handing in their track capacity request, Eurailscout receives their assigned track capacity which they may use for execution of the inspections.

Eight weeks before execution of a measurement run the path for a specific day as determined in the ‘annual plan’, is checked and where necessary updated with for example track sections missed in previous runs. At the moment the planners finished a path for an inspection train run, a timetable needs to be requested. Creation of the timetable is done by Dagplan and Lokaal Plan. Dagplan is a department of NS, the Dutch national railway company, and is responsible for scheduling trains on the main lines between stations/sidings (on the ProRail managed part of the railway network). Lokaal Plan is like Dagplan a department of NS performing the scheduling of trains at stations, which is normally done by ProRail (see paragraph 3.2 and 3.3 for the process of scheduling executed by Dagplan and Lokaal Plan). These two parties are chosen by Eurailscout because they have the authority to make changes to passenger train schedules if this would fit the inspection train paths better.

To request a timetable for an inspection run the planning department of Eurailscout makes a detailed train specific script, containing for the whole path the track sections to be measured and the limitations of the measurement train (for example maximum measurement speed), see Figure 8 for an example.

Datum: dinsdag 10 juli 2012
Versie: INHAAL uitval dag 4a en 5

Aanvraag UST96

dinsdag 10 juli 2012

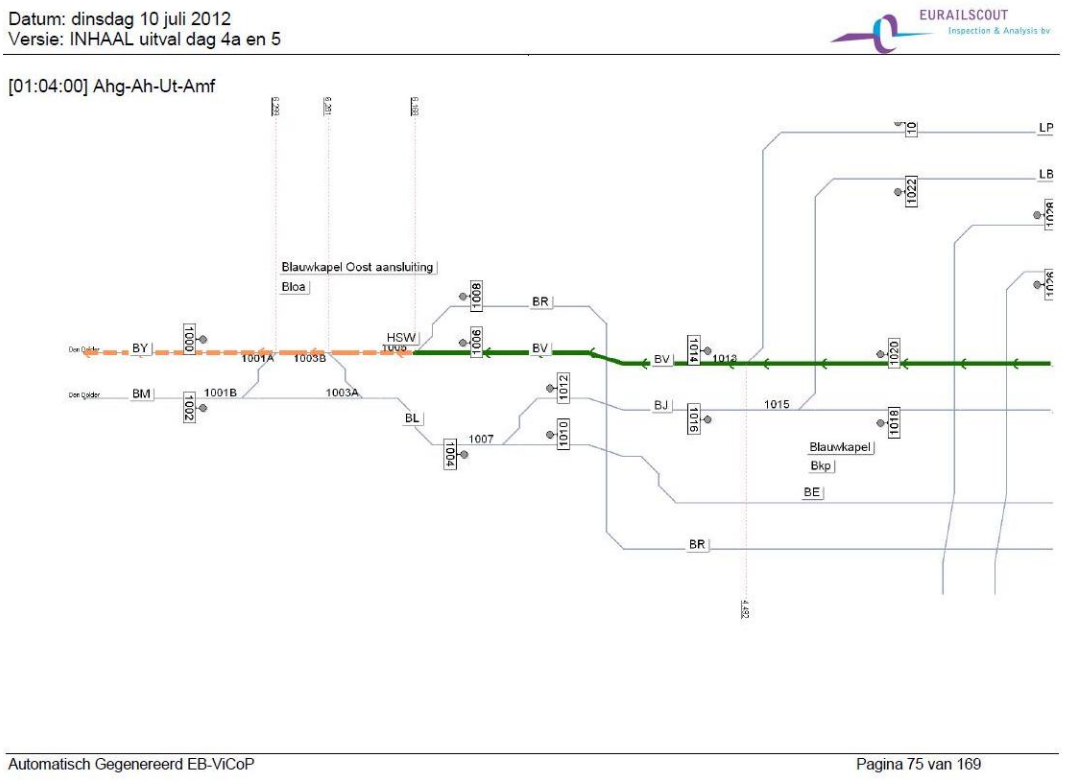
Gecontroleerd met rittenstaat door

Meetritleider / Machinist

Datum:	Paraaf:
Naam:	

Automatisch Gegenereerd EB-ViCoP

Pagina 1 van 169



Datum: dinsdag 10 juli 2012
Versie: INHAAL uitval dag 4a en 5

[01:04:00] Ahg-Ah-Ut-Amf

Automatisch Gegenereerd EB-ViCoP

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Figure 8: Two pages of a script

Top page is a cover; the lower a page with routing information. It shows a schematized rail network with in green the section to be measured and in orange the section in which no measurements have to be executed ('transport')

When a timetable is defined, Eurailscout receives around three weeks before execution the detailed timetable (the application) from Dagplan. The Eurailscout planners check whether the assigned train paths correspond to their request. If this is the case the scheduling is done and ready for execution. If not, changes are requested via Dagplan. A script complemented with the established timetable is converted into a route book for the train crew. Some trains work with an offline database for storage of the collected data. The basis of this database is also constructed with the route book. Furthermore the route book is sent (one week before execution) to the dispatchers and other parties involved, making sure they are aware of the oncoming Eurailscout train in the near future and the specific requirements this train has. Figure 9 presents the current timeline in the planning process graphically.

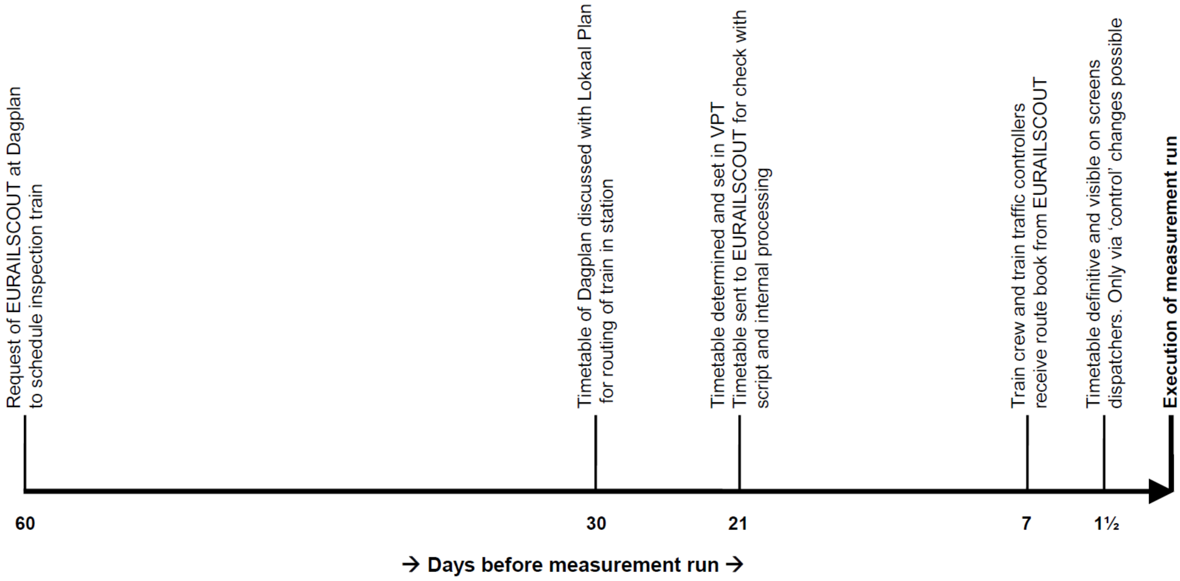

Figure 9: Timeline current planning process inspection trains Eurailscout (for details about the scheduling by Dagplan and Lokaalplan see paragraphs 3.2 and 3.3)

Any changes to the determined schedule within the seven intervening weeks between determining the measurement train timetable and sending the route book to the train crew/dispatchers, can be made by Dagplan (and Lokaal Plan). Changes to the schedule arising one week before execution, can basically only be made via the so called 'control'. 'Control' is part of the general railway planning/execution process in which actual disruptions or requests are handled via direct communication between among others dispatchers, train operating companies and train drivers. Eurailscout's planning department also has a 'control' section which 24 hours a day can be contacted by Eurailscout train drivers, dispatchers and national train traffic control for questions about for example rescheduling of Eurailscout trains. The 'control' section of Eurailscout consists of one planner who - in rotating shifts - is 24 hours a day reachable. In case of disturbances in the execution of the inspections, the 'control' of Eurailscout assesses the situation and reacts if necessary by requesting new timetables directly at dispatchers in cooperation with involved dispatchers and train crews.

Due to all kinds of disturbances (like track failures, intervening actions of dispatchers or malfunctioning equipment) it is possible that not all inspections can be executed as planned. At the planning department they keep a measurement system specific list including the track sections that could not be measured. For possible cost reclamation also the cause is noted. With this list a planner has an overview of track sections which still need to be measured. Combined with the contractual established time period in which the measurements have to be executed again, a new schedule for the train is made to cover these missed tracks.

The time period in which measurements have to be redone (for example finishing the measurements within 4 weeks of the initial run) is contractual established between Eurailscout and ProRail. ProRail uses a bonus/malus motivation for Eurailscout to finish measurements in time. Both the contract and the bonus/malus system put a high pressure on the scheduling team and demands flexibility of train crew and dispatchers.

Incidents disturbing the planned inspections having a cause which can be assigned to ProRail, are compensated by them. If the cause of such a disturbance can be pointed to Eurailscout, the eventual extra run (assumed on another day) will be on their bill. Efficient rescheduling prevents the consequences. Measurement disturbing decisions made by dispatchers are more difficult to assign to a specific party. Dispatchers have to deal with the actual situation and make decisions aiming at minimizing the disturbance of the total train service. Unforeseen circumstances like road-rail accidents, trackside fires or weather circumstances form a grey area. These disturbances cannot be accounted for by any party involved. As a consequence extra inspection runs arising from these disturbances are on the bill of Eurailscout. Again efficient rescheduling can reduce the extra costs involved.

During the measurements the train crew accurately follows the actual path driven compared to the planned path. Deviations are drawn digitally and/or on paper in the printed route book. After the inspection run is executed the actual driven path is inserted in EB-ViCoP. Now the path is stored, deviations from the plan can easily be shown and ´missed´ sections can be planned for remeasurements.

Every inspection run consists of parts the train actually measures and of parts in which the train is in ‘transport’ to the next measurement section. During transport normally no measurements are executed. However in case tracks are driven which were missed in previous runs, the transportation phase can be changed into measurements. All this happens in close cooperation with the Eurailscout planning department which determines the tracks for remeasurements and how these can be combined in the already established paths. The latter is coordinated with dispatchers or Dagplan/ Lokaal Plan depending on the time period under consideration. If missed track sections cannot be included in already planned paths within the remeasurement time period, special remeasurement deployments will be planned. In these runs as many as possible track sections that were missed previously, are combined to cover the tracks within the remeasurement time period.

The data collected by the trains are analyzed by Eurailscouts data processing center (DPC). They check the data for errors, situations requiring immediate intervention and completeness. Finally the data collected are presented in a standard format and sent to the client. If during data processing is observed that a measurement system has not worked correctly or has not worked at all, this is communicated with the planning department for remeasurements.

As mentioned before, some trains use an offline database for storing the data. This database is filled with the assigned train path. Deviations of the predetermined path are not automatically processed in the database. If deviations occur the database is no longer in line with the actual driven path, causing a mismatch between the planned ‘database’ path and the actual recorded path. Afterwards this needs to be corrected by the data processing center before the data are handed over to the client.

The planning department is also responsible for scheduling the crew including hotel reservations for personnel not able to return to their homes, because of for example the distance. Furthermore they plan regular or incidental maintenance windows for the measurement trains as indicated by the technical department.

In appendixes A2 the total planning process is schematically presented.

3.2 Dagplan (NS)

Dagplan - a division of NS, the Dutch national railway company (Nederlandse Spoorwegen) - is responsible for the scheduling of all trains on the main lines between stations and sidings.

As mentioned in the paragraph about the planning process within Eurailscout (paragraph 3.1), Eurailscout planners determine the preferred routing of the measurement trains in a script. To request a timetable a script is sent to Dagplan. Different line colors marking the requested inspection path, divide the path in measurement sections (unless there is absolutely no alternative, preferably no changes to path) and transportation sections (changes to path may be applied). With these drawings Dagplan determines a timetable for the measurement trains in the national railway timetable.

At the moment Dagplan uses the VPT-Planning system (Vervoer Per Trein, transport per train). In VPT-Planning the planners of Dagplan schedule trains using time-distance diagrams. Figure 10 presents an example of a time-distance diagram. It shows on the horizontal axis distance and on vertical axis time. Diagonal lines represent trains. The VPT-Planning system shows the Basic Hour Pattern (BHP: an hourly repeating sequence of trains) of the national railway timetable.

Dagplan planners examine the time-distance diagrams of a railway section (for example between two stations or between a station and a junction) for a gap large enough to insert a measurement train, considering the specific requirements of each train.

Dagplan communicates with Lokaal Plan about the measurement trains they scheduled on the mainlines. Lokaal Plan in turn determines the detailed timetable and routing in the stations/sidings (see paragraph 3.3). For scheduling and routing a measurement train at these locations Lokaal Plan uses the arrival and departure times at a station/siding determined by Dagplan.

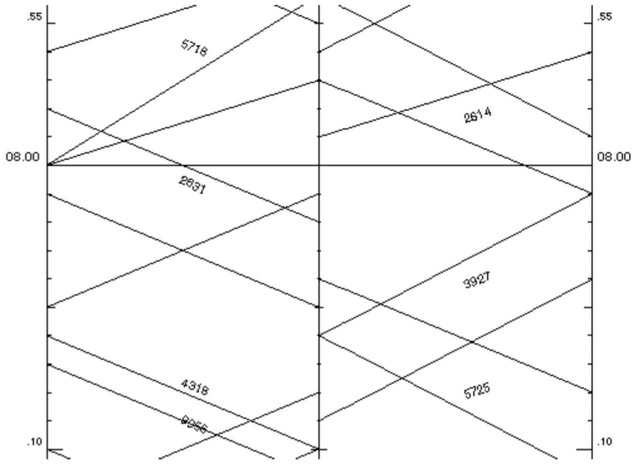

Figure 10: Example of a time distance diagram (source: [22])

This is an iterative process; if Lokaal Plan is not able to schedule the extra train in a station at the times Dagplan determined, then Dagplan has to reschedule the extra train on the mainline (arrival/departure time or if possible the arrival or departure track). Final result of this iterative process is a timetable for the measurement run under consideration. This timetable is entered in VPT-Planning. Next, a document (the ‘application’) including the timetable with the tracks to drive on the main lines and stations, is exported and sent to Eurailscout.

Appendix A4 contains more details about the planning process of NS Dagplan.

3.3 Lokaal Plan (NS)

Lokaal Plan is like Dagplan a division of NS and responsible for scheduling and routing trains through large stations (for example Utrecht central station) and sidings (for example Amersfoort Bokkeduinen). Normally this a task of ProRail; for stations however this task is now transferred to NS. Spread across the Netherlands there are several Lokaal Plan departments, each with its own managed area consisting of several stations and sidings.

Lokaal Plan uses the program ‘Lokaal Plan’ and VPT-Planning for scheduling. VPT-Planning is the same system as used by Dagplan (see paragraph 3.2) In the program ‘Lokaal Plan’ station and siding tracks are schematically visualized as shown in Figure 11. It shows horizontal lines each representing a station track over a specific time period.

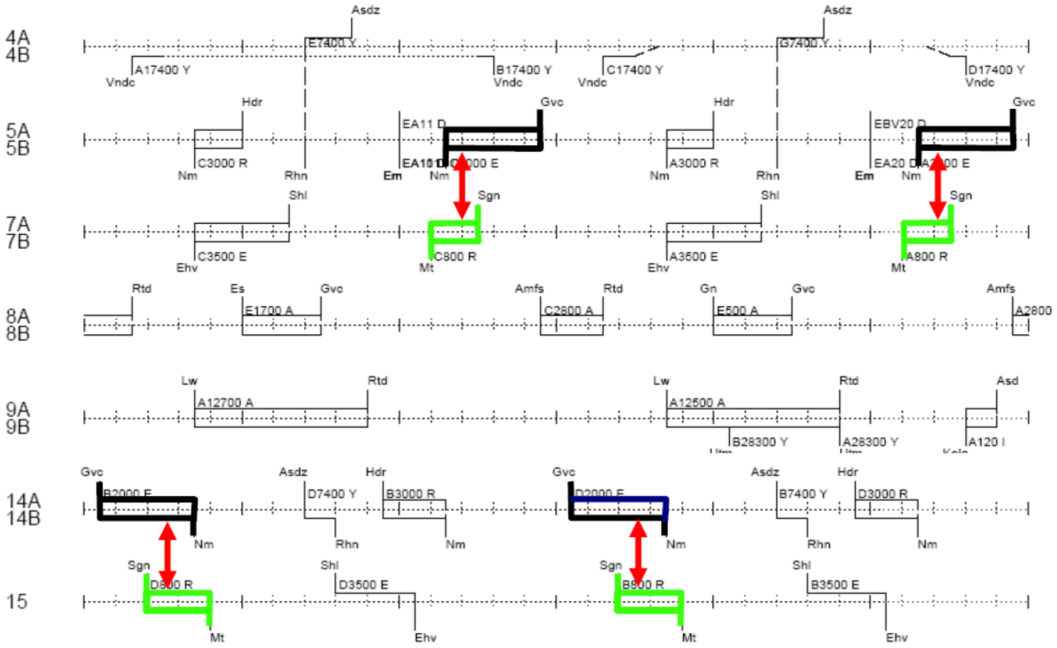

Figure 11: Example of station track occupation graph of Utrecht Central station. (source: [22])

In Figure 11 the markings at each station track represent trains occupying a platform track for a certain amount of time. Data added to these markings show train numbers and origin/destination stations. The red arrows show some direct (cross-platform) connections offered.

As soon as Dagplan has determined a timetable on the mainlines, they arrange a meeting with all the Lokaal Plan departments the inspection path will cross. During these meetings members of Dagplan discuss with the Lokaal Plan planner(s) whether the arrival times and tracks at stations are free for the measurement train at the moments Dagplan came up with. A planner of Lokaal Plan checks with the platform occupation graphs whether this is the case. Based on the platform occupations and the necessary headway/cross over times between consecutive or opposite trains, the planner of Lokaal Plan decides whether the times as established by Dagplan are ok or need some adjustments. If necessary and possible, Lokaal Plan has like Dagplan the authorization to schedule other trains at other platforms to make way for the measurement train.

3.4 Final timetable

Changes determined in the meeting between Dagplan and Lokaal Plan are entered in VPT-Planning by Dagplan. The timetable for a measurement train run is now marked as final. Periodically VPT-Planning updates overnight to make the changes visible in the timetable. As soon as this process is finished, the inserted trains are fixed in VPT-Planning and visible in the station occupation graph of Lokaal Plan. 36 Hours before the ‘timetable day’ starts, the data of VPT-Planning is sent to the national railway traffic management and the trains become visible on the screens of the dispatchers.

Although the timetable seems to be final, in fact it is not. In the time period between entering the established measurement train timetable and the moment of sending it to Eurailscout (approximately three weeks before execution), the timetable still can change. If for example a freight company wants to drive a train just in front or behind the Eurailscout train, the latter can be planned earlier or later if that fits the timetable better. Even when the timetable is processed by Eurailscout into a route book and is sent to the dispatchers, the timetable can change. For example if the dispatcher thinks the arrival track does not suit the daily situation, he can change the timetable. Furthermore on the day itself he has the authorization to make changes in the planned schedule if it suits the situation at that moment better.

Focus in this master thesis research will be on the planning process at Eurailscout, keeping in mind the requirements and communication with Dagplan (and Lokaal Plan).

3.5 DONNA (SD)

During this master thesis VPT-Planning was replaced by a new planning system: DONNA. DONNA is developed to make the planning process more efficient and less sensitive for (human) mistakes. As soon as DONNA is replacing VPT, Dagplan and Lokaal Plan will be merged together. This new department is then responsible for the creation of timetables and the communication with the clients. DONNA is developed to make the train scheduling process more transparent, better organized and better to understand for the involved parties. Furthermore the number of involved parties in the scheduling process can be reduced, decreasing the risk of miscommunication. Unfortunately no figures are available about miscommunication in the scheduling process.

Advantage of DONNA is that it allows the planners to create train paths from track to track instead of the current separation of main lines and stations. The system itself will support the planner in finding a suitable time window and locating conflicts. Another advantage of DONNA is that it is partly an internet application, allowing railway operating companies to see their trains and corresponding timetables in the national railway timetable (both graphical as textual). Railway operating companies have the possibility to request changes and follow the planning process via the internet application.

The scheduling of the Eurailscout trains will be performed in DONNA ‘SD’ (in Dutch: DONNA ‘Specifieke Dagen’, translated: DONNA ‘Specific Days’). In this version of DONNA non-regular trains like the inspection trains, maintenance trains and historic trains, will be planned. DONNA ‘SD’ shows the Basic Hour Pattern (BHP, see paragraph 3.2) and allows the planner to schedule the additional trains with minimal changes to the BHP.

During this master thesis research DONNA was gradually rolled out. It will take some time before DONNA is fully implemented and operational. Therefore the research is based on the old VPT system. Where suggested improvements for the current planning process with VPT already (or partly) will be solved with the introduction of DONNA, this will be noted. If improvements in DONNA are necessary for more efficiently scheduling of Eurailscout trains, this will be noted as well.

3.6 Intermediate conclusions

From the paragraphs in this chapter it becomes clear that it is a complex task finding a path for the inspection trains covering all tracks to be inspected. The software package EB-ViCoP provides some features that help the Eurailscout planners in finding a suitable inspection path. In the inspection train scheduling process multiple parties are involved. Because Eurailscout is not able (with DONNA they are) to see timetables at railway lines, their routing plans have a pure theoretical basis. The planners try to include experiences from previous executed inspections into new inspection train paths.

Dagplan and Lokaal Plan are responsible for the timetable creation process. Dagplan communicates with Lokaal Plan about the timetable creation and with Eurailscout about the path to be driven and the final timetable. In this chain of parties the risk of miscommunication is always present. As soon as VPT is replaced by DONNA which includes a merge of Dagplan and Lokaal Plan, the chance of miscommunication in the scheduling process becomes smaller. Unfortunately no statistical figures are available about miscommunication in the scheduling process and therefore this is not further elaborated.

4 Current efficiency Eurailscout

As mentioned in the problem description (paragraph 1.2) the latest contract between Eurailscout and ProRail includes the term that starting 2014 an annual 10% efficiency improvement needs to be established in the execution of the track inspections. To determine whether a 10% efficiency improvement is reached, first the current planning and execution efficiency have to be determined.

In paragraph 4.1 the data used for this analysis are described. Paragraph 4.2 presents the analysis of the current efficiency performance of both the inspection run planning and realization by the trains under consideration. Paragraph 4.3 elaborates on the disturbances that occurred in the execution of the inspections and this chapters ends with a conclusion (paragraph 4.4). More details of the analyses executed, can be found in appendixes A6 and A7.

4.1 Dataset

Besides planning functionalities (see paragraph 3.1), EB-ViCoP also provides functions to evaluate performances. This allows the planners as well as the management to assess the overall performance of the measurement trains.

One of the overviews EB-ViCoP can generate is based on the planned and realized paths of the trains. The software does this by generating a list with measured and total kilometers driven (the difference is the total number of transport kilometers) per run. For the analysis in this chapter these figures are expressed as a ratio: measured kilometers divided by the total travelled kilometers. Expressing efficiency in this ratio allows to evaluate trains individually and to compare trains with each other. A ratio value of 1.0 represents 100% efficiency (all the driven kilometers were measured), a value of 0.0 represents ‘zero’ efficiency[2] or transport only. Table 2 shows an example of one deployment in the campaign of the UFM120 when it is exported from EB-ViCoP. Both planned and realized efficiencies of the deployments in the ProRail campaign are evaluated and compared.

Each row in Table 2 represents a train movement of one deployment (in this case day ‘A’), with the respective details shown in the fourth column. The fifth column displays the total travelled kilometers per train movement, the sixth column the measured kilometers. In the last column on the bottom row the efficiency ratio of this specific day is shown, calculated by dividing the sum of total measured kilometers by the sum of total driven kilometers. Because this ratio is calculated per day and not per train movement, only the ratio in the bottom row is shown.

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[2] ‘Zero’ efficiency may occur in case of measurement system breakdowns for example. In that case kilometres were driven although no inspections could be performed. Sometimes it is necessary to relocate a measurement train to a faraway starting point, to start the measurements on the next day efficiently. During such a transport no measurements are planned resulting in zero percent efficiency.

Table 2: Example export from EB-ViCoP

Dag-details	*Datum*	*Tijd*	*Details*	*Lengte Totaal [km]*	*Lengte Meten [km]*	*Ratio*
A	18-sep-11	9:20:00	(UFM)52333D(Amf V 09:20 - Bkd A 09:23)	2.108	0.000	
	18-sep-11	9:28:00	(UFM)52334D(Bkd V 09:28 - Zlge A 10:13)	90.273	87.947	
	18-sep-11	10:20:00	(UFM)52335D(Zlge V 10:20 - Zlptt A 10:23)	1.859	0.818	
	18-sep-11	10:28:00	(UFM)52336D(Zlptt V 10:28 - Zlge A 10:31)	1.923	0.780	
	18-sep-11	10:40:00	(UFM)52337D(Zlge V 10:40 - Zlra A 10:46)	2.195	1.130	
	18-sep-11	10:51:00	(UFM)52338D(Zlra V 10:51 - Lw A 11:55)	99.676	98.974	
	18-sep-11	12:33:00	(UFM)52339D(Lw V 12:33 - Stv A 13:27)	59.937	59.098	
	18-sep-11	13:30:00	(UFM)52340D(Stv V 13:30 - Lw A 14:19)	59.936	12.756	
	18-sep-11	15:06:00	(UFM)52341D(Lw V 15:06 - Hlgh A 15:34)	25.561	1.902	
	18-sep-11	15:49:00	(UFM)52342D(Hlgh V 15:49 - Gn A 17:23)	81.032	79.794	
	18-sep-11	17:25:00	Rangeerregel 505242 (Gn) van spoor 37 naar spoor 4b	0.974	0.335	
	18-sep-11	17:29:00	Rangeerregel 515242 (Gn) van spoor 4b naar spoor 37	0.974	0.000	
	18-sep-11	17:32:00	Rangeerregel 525242 (Gn) van spoor 37 naar spoor 30	0.890	0.000	
				427.338	**343.534**	**0.804**

In the contract between Eurailscout and ProRail it is stated that the 10% efficiency improvement has to be measured with respect to the year 2012. Because the year 2012 is the period in which this master thesis took place, the year 2011 is used as reference year supplemented with the first half (1st January – 30 June) of 2012. Usage of data from 2011 does not create a problem, because it is comparable with the whole year 2012 regarding the contractual kilometers that have to be measured. In the analysis the data is split into three categories: 2011, first half of 2012 and overall (= 2011 + first half of 2012). Some figures of the dataset used in this analysis, are given in Table 3. Information about the excluded deployment days and other necessary adjustments on the dataset before the analysis can be executed, are elaborated in appendix A5.

Table 3: Dataset overview

			Total number of deployments	**Total remeasurement deployments**	**Total night runs**	**Excluded number of deployments due to inaccuracy**
Planned	UFM120	Overall	137	31	7	2
		2011	96	21	4	1
		2012	41	10	3	1
	UST96	Overall	125	16	10	2
		2011	85	11	6	0
		2012	40	5	4	2
	UST02	Overall	97	11	32	2
		2011	58	7	20	2
		2012	39	4	12	0
Realized	UFM120	Overall	127	31	7	2
		2011	88	21	4	1
		2012	39	10	3	1
	UST96	Overall	114	16	10	2
		2011	76	11	6	0
		2012	38	5	4	2
	UST02	Overall	90	10	30	2
		2011	56	7	20	2
		2012	34	3	10	0

4.2 Efficiency analysis

In this paragraph the efficiency performances of the trains are compared individually and with each other. Appendix A6 presents more analyses for each train separately.

To assess the train specific performance, the data of the 2011 and first half of 2012 are compared to each other and to the overall performance (2011 + first half of 2012), using Microsoft Excel and IBM SPSS Statistics 19. The data are visualized in so called 'boxplots'. A boxplot shows the total range of the dataset with the box marking the middle 50% of the data. Using this graphical presentation the whole dataset is fitted into one graph and some basic properties of the dataset can be read from this visualization.

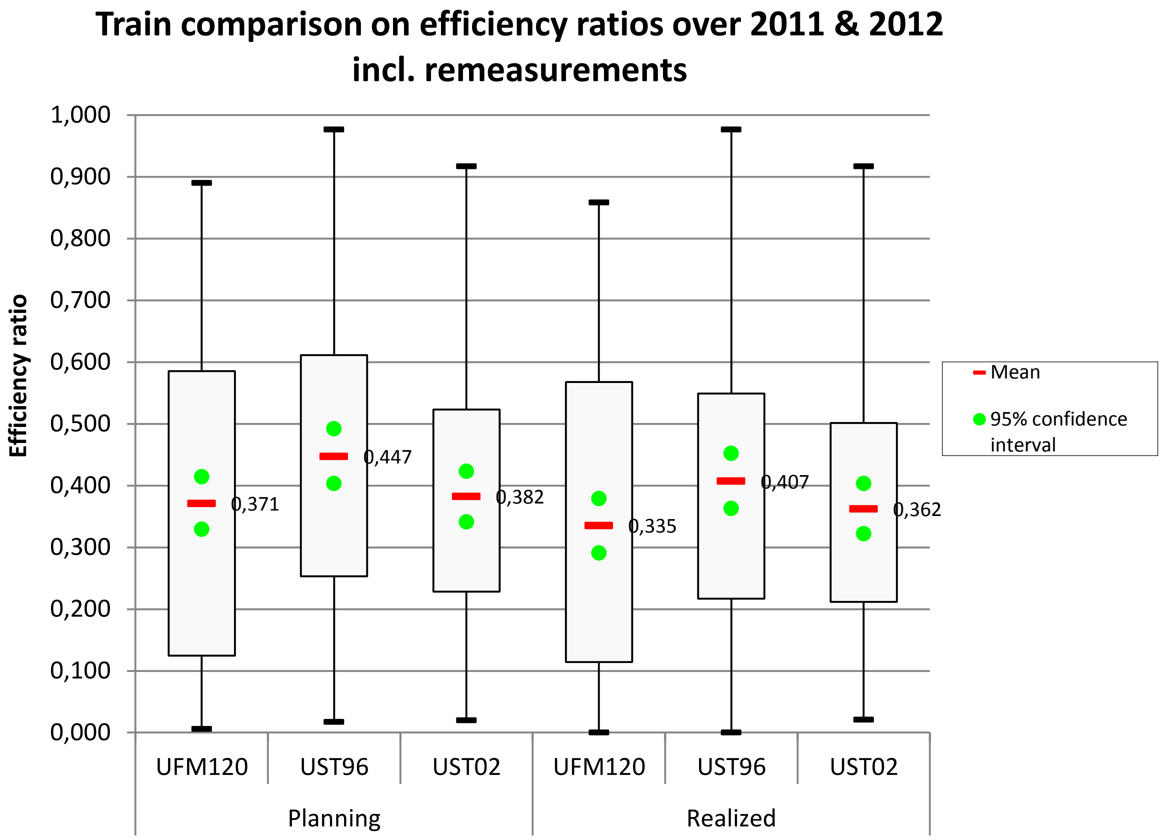
All distributions are tested on normality and (student) t-tested with significance level 0.05 (5%) to check for significant differences between the distributions. Any p-value (chance) larger than 0.05 means the difference is not significant, any p-value smaller means there is a significant difference between two distributions. The shown confidence intervals are based on the means of the distributions.

Tests applied in this analyses are a comparison between the trains on the efficiency in both the planning/realization phases (with and without remeasurements) and a test on difference between the planned and realized efficiencies train specifically. The former test is applied to determine whether there exist significant differences between the trains regarding the planning/execution and if there are what causes may explain these differences. Goal of the latter test is to see whether there exist significant differences between the planning and realization of measurement runs.

Figure 12 presents a boxplot including all three trains under consideration. Immediately visible is the difference between the UFM120 (and with a smaller difference also the UST02) and the UST96 in both the planned and realized efficiency. This difference is significant for both the UFM120 and UST02 in comparison with the UST96 (see Table 4). For the UFM120 this difference can be explained by the higher number of remeasurement deployments by the UFM120 compared with the UST96 (32 versus 16 respectively). Without the remeasurement deployments the difference between the two datasets is not significant anymore (see Figure 13 and Table 5).

Compared to the UST96, the UST02 had a similar number of remeasurement deployments (16 versus 12) and more night runs (30 versus 10) but even when both are excluded the performance difference stays significant. In the data no clear cause for this difference could be found, but the planner of both ultrasound trains provided some insights in a cause. Inspection train UST02 is used to measure single track lines and yards, while the UST96 is used to measure long double track lines due to its long turnaround times. Because the UST02 measures all single track lines it has a lower efficiency rate on those deployments, caused by the fact that in one direction everything is measured on such a single track line while on the way back nothing has to be measured anymore (='transport'). Furthermore the UST02 makes many transport kilometers to measure yards near the larger stations (Amsterdam, Utrecht, Rotterdam, etc.) and to measure the railway lines crossing the border. The UST96 is used for inspecting mainlines to prevent a high number of direction changes which takes substantially more time for this vehicle compared to the UST02.

Comparing the realized efficiency with the planned efficiency for each train individually shows there are no significant differences. Including or excluding the remeasurements give the same results (see Table 4 and Table 5). Table 6 shows the ratio of the remeasurement deployments over the total number of normal deployments. Remarkable is the high number of remeasurement deployments of the UFM120. A cause is found in the disturbances occurring during the realization of the measurements, as discussed in paragraph 4.3.1.

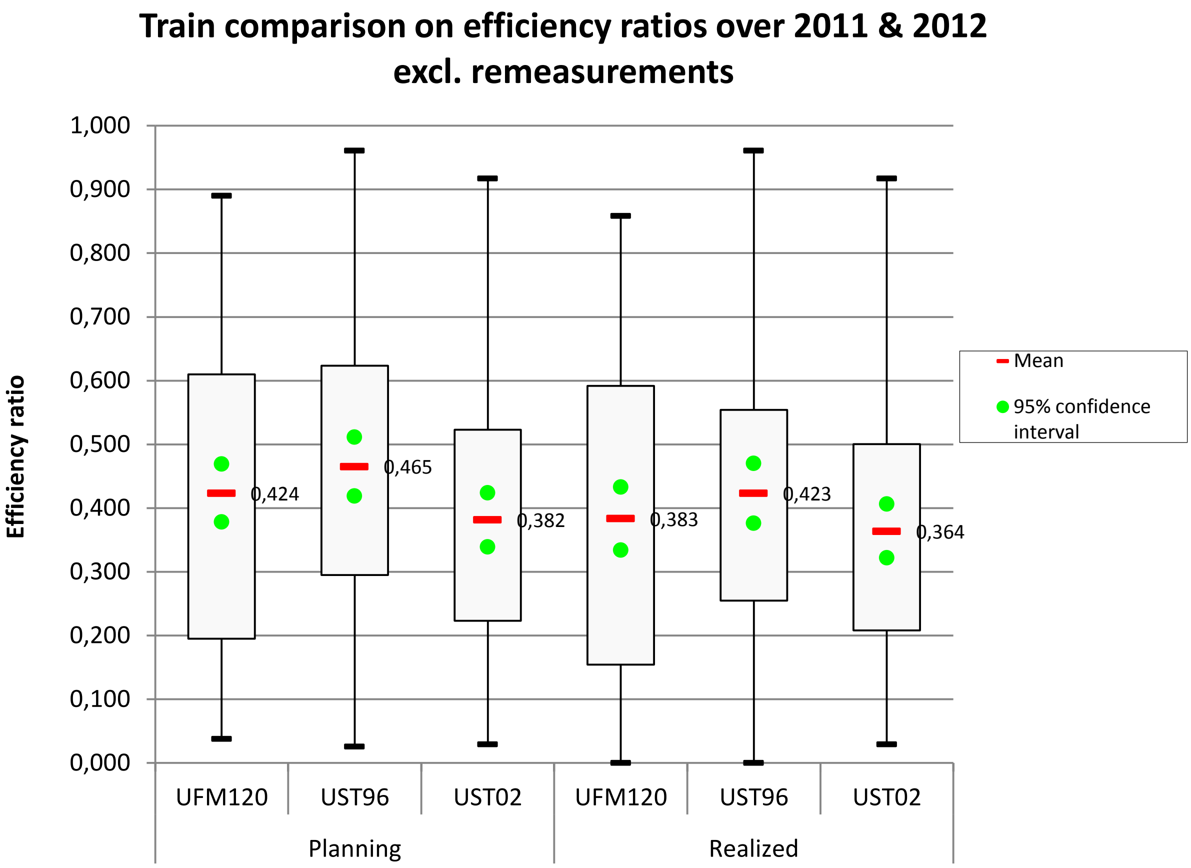


	Planning			Realized		
	UFM120	UST96	UST02	UFM120	UST96	UST02
# Arg	137	125	97	127	114	90
Min.	0.006	0.017	0.020	0.000	0.000	0.021
25th percentile	0.124	0.253	0.229	0.114	0.217	0.212
Median	0.325	0.457	0.383	0.297	0.421	0.355
75th percentile	0.585	0.611	0.523	0.568	0.549	0.502
Max.	0.890	0.977	0.917	0.858	0.977	0.917
Mean	0.371	0.447	0.382	0.335	0.407	0.362
95% CI low	0.329	0.403	0.341	0.291	0.363	0.322
95% CI high	0.414	0.492	0.423	0.379	0.452	0.403
St. dev	0.251	0.249	0.203	0.250	0.240	0.192

Figure 12: Boxplot comparison trains incl. remeasurements

Table 4: (Two sided) p-values datasets trains compared incl. remeasurements

	UFM120 Planning	UST96 Planning	UST02 Planning	UFM120 Realized	UST96 Realized	UST02 Realized
UFM120 Planning		0.015	0.708	0.248	-	-
UST96 Planning			0.034	-	0.206	-
UST02 Planning				-	-	0.490
UFM120 Realized					0.024	0.373
UST96 Realized						0.141
UST02 Realized						



	Planning			Realized		
	UFM120	UST96	UST02	UFM120	UST96	UST02
# Arg	106	109	86	96	98	80
Min.	0.037	0.025	0.029	0.000	0.000	0.029
25th percentile	0.195	0.295	0.223	0.154	0.255	0.208
Median	0.462	0.470	0.385	0.366	0.440	0.366
75th percentile	0.610	0.623	0.523	0.592	0.554	0.501
Max.	0.890	0.961	0.917	0.858	0.961	0.917
Mean	0.424	0.465	0.382	0.383	0.423	0.364
95% CI low	0.378	0.419	0.339	0.334	0.376	0.322
95% CI high	0.469	0.511	0.424	0.433	0.470	0.406
St. dev	0.236	0.242	0.197	0.241	0.233	0.187

Figure 13: Boxplot comparison trains excl. remeasurements

Table 5: (Two sided) p-values datasets trains compared excl remeasurements

	UFM120 Planning	UST96 Planning	UST02 Planning	UFM120 Realized	UST96 Realized	UST02 Realized
UFM120 Planning		0.205	0.183	0.237		
UST96 Planning			0.009		0.205	
UST02 Planning						0.550
UFM120 Realized					0.249	0.542
UST96 Realized						0.062
UST02 Realized						

Table 6: Ratio remeasurement runs over normal runs (data 2011 + first half 2012)

	UFM120	UST96	UST02
In 2011 and first half 2012 realized number of:			
Normal runs	96	98	90
Remeasurement runs	31	16	10
Ratio	**32.3%**	**16.3%**	**12.5%**

4.2.1 Intermediate conclusions

From the presented analysis it is concluded that there is a difference in efficiency between the planning and execution of the inspections. Although not significant for all three trains under consideration, the affected kilometers can be substantial. Reason why paragraph 4.3 elaborates on the causes and identifies possible improvements.

Furthermore it is concluded that there is a difference between the inspection trains regarding the efficiencies. Remarkable is the high performance of the UST96 in comparison with the UFM120 and UST02. The UFM120 and UST02 are more or less comparable in their performances. As cause can be mentioned the fact that the UST96 is used to measure long continuous paths. A change of direction costs relatively much time compared to the UFM120 and UST02 due to the necessary drive around the flat car by the measurement coach. The UFM120 and UST02 drive more paths in which multiple turnarounds have to be made. Both trains are used to measure single track lines in contrast to the UST96. Single track lines have by definition a lower efficiency rate due to the fact that in one way everything is measured, while on the way back most (or all) tracks already have been measured.

Remeasurements have a negative effect on both the planned and realized efficiency, caused by the relative higher number of ‘transport’ kilometers compared to the measured kilometers. In the remeasurement runs a selection of ‘missed’ track sections from previous runs are combined into one path to cover these tracks sections once again. Coupling the ‘missed’ track sections cost many transport kilometers resulting in a reduction of the efficiency ratio. When excluding the remeasurements from the analysis the difference between the performances of the UFM120 and UST96 becomes insignificant, while it stays the same between the UST02 and UST96. Cause for the latter is that the UST02 measures all single track lines and it makes many transport kilometers to measure station yards and border crossing railway lines which cannot be measured with the UST96.

4.3 Causes for differences between planning and execution

Paragraph 4.2 presented a comparison between the planned and realized efficiency. In all cases there exist a difference between them. In this paragraph causes for these differences are evaluated. Like the current efficiency analysis this evaluation is made over the time period 2011 and the first half of 2012.

The evaluation is based on lists containing detailed information about disturbances of the inspections. These lists are made by the Eurailscout planners in cooperation with Eurailscouts DPC (Data Processing Center). In these lists only the track sections are included that should but could not have been measured due to any cause. Deviations of the planned ‘transport’ sections of an inspection run are excluded of this list because these deviations do not influence the measurements itself.

Because these lists are made by Eurailscout one could assume these lists are biased towards Eurailscout regarding remeasurement cost compensation. The opposite is true: all the disturbances and their consequences are communicated with ProRail, which in turn checks the list with their own data. In case ProRail could be held responsible for disturbances they compensate Eurailscout. Because of this check the disturbance lists need to be reliable.

Several categories are used to sort the disturbances, which are registered per train movement in a measurement run. Thus in a measurement run multiple types of disturbances can occur, for example in one inspection deployment multiple measurement system failures and a ProRail emergency can occur. Logically ‘total breakdown’ of an inspection train only happens once a day and is therefore the only category registered in days.

In the list below the used categories are described. Appendix A3 shows the locations in the planning and execution process of the measurements, where disturbances occur.

- *Measurement system*
  Failure of one or multiple inspection systems. The measurement equipment is advanced but also ‘sensitive’ technology. A failure of a measurement system can have quite large effects on the planning. Especially because there are contractual requirements for the time period in which the ‘missed’ track sections or a complete run has to be remeasured. Complicating factor is that some trains have high deployment frequencies making rescheduling of ‘missed’ track sections a difficult exercise.

- *Wrong path by dispatcher*
  Dispatchers assigning other paths to the inspection train as planned. This can have all kinds of causes:
    - Trains occupying the requested track(s)
    - Scheduling conflicts (double assignment of a track)
    - Priority for other trains (most of time passenger trains)
    - Traffic controller is unfamiliar with the requirements of the measurement trains
    - Etc.

- *Tracks occupied*
  Other trains occupying tracks to be inspected.

- *Emergency ProRail*
  Any emergency occurring at the rail network, like road/rail or rail/rail collisions, trackside fires, unauthorized people in the track, etc.

- *Tracks out of service unforeseen*
  Track failures like defects on switches, signals, railroad crossings or emergency maintenance, etc.

- *Tracks out of service foreseen*
  In case tracks are out of service due to planned maintenance work
  (for example at track or station) this category is used.

- *Train technical*
  Failures of the inspection train not related to any measurement system. If due to a technical failure of the train a whole measurement day is cancelled, this is assigned to the category ‘Total breakdown’.

- *Total breakdown*
  Failure of the equipment causing cancellation of a whole measurement day before it is started. Also in case weather circumstances cause cancellation of a whole day, this category is used.

- *Weather circumstances*
  Bad weather circumstances (snowfall, thunderstorms, etc.) impeding the execution of the measurements.

- *Route knowledge*
  A train driver which does not have the required experience to drive a specific route and consequently is not admitted to drive the inspection train there.

- *Capacity limitations*
  If a track section is used close to its capacity and consequently no path is available for the inspection train, this disturbance category is used.

- *Timetable exceeded due to delay*
  Especially the ultrasound trains are not always able to drive with the speed as scheduled. The ultrasound inspection trains are deliberately planned with a higher measurement speed as they can drive, to keep them in a specific regime. All trains on the Dutch rail network drive in a certain regime (e.g. passenger or freight train regime) based on the type of train and its speed. Basically the inspection trains drive under the freight train regime. A train with a maximum speed lower than 60km/h, is categorized in a special transport category. Disadvantage of this special transport category is that it has much more limitations and planning requirements, reason why Eurailscout prevents their trains from running in this category. By requesting timetables for the ultrasound trains with speeds not lower than 60km/h, this is prevented. Planning the inspection trains in the freight train regime, results for the ultrasound trains in a high risk of driving delayed. When this is causing too much knock-on delays for other trains, it will be directed off the mainline by the dispatcher. Next the ultrasound train has to wait until a suitable train path becomes available to continue the measurements.

- *Else*
  Category containing other types of disturbances not possible to assign to the previous mentioned categories (shortage of train personnel or accidents with a Eurailscout train for example).

The lists with the disturbances occurred during inspection runs contain also information about the responsible party. In the summation below these parties are listed:

- *Eurailscout*

- *ProRail dispatcher*
  Responsibilities that specifically can be pointed to ProRail dispatchers

- *ProRail general*
  All responsibilities that can be pointed to ProRail not being responsibilities of dispatchers

- *NS Dagplan*

- *NS Lokaal Plan*

- *None*
  Disturbances of which the responsibility cannot be pointed to any party. E.g. weather circumstances

- *Unknown*
  If the lists do not mention a responsible party, this category is used

To present a complete overview all the categories included in the disturbance lists are used. In view of the research objective of finding possible improvements in the planning and execution of the inspection runs, only disturbance categories and responsible parties Eurailscout can influence are important. In the next summation these are listed. Also the means Eurailscout can use to influence the specific party are mentioned.

- *Disturbances*
  - Measurement system
  - Wrong path by dispatcher
  - Tracks occupied
  - Tracks out of service foreseen
  - Train technical
  - Total breakdown
  - Route knowledge
- *Responsible parties*
  - ProRail dispatcher
    Method: inspection run route book, direct contact by telephone or e-mail
  - ProRail general
    Method: direct contact by telephone/mail with regional and national train traffic control
  - NS Dagplan
    Method: inspection run script, direct contact by telephone, e-mail or meetings
  - NS Lokaal Plan
    Method: no direct contact (possible), communication via NS Dagplan

Most of the disturbances mentioned assignable to the above listed parties, may be influenced by Eurailscout for improvement in the future. Chapter 6 present possible improvements Eurailscout can initiate.

4.3.1 Disturbance analysis UFM120

Based on the disturbance lists of the UFM120 measurement train, the following figures can be distilled:

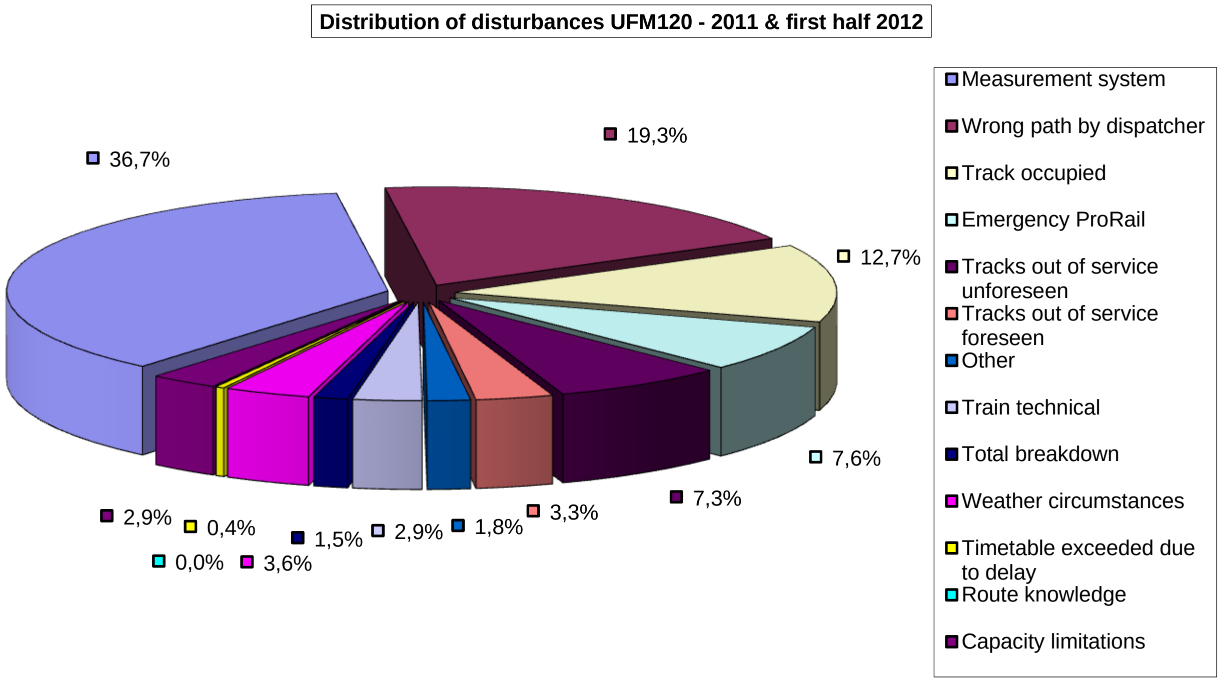


Figure 14: Distribution of disturbances occurred in realization measurements UFM120

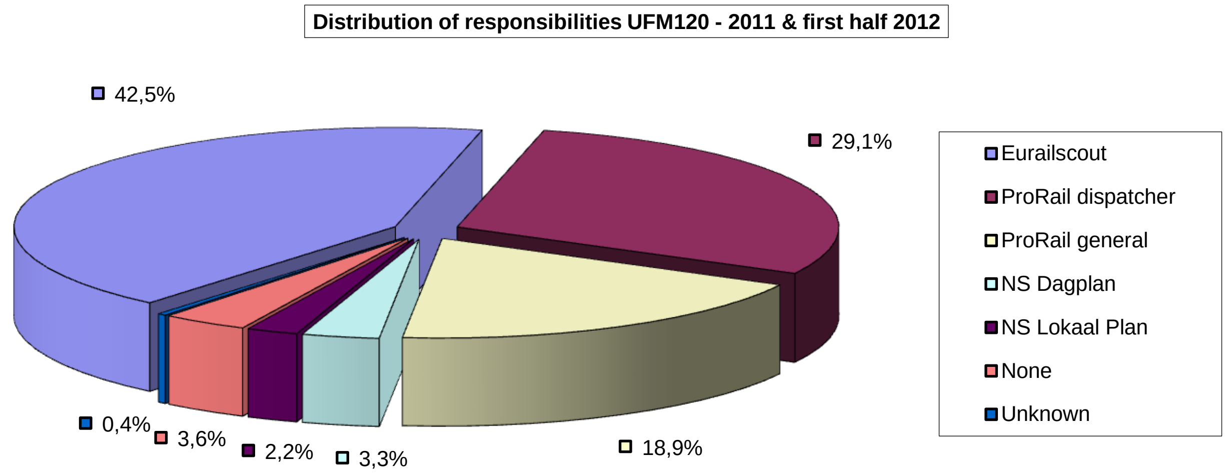


Figure 15: Distribution of responsibilities measurement disturbances UFM120

Looking at Figure 14 and Figure 15 it can be seen that most disturbances in the realization of the inspections by the UFM120 are caused by one or multiple defects on the measurement systems. This is followed by wrong path assignments by dispatchers and inspection track occupations (respectively 37%, 19% and 13%). Figure 15 shows that approximately 43% of all disturbances can be assigned to Eurailscout followed by 29% to ProRails team of dispatchers and 19% to ProRail in general. At the same time both NS Dagplan and Lokaal Plan do not have a high share in the disturbance responsibilities, implying relative few scheduling problems in the realization phase.

Both Figure 14 and Figure 15 describe the occurrence frequency of the disturbances but do not present any scale about the impact on the planning and realization. In appendix A7 figures about the scale of the impact the disturbances have, are shown. The disturbances are therefore expressed in the average affected kilometers. The figures in the appendix demonstrate that the disturbance category with the highest impact is (logically) a total breakdown, followed by train technical and measurement systems failures. Regarding the total affected measurement kilometers, the assignment of wrong paths by dispatchers, inspection track occupations and emergencies also have an high impact on the planning of the UFM120, due to the fact that they occur often.

Due to the large amount of inspection systems mounted on the UFM120, a failure of one of them already requires a remeasurement run. Consequently the UFM120 had substantially more remeasurement deployments compared to both ultrasound trains (see Table 6 in paragraph 4.2).

Overall the conclusion is that for the UFM120 many of the deviations from the planning are caused by malfunctioning measuring equipment or defects on the train itself. Responsible for relative large disturbances is ProRails team of dispatchers by assigning wrong paths to the train and having inspection tracks occupied by other trains.

4.3.2 Disturbance analysis UST96 and UST02

When the same analysis is performed for both the UST96 and UST02, the following figures occur:

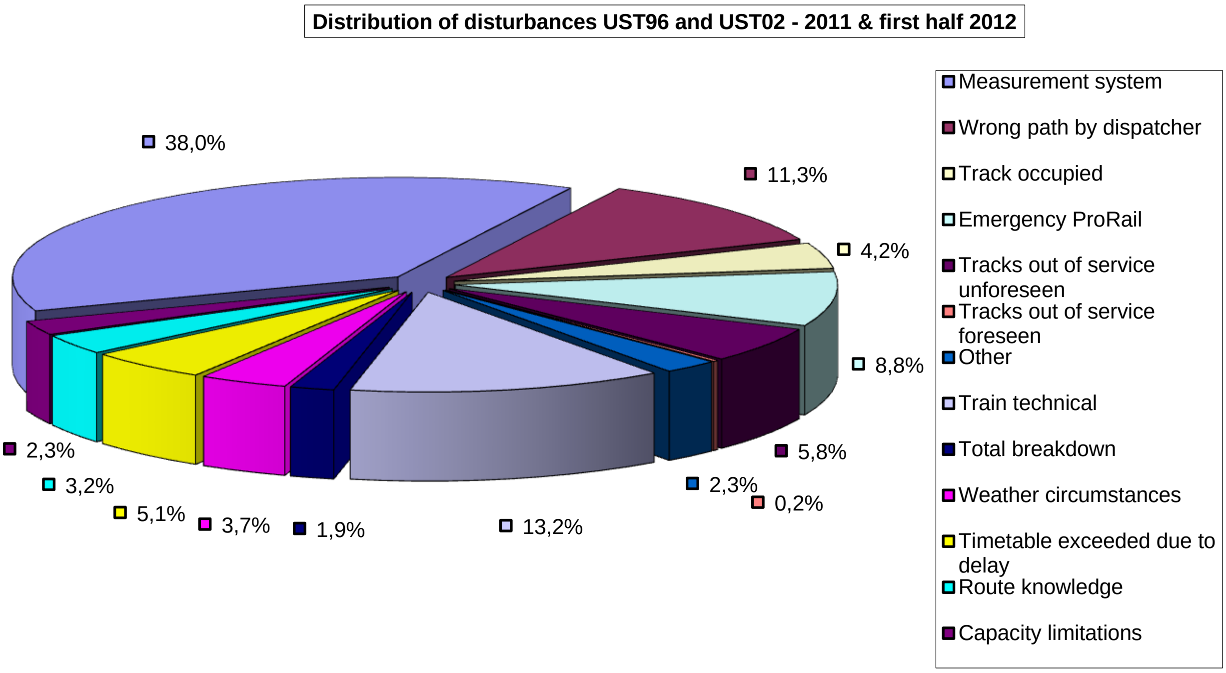


Figure 16: Distribution disturbances occurred in realization measurements UST96/UST02

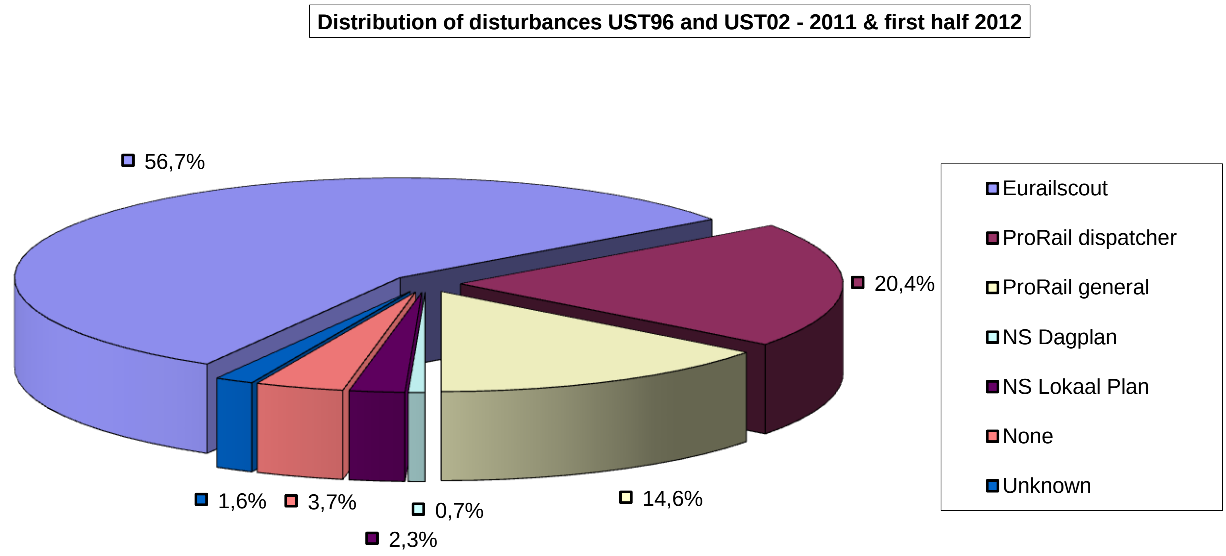


Figure 17: Distribution of responsibilities measurement disturbances UST96 and UST02

Figure 16 and Figure 17 show that most disturbances in the measurements of the UST96 and UST02 are caused by failures of the measurement systems, train technical failures and dispatchers assigning wrong paths (respectively 38%, 13% and 11%). Figure 17 shows that the main responsible party is Eurailscout (57%) followed by ProRails dispatcher team (20%) and ProRail in general (15%). As with the UFM120, the shares of NS Dagplan and Lokaal Plan are relatively small implying again few scheduling problems in the execution of the measurements. Appendix A7 contains more details about the inspection disturbances for both USTs.

Like with the UFM120 the total breakdown disturbances have the highest impact on the planning and execution of inspection runs, due to the fact that these days have to be planned again. Based on the impact for a single occurrence of a disturbance the total breakdown category is followed by train technical failures, lack of route knowledge and failures of the measurement systems. Regarding the total affected kilometers (see appendix A7) the categories ‘emergency ProRail’ and ‘delays causing timetable exceedence’ must be added to the list of disturbances as well for having a high impact on the planning of both ultrasound trains.

4.4 Conclusions efficiency analysis

From the performance analysis of the inspection/measurement trains under consideration, the conclusion is that the planned efficiency is in all cases slightly better in comparison with the realized efficiency. In almost all cases the differences are not significant. For the purpose of this research however the disturbances are studied to determine whether improvements in this field are possible.

The difference between planning and execution is caused by many types of measurement disturbances that occur. Most of them are related to failures of the measurement systems or train technical failures for all three trains. Another type of disturbance with an high impact is the assignment of wrong paths by dispatchers, a responsibility of ProRails team of dispatchers.

Few disturbances can be assigned to NS Dagplan or NS Lokaal Plan, implying relative few problems during the inspections that can be traced back to the scheduling process.

For the year 2011 and the first half of 2012 together, all disturbances led to many remeasurement deployments: for the UFM120, UST96 and UST02 respectively 31, 16 and 10 remeasurement deployments on a total of 96, 98 and 80 inspection runs (see Table 6). The higher number of remeasurements for the UFM120 can be explained by the amount of inspection systems this train uses (more than 10 systems at the same time). As soon as one of these systems fails, most of time a remeasurement run has to be made to cover ‘missed’ track sections.

Taking into account all the disturbances that can occur in the daily practice and the fact that these trains are scheduled between the busy Dutch passenger rail services, it can be stated that the overall performances of these three trains are quite good already. The analyses showed that there are no significant differences between the planning and execution of the measurements. Some improvements can be found in solving the disturbances. However because the analysis showed that the execution of the measurements do not differ significantly from the planning, no further research is done into this subject.

The next section of this research focusses therefore on the planning methods used to create the inspection routes and whether improvements in these methods are possible. Chapter 5 elaborates on this study and the results obtained.

5 Routing models

As the analysis in chapter 4 showed, there are no significant differences in efficiency between the planning and execution of the inspections. Some improvements can be distilled from the disturbances occurring, but further efficiency improvements must be searched in the way the trains are planned.

Presented in this chapter are routing models to search for more efficient routing methods. Outcomes are used to develop recommendations for improvements in the real planning of the inspections by train. The generated paths are compared on their efficiency ratios and the time required to drive the path.

Included in this chapter are the modeling approach, setup of the models, results and conclusions that can be drawn from the results. Paragraph 5.1 first discusses the routing philosophies that are or can be used and the chosen philosophies for the routing models, followed by the precise purpose description and required input in paragraph 5.2. Trade-offs, assumptions and limitations are discussed in paragraph 5.3. The functioning of the models is elaborated in paragraph 5.4, paragraph 5.5 contains a calibration of the models. Paragraphs 5.6 and 5.7 elaborate about the results obtained and the conclusions that can be drawn from these results.

5.1 Routing methods for inspection trains

Most important part of the planning process is the creation of the paths. As described in chapter 3 the Eurailscout planner creates a path on a schematical map of the railway network based on the contractual requirements, train specifications and experiences from previous runs. The planner of Eurailscout creates a path without taking into account other railway traffic (data is not – publicly – available). However, based on his experience, he includes solutions for limitations imposed by other railway traffic. Later on in the process of timetable generation, all the limitations imposed by the daily train traffic are dealt with.

Except for selecting a path covering the tracks to be inspected, the Eurailscout planner has to deal with many other constraints. For example: the maximum continuous path possible (both in time and distance), water/fuel intake locations, turnaround times, etc. With these restrictions the planner tries to create an efficient path based on previous runs and experience. In order to do so several main routing methods can be used:

- *Measuring long lines*
  Method in which the paths are made as long as possible without a change of direction. The path Amersfoort – Amsterdam Central station – Den Helder and vice versa, is an example of a path created following the principle of driving long lines (see Figure 18).

Figure 18: Example path 'measuring long lines' (source map: www.ns.nl)

Advantages:

- *Long continuous run*
- *Few direction changes, saving time*

Disadvantage:

- *Sensible for disruptions due to the long distance over multiple corridors*

- *Measuring corridors*
  Inspection runs on a specific corridor (for example Utrecht Central station – Arnhem, green line in Figure 19). The measurements are executed on all tracks to be measured on this corridor, before continuing to the next one. So, the inspection train will be crossing this corridor several times in both directions until all tracks that need inspection are driven, before continuing to the next corridor (for example Arnhem – Nijmegen, blue line in Figure 19).

  Advantages:
  - *Focus inspections only at one corridor at the time, decreasing the risk of missing track sections*
  - *Once covered this corridor may be crossed over any track in subsequent runs*

  Disadvantages:
  - *Hindrance for other train traffic at corridor*
  - *Risk of finishing the measurements at the starting station while inspections need to continue at station at other end of corridor, causing much 'transport' kilometers*

Figure 19: Example path 'measuring corridors' (source map: www.ns.nl)

- *Measuring regions*
  Inspections are executed in a specific region. For example all tracks in the northeast region of the Netherlands being measured in two or three days.

  Advantage:
  - *Whole area covered in few days*

  Disadvantages:
  - *Train and crew possibly need to stay overnight in the region to prevent time loss and transport kilometers when returning to home base Amersfoort*
  - *When measurements are finished the train possibly needs to return to the region for remeasuring 'missed' track sections*

To study the most efficient routing method, the list of routing methods is supplemented with the following new routing method:

- *Measuring yards first*
  In advance of inspecting an open line, the yards at the larger (intercity) railway stations (Amsterdam-, Utrecht-, Rotterdam-Central station) are completely inspected. This method makes it possible to cover one or two large stations during a day. Advantage of this method is that as soon as these inspections are finished, it does not matter how these stations are passed in following inspection runs. This makes the routing and planning easier at these highly utilized locations.

This set of routing methods is not complete, one can for example also think of:

- *Measuring/driving circles*
  Especially for the UST96 which needs a flat car for detection purposes, driving in circles can be useful. When driving in circles the train does not have to change direction along its path (see for an example Figure 20). This will save turnaround time which are in case of the UST96 20 minutes. However this method is not used in the routing models because there are only a few (continues) circles possible in the Dutch railway network. Furthermore these circles cannot easily be interconnected which makes this method in advance inefficient.

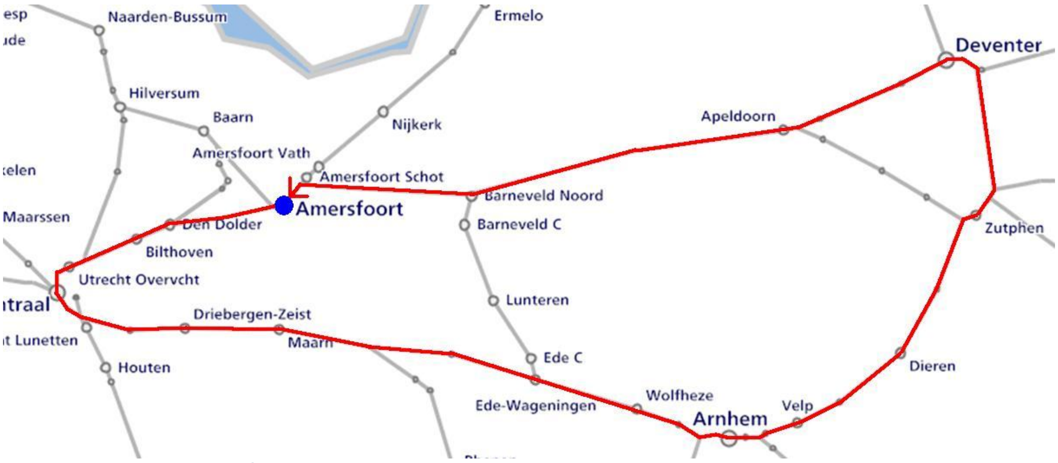
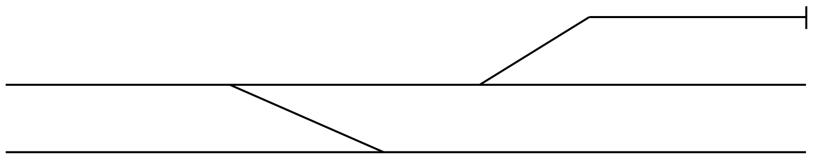


Figure 20: Example of a possible routing according to the routing method 'driving circles' The path starts and ends in Amersfoort without a change of direction (source map: www.ns.nl)

- *'Zigzagging'*
  With zigzagging the measurement train stops at each switch on the mainline, to measure the switch first before continuing to the next switch (for an example see Figure 21). Like measuring in circles this method is in advance inefficient and even impossible to carry out. Due to the busy Dutch railway network it is not allowed to stop on the mainline, to measure the switch in all possible crossing directions before continuing the inspection on the mainline. This would cause too much hindrance for other rail traffic. The VST-trains (video capturing) use a derived version of this method, however the VST-trains are no subject of study in this research (see chapter 1).

Track layout:



Example path according to ‘zigzagging’:

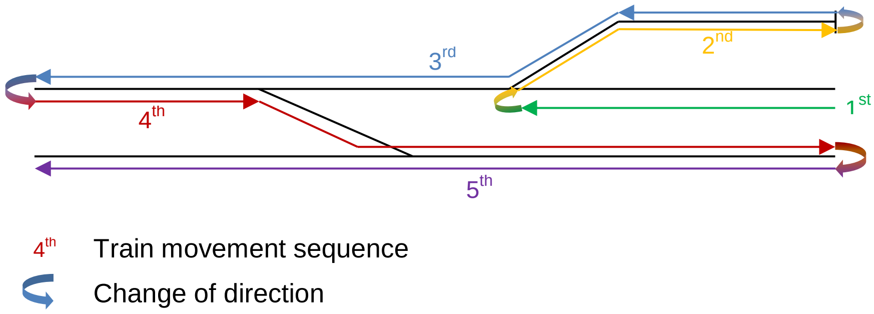


Figure 21: Example of a possible path according to the routing method ‘zigzagging’

Currently the measurement train paths are created heuristically based on previous runs adapted with the knowledge and experience from the planners. The resulting paths are most comparable with ‘measuring long lines’. However, locally also influences of the other mentioned routing philosophies are present.

In this thesis the choice is made to study the philosophies ‘yards first’ and ‘measuring corridors’, because they are the most interesting for Eurailscout. Routing philosophy ‘long lines’ is not studied because the current routes are basically derived from this routing method. ‘Measuring regions’ is left out of the evaluation because this method is composed of the above mentioned methods which are executed during multiple days. Furthermore the network needed to test this routing method would get too large for this research.

The following paragraphs present the setup of the routing models and results obtained.

5.2 Purpose and required input

The purpose, required data and the setup of the models are discussed in this paragraph. In paragraph 5.3 the trade-offs, assumptions and limitations are elaborated.

Purpose

Purpose of the models is to determine a theoretical most efficient (efficiency ratio optimum) path according to one of the routing philosophies under consideration, on the line Utrecht-Amsterdam-Alkmaar for the UFM120, UST96 and UST02. The outcomes are compared on overall and map specific efficiency ratios (see Table 7 for details about how the considered line is split up in several maps). Furthermore the results are compared on the time needed to cover the tracks to be inspected. Two models are built, one for each routing philosophy studied.

The results of the models are used to determine whether a more systematic instead of the current heuristic approach can improve the efficiency ratios. Obviously the outcomes of the models are purely theoretical and adjustments have to be made to compare the outcomes with the reality. However the outcomes indicate theoretical possible efficiency ratios for the routing philosophies under consideration and are therefore worthwhile.

Required data
The routing models are built in MATLAB (version MATLAB R2010bSP1), a technical programming software able to solve all sorts of mathematical problems, by writing scripts and usage of integrated solvers. For this research MATLAB was preferred over for example Excel and Labview because of its calculation and visualization abilities and the experience the author already had with this software.

As described previously, the two models are used to find the most efficient routing method for an inspection train over a network. The network used is the railway line between Utrecht Central station and Alkmaar via Amsterdam Central station, see Figure 22. This line is chosen because of its dual character: it is a busy line with multiple parallel tracks between Utrecht and Zaandam, but it contains also a more ‘standard’ track layout between Zaandam and Alkmaar. The track layouts at Utrecht and Amsterdam Central station are complex with many switches and platform tracks. On the contrary the track layout between Zaandam and Alkmaar is more simple with two opposite tracks and some turnouts to overtake tracks at (intermediate) stations. The real length of this line is approximately 82.0 kilometer (measured with Google Earth™ (2013)), the model length is approximately 81.8 kilometer.

This line allows to test the routing philosophies under consideration:

- ‘Measuring yards first’
  The yards at the larger (intercity) stations (Utrecht, Amsterdam, Zaandam, Uitgeest, Alkmaar) are inspected first before the run continues on the other tracks
- ‘Measuring corridors’
  In the model network two corridors are present: Utrecht Central station – Amsterdam Central station and Amsterdam Central station – Alkmaar. For this method it is assumed that changing direction on the open tracks is not allowed and therefore the train must continue to a station at one of the ends of the open track, to change direction there.

The tracks to be inspected are collected from the ProRail contract of 2012. This contract is chosen because the efficiency analysis is also based on the year 2012 (and 2011 which is almost the same contract).

Figure 22: Line used in the MATLAB models (source map: www.ns.nl)

In Figure 23 the input and output of the models is presented.

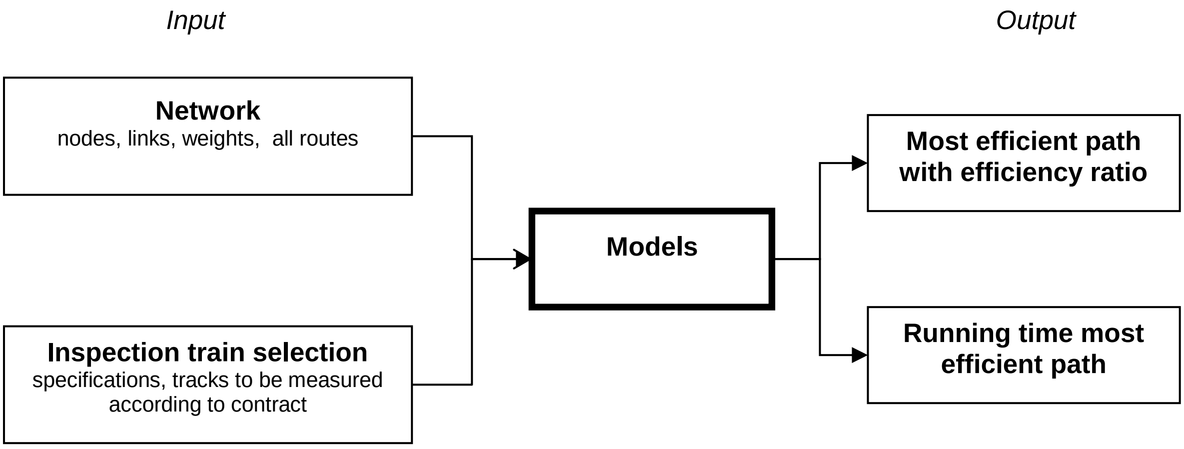


Figure 23: Schematical presentation of the in-/output of the routing models

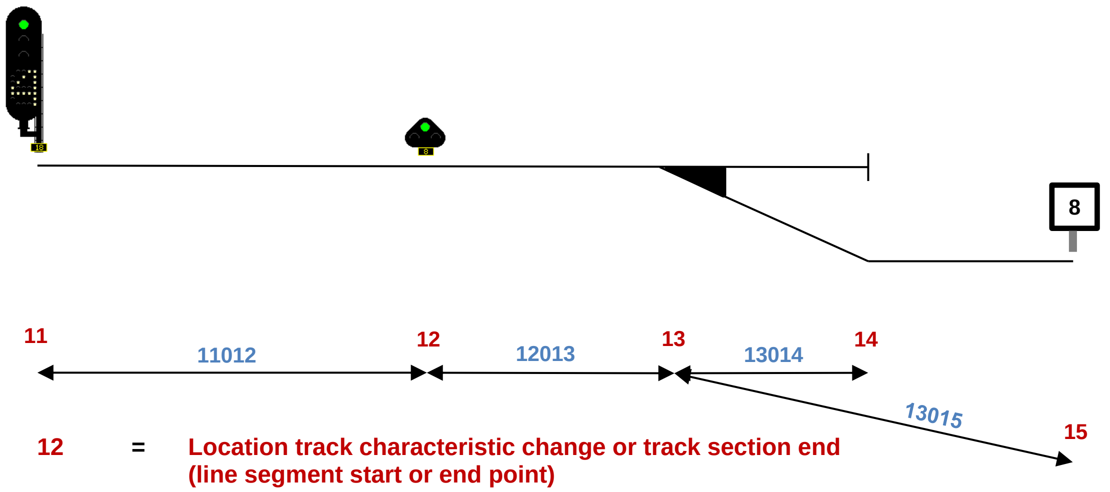
As mentioned in Figure 23 the models need as input:

- Railway network
  The network for the MATLAB models consists of two layers. First layer is the network layout. As used by Peng et al. [3] the network layout is made with nodes and uses undirected links to connect the nodes. The more nodes are in a network the longer it takes to calculate the path. Therefore and for visibility reasons the complete network is split into nine maps, Table 7 presents an overview. Appendix A8 presents the maps.

Table 7: Overview of railway line Utrecht Alkmaar split up over nine maps

Map number	Station or open track	Covered distance [km]	Number of included stations	Connected with map(s)
1	Utrecht Central station	2.1	1	2
2	Utrecht Central station – Amsterdam Central station	34.8	8	1,3
3	Amsterdam Central station	4.9	1	2,4
4	Amsterdam Central station – Zaandam	9.0	1	3,5
5	Zaandam	2.5	1	4,6
6	Zaandam – Uitgeest	9.7	4	5,7
7	Uitgeest	2.2	1	6,8
8	Uitgeest – Alkmaar	14.7	2	7,9
9	Alkmaar	1.9	1	8
Total		**81.8**	**20**	

Data for the network is compiled from infrastructure maps published by ProRail and the Eurailscout planning software EB-ViCoP. From these two sources an Excel file is made containing links with their unique identification number, metadata (max. speed, length), their start/end point and the x,y coördinats of the start/end point. Start/end point of a link can be a signal, new speed regime (indicated by signals or signs), a switch or a buffer stop. Figure 24 presents the method used to convert the real track layout to the model network. A link-id is the start and end point number separated by a zero.



12 = Location track characteristic change or track section end (line segment start or end point)

13014 = Link id

Figure 24: Conversion of real track layout to model network layer 1

Second layer of the model network is the layer only containing the locations of the signals and buffer stops where the measurement trains can change direction. In this second layer the nodes (the signals or buffer stops) are connected by a series of links out of the first layer making up a route in the second layer (see Figure 25).

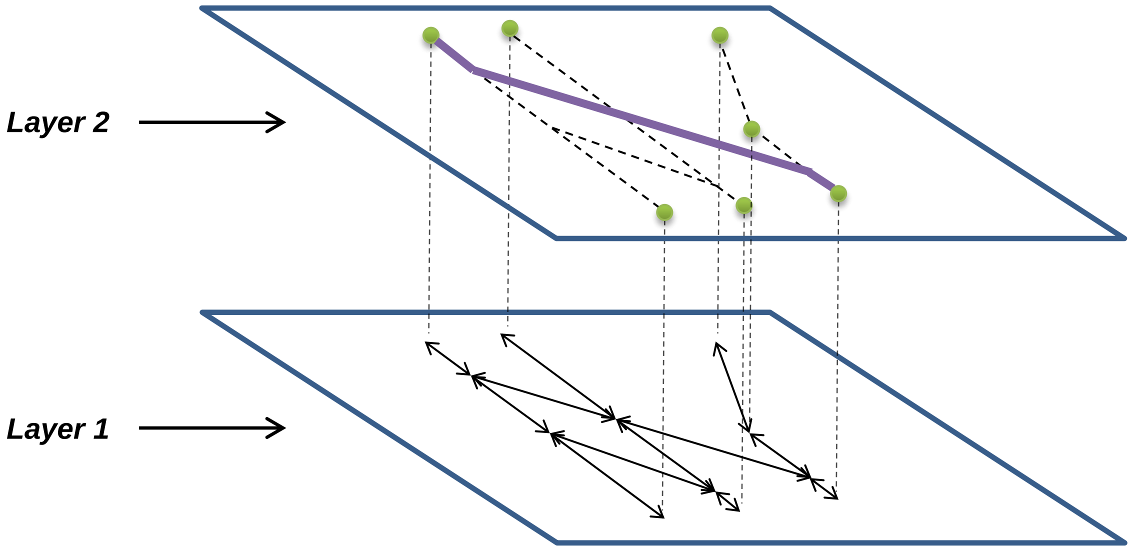


Figure 25: Visualization layers in network
The purple line in layer 2 is connecting two signals via a route containing links of layer 1

From now on the following definitions are used:
Node: signal or buffer stop out of layer 2 (green points in layer 2, Figure 25)
Link: track element from layer 1 (black lines layer 1, Figure 25)
Route: a sequence of links connecting two nodes (purple line layer 2, Figure 25)
Path: a sequence of routes forming a path over the network via multiple nodes

The Excel file containing the network is loaded into MATLAB for further processing. In MATLAB the maps of the network are drawn by plotting the links based on their x,y-coordinates. Only the x-coordinates are on scale, the y-axis has a different scale for visibility purposes. The distances however are approximating reality because they are extracted from the ProRail infrastructure maps.

- Train selection
  As mentioned in chapter 1, each train has its own requirements and limitations. These specifications are stored in another Excel file that is imported into the MATLAB models, as soon as an inspection train is chosen for which the routing models will be executed. The Excel file contains the maximum speeds during measurements/transport and the short and long turnaround times (see Table 8). For both the UFM120 and UST02 the short and long turnaround times are the same. For the UST96 the short turnaround time is 5 minutes (when in turns without driving around its flat car) and 20 minutes when it needs to drive around its flat car. By loading the train characteristics, the contract from EB-ViCoP for the selected inspection train is loaded as well.

Table 8: Train characteristics used in models

Train	Max. transport speed [km/h]	Max. measuring speed [km/h]	Turnaround time long [s]	Turnaround time short [s]
UFM120	120	110	300	300
UST96	100	60	1200	300
UST02	100	60	420	420

5.3 Model trade-offs, assumptions and limitations

During the development of the routing models some trade-offs were made and several assumptions/limitations are dealt with. This paragraph elaborates on the choices made and the limitations the models have.

Trade-offs made

In the development of both routing models several trade-offs were made. Algorithm specific trade-offs are discussed in paragraph 5.4, where the developed algorithms are schematically presented and elaborated. General trade-offs are discussed in this subparagraph.

- *Inspection frequencies are set to 1x for all tracks to be inspected*
  In reality each track section has its own inspection frequency depending on tonnage transported and usage (see paragraph 3.1). For the model all tracks are assumed to be inspected with the same frequency allowing coupling them together into one path. Adding inspection frequencies would increase the degree of complexity in such a way, that finding a solution method would not be possible during the available time period of this research.

- *Only tracks to be inspected on the line Utrecht – Alkmaar are included*
  Especially at the stations there are connections with other railway lines. Also on these lines track inspections need to be executed. Because these tracks are measured at the moment the inspection train departs from the station onto this other railway line, the connecting tracks at the station are excluded from the model. The focus lays on the line Utrecht – Alkmaar only. Including other railway lines requires another model that assesses the routing of the inspection train at a higher network level. This model then needs to determine in which sequence lines need to be driven. Developing this higher level network model is beyond the scope of this research.

- *Network is manually build, not extracted from EB-ViCoP database*
  EB-ViCoP uses a database containing among others the network layout. Using this database is the most obvious, however MATLAB must be programmed to read the data. Beforehand it is estimated that building the network manually requires less time than programming MATLAB to read the EB-ViCoP database.

Assumptions

Several assumptions in the models are elaborated in the following summation:

- The models overall
  - *Inspection runs always start at Utrecht Central station*
    node 75 on map 1, see Appendix A8.

  - *All routing methods end at a node from where the home base in Amersfoort can be reached.*
    On map 1 ‘Utrecht’ this is node 74, on map 3 ‘Amsterdam’ this is node 151, see Appendix A8. This assumption causes the train to return to one of these nodes (the one closest by) if its path ends at another node or another map.

  - *Local (per map) optimization will result in a sufficient reliable and realistic outcome.*
    A model that calculates an optimal path over the whole line between Utrecht and Alkmaar at once, would become too complex for this master thesis. Therefore the assumption is made that solving the routing problem locally (at each map) will results in sufficient reliable and realistic results.

  - *Working time hours*
    According to the current health and safety regulations a maximum number of working hours exists for the train staff. There are some exceptions where under certain strict conditions extension of the shift is possible. In the models this restriction on the maximum working hours is not included with the purpose to obtain an optimal theoretical model.

- Network
  - *An inspection train can only change direction at one of the nodes in layer 2 of the network representation*
    In reality it may be possible that a driver in close coordination with the dispatcher, is allowed to change direction at another location. In the models changing direction is only allowed at the nodes in layer 2 representing signals or buffer stops.

  - *All tracks are undirected*
    All tracks in the model can – if necessary – be driven in two directions. In reality this may not be possible but keeping in mind the purpose of the models (finding the theoretical best efficiency ratio possible) it is allowed.

  - *All routes between any pair of nodes in layer 2 are available*
    Due to other train traffic or safety system limitations, in reality not all routes in a network can be driven although the infrastructure allows it. For the models it is assumed that all routes are available.

  - *The presence of diesel and water intake locations are left out of the models*
    Regarding the purpose of both models, these locations are not considered.

- Inspection train selection
  - *Changing direction is everywhere possible, regardless of the inspection train chosen*
    The UFM120 and UST02 can change direction everywhere. Because the UST96 needs to drive around its flat car when changing direction, it requires a parallel track interconnected with switches. In the efficiency ratios extracted from EB-ViCoP (see chapter 4) this drive around is not included. Therefore these drive around movements are also left out of the efficiency ratio calculation in the models. Furthermore it is assumed that the UST96 may also push its flat car with a maximum speed of 40 km/h at station yards (short turnaround time, see Table 8). When it leaves the station to drive towards the next station via an open track, the flat car must be coupled at the rear of the coach requiring a drive around resulting in a long turnaround time.

  - *Simplified running time estimation*
    Train running time estimation is kept as simple as possible. It is calculated by dividing the length of a track section by the maximum speed allowed or possible (in case the measurement speed is lower than maximum track speed for example). To compensate for acceleration/ deceleration and deviations in the maximum measurement/transport speed, a 10% surplus is added to the calculated running times (see paragraph 5.5 about calibration).

Limitations

To ease the optimal path finding process some simplifications are made in the models. In the previous section the assumptions made are summed. These assumptions affect the outcomes of the models. The summation below lists the limitations:

- *Execution of the optimal path finding process – according to a certain routing method – is performed on a network free of other train traffic*
  Because other train traffic is not present in the models it cannot influence the routing process. Outcomes of the models are therefore completely theoretical and not one to one comparable with reality

- *Only tracks to be inspected belonging to the line Utrecht – Alkmaar are included*
  As mentioned in the model trade-offs (see page 41) only the tracks to be inspected belonging to the line Utrecht – Alkmaar are included in the models. When another model is developed that determines the sequence in which lines are driven, the tracks that could be assigned to the line Utrecht – Alkmaar can be determined better. Now the station tracks are assigned manually to the line Utrecht – Alkmaar.

- *The connecting stretches between the found path and the home base in Amersfoort, are not included in the model*
  For both models it is assumed that all paths start at node 75 in Utrecht (map 1) and end at node 74 in Utrecht or 151 in Amsterdam (respectively maps 1 and 3). The path section between these nodes and Amersfoort is not included because it is part of another railway line (respectively Utrecht-Amersfoort and Amsterdam-Amersfoort). Because this line is not in the studied network the possible efficiency on this stretch cannot be determined and is therefore neglected.

5.4 Functioning routing models

With the previous described input, the models are now able to calculate the optimal inspection paths. This paragraph describes the steps the models execute to evaluate the routing method. Each model is discussed in a separate paragraph: model 1 ‘Yards first’ in paragraph 5.4.1, model 2 ‘Corridor routing’ in paragraph 5.4.2. Next the mathematical backbone of both models is presented in paragraph 5.4.3 followed by an elaboration on the running time calculations in paragraph 5.4.4. Referenced MATLAB network maps can be found in appendix A8.

5.4.1 Model 1: ‘Yards first’

Purpose of the ‘yards first’ model is to inspect all tracks at the larger yards first before measuring the open tracks, as also mentioned in paragraph 5.1. As soon as a yard is inspected completely, the shortest path covering the largest distance of tracks to be measured on the open track to the next large yard, is selected. From Utrecht to Alkmaar this process is continued until on the way back (Alkmaar – Utrecht) station Uitgeest is reached (see Figure 26). Uitgeest is the first station on the way back from Alkmaar towards Utrecht where all tracks already have been inspected. In Uitgeest the shortest path is chosen from the entry point of the station towards the exit point. The entry node is known from the path on the open track between Alkmaar and Uitgeest. The exit node is determined by selecting the best path (shortest path containing the largest distance of track to be measured) on the open track between Uitgeest and Zaandam.

On the open track between Uitgeest and Zaandam the same process as applied to inspect the yards first is used to measure the remaining tracks on this open track. Starting at Zaandam a new open track routing algorithm is applied on the open tracks between Zaandam – Amsterdam and Amsterdam – Utrecht. This second algorithm is used to let the inspection train drive an open track several times to cover all remaining tracks to be measured. At the stations on both ends, the algorithm choses the shortest path to the next best start node on the open track, determined by preselecting the next best open track path.

As soon as one open track is completely covered, the shortest path through a station is selected towards the start node on the next open track. This start node is again determined by preselecting the best path on the next open track. When the last tracks on the open tracks are covered, the algorithm selects the shortest path towards the nearest model exit point (see paragraph 5.3 ‘assumptions’).

Figure 26 schematically visualizes the elaborated algorithm scheme. In the next paragraphs the ‘station routing’ and ‘open track routing’ algorithms are discussed in more detail.

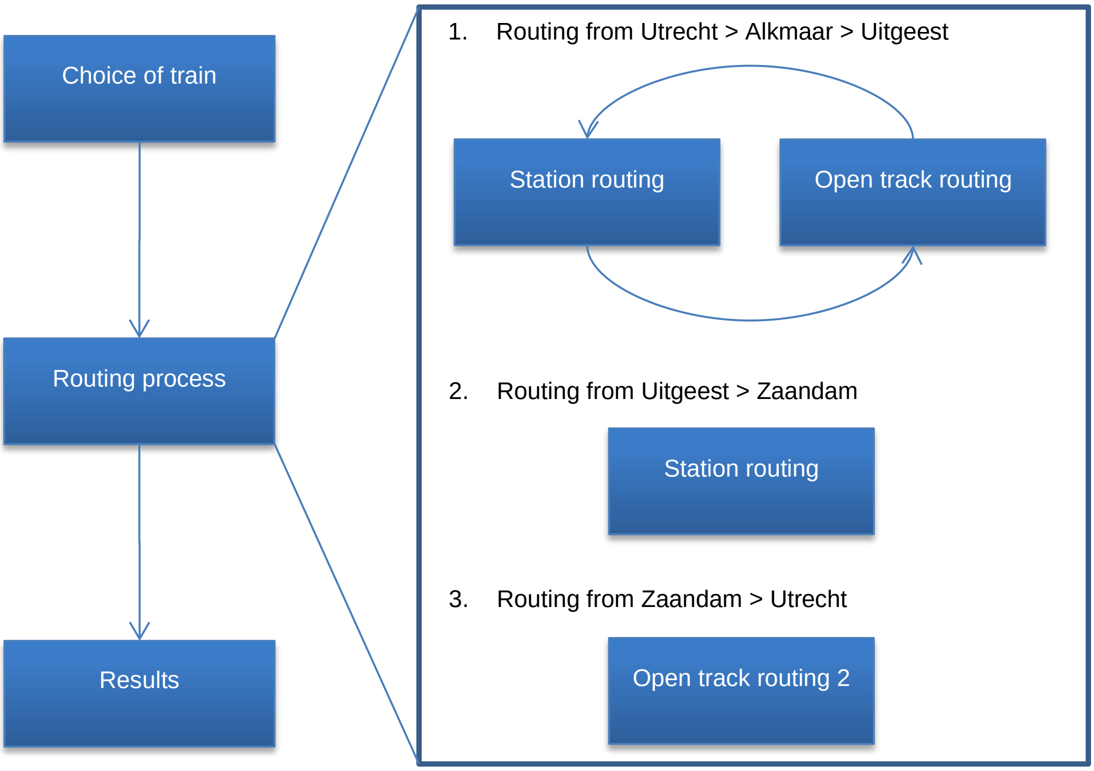


Figure 26: Schematical representation 'yards first' algorithm

Station routing

The station routing process starts by creating an assignment map (Bovy et al. [23]) in which on the vertical axis all routes between every directly connected node in layer 2 are presented, and on the horizontal axis the links in layer 1 that need to be inspected/measured (see the example in Figure 27 and Table 9). All routes directly connecting nodes are predetermined. The assignment map is filled using a determination process. If a link to be measured is present in a route on the horizontal axis, an '1' is placed in the corresponding cell and otherwise a '0' is placed. On top of each column the sum of that column is written, representing the number of routes the link to be measured occurs in.

Purpose of the assignment map is to generate a list of routes that need to be driven to cover the links to inspect on the selected map. Generating this list starts with searching the 'summated column' row for links that occur in one route only, or in other words: search the row for an '1' (from left to right). These routes must be driven to cover the specific link. The row of the route containing the link to be measured, is checked whether there are more links to be measured in this route. All columns of links contained in the selected route are removed from the assignment map. As soon as all the ones in the 'summated column' row are covered, the next minimum value is looked for (again from left to right). In case this value occurs multiple times in this row, efficiency ratios of the routes in which this link is present are calculated (total length links to be measured in route over total route length). The one with the highest efficiency ratio is chosen. In case multiple routes have the highest efficiency ratio, the route with the longest measuring distance is chosen. If even then multiple options are left, the first route is selected.

Again the columns of the links to be measured present in the selected route, are removed from the assignment map. Until the assignment map no longer contains links to be measured, this process is continued. In appendix A9 the process as elaborated is explained using the example situation shown in Figure 27 and Table 9.

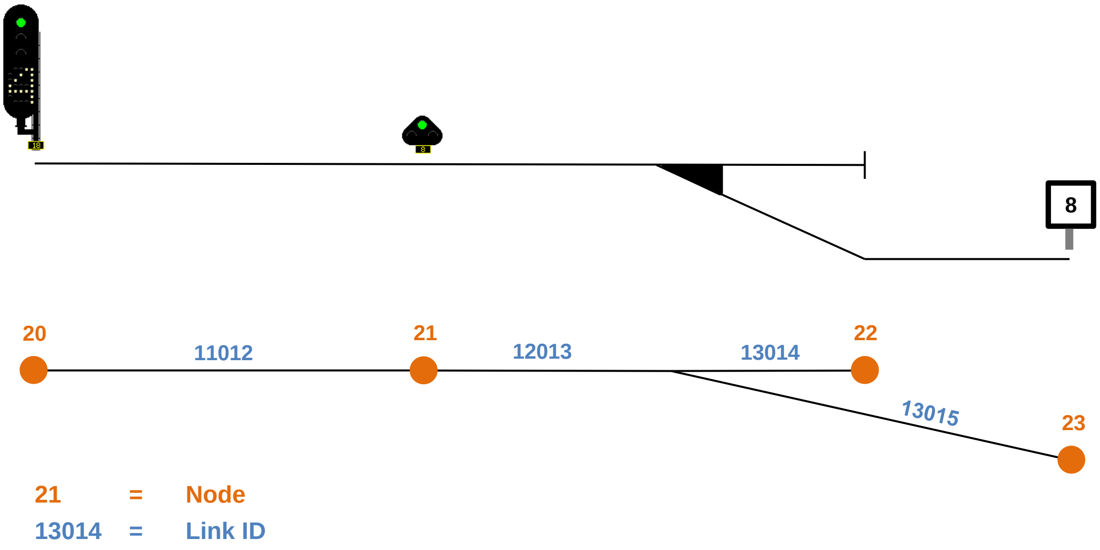


Figure 27: Example situation
(Same situation as shown in Figure 24)

Table 9: Assignment map belonging to example situation in Figure 27

			Links to be measured			
		Link-ID	11012	12013	13014	13015
		Link length	150	50	50	100
		Occures in … routes	1	2	1	1
Start node	End node	Route length [m]				
20	21	150	1	0	0	0
21	22	100	0	1	1	0
21	23	150	0	1	0	1

Result of filtering the example assignment map in Table 9 is the following list of routes that need to be driven to cover all links to be inspected:

Routes to be driven:
- 20-21
- 21-22
- 21-23

Next step in the station routing algorithm is finding all shortest paths between every pair of nodes present in the map using the Dijkstra algorithm [23], following by determining whether the nodes in the list of routes to be driven, are odd or even. An odd node is a node where an odd number of routes is connected to. To create a path out of the list of routes, all nodes that will be passed have to be even except for the start and end node. These two nodes are specified on beforehand and both will be crossed once: start node when the path starts and the end node once when the path is finished and continues to the next map.

Making all nodes even is the last step before the path can be created. In the set of odd nodes it is checked which nodes can be directly connected. For the remaining odd nodes stepwise the shortest path to any of the remaining odd nodes is checked. The path with the shortest distance is route by route added to the list of routes to be driven. In the example situation of Figure 27 (if the start node is 20 and end node is 22) one route must be added to make all other nodes even: route 23-21.

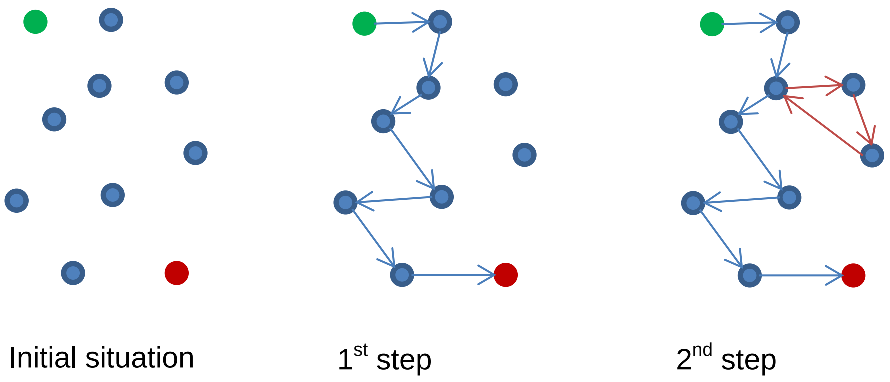
Routes to be driven:

- 20-21
- 21-22
- 21-23
- 23-21

When all nodes are even except for the start and end node, the path creation process can start. This process is a derived version of the method applied by Edmonds and Johnson [5] also known as creation of an Euler tour. Steps applied to create the path are:

1. Create a path out of the set of routes to be driven, starting and ending at the specified start and end node. Not necessarily all paths have to be included yet. In the selection of the next route, the driving direction on the current route is taken into account to minimize the number of direction changes.
2. Find a node in the already found path where a new chain of routes can be inserted.

This process is continued until the list of routes to be driven is empty. Visually this path creation process is shown in Figure 28.


Initial situation

1st step

2nd step

Figure 28: Visualization path creation process

When applied on the example situation the following path is created in step 1: 20-21 – 21-22. In step 2 the remaining routes are inserted, the final path now becomes: 20-21 – 21-23 – 23-21 – 21-22.

When the path is drawn, its length is calculated and the set of links to be measured on this map is updated. Schematically the process of station routing is presented in Figure 29.

<u>Open track routing</u>

The process of open track routing is quite similar to the station routing process but has less steps. It also creates an assignment map with the links to be measured and executes the Dijkstra algorithm. Then the open track routing algorithm determines the shortest path from the start node to the (predetermined) preferred end node out of the matrices resulting from the Dijkstra algorithm. Preferred in this case means that the end node is chosen on a track that in reality has the same normal driving direction. For example on map 1 Utrecht (see appendix A8) the nodes 78,79,80 have in the national railway timetable a normal driving direction towards Amsterdam, while nodes 81,82 have a normal driving direction from Amsterdam towards Utrecht. When this path is chosen the last step is updating the links to be measured (removing the links that are covered in the shortest path), path length calculation and drawing the path on the map (see Figure 29).

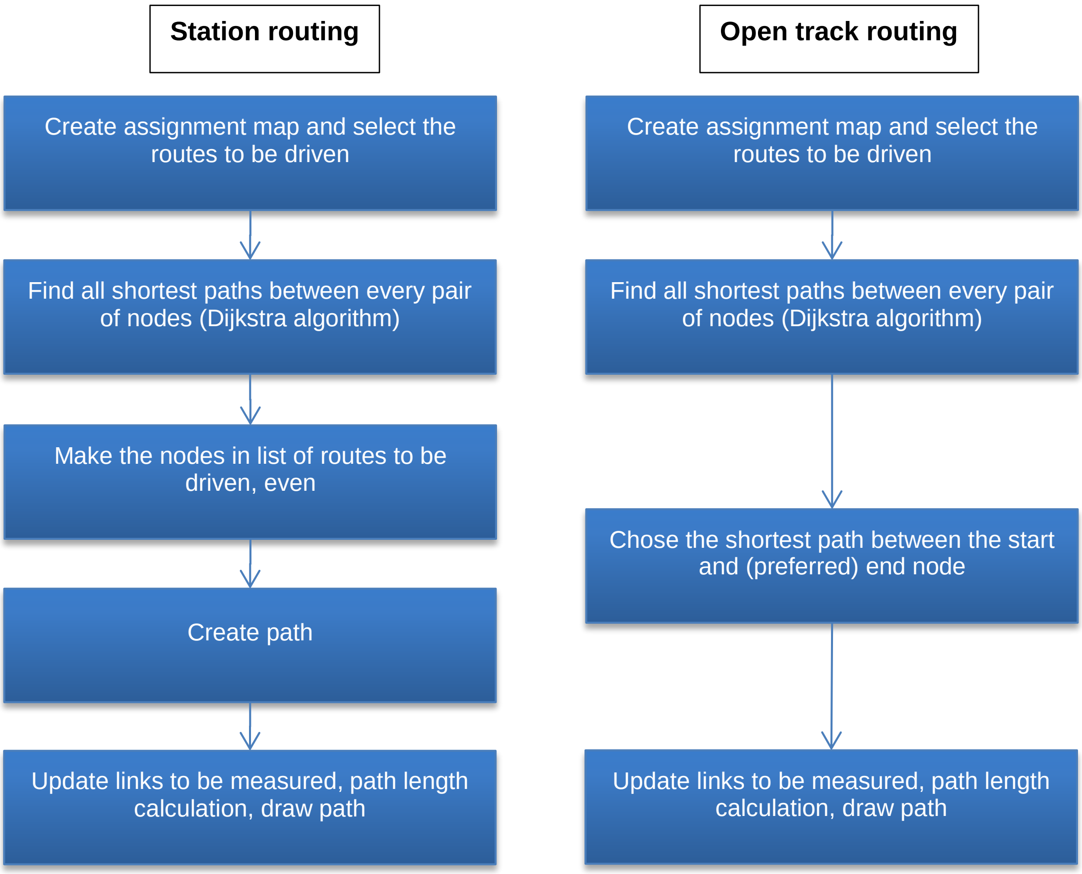


Figure 29: Schematical representation station and open track routing yards first model

<u>Open track routing 2</u>

The second version of the open track routing algorithm determines the paths that need to be driven over the whole open track with direction changes at the stations on both ends, to cover all remaining links to be inspected. At first the algorithm determines all paths possible over the open track interconnecting the border nodes and buffer stops. Out of all paths possible the one containing the longest length of links to be measured is chosen and drawn. Before continuing to the station the same method is used to select the next best path over the open track but now in the opposite direction. By doing this the start (last node in current path on open track) and end node (first node in next best path on open track) on the station are known. Now the shortest path –using the Dijkstra algorithm – through the station connecting these two nodes is chosen and drawn.

This process is continued until all links to be measured on an open track are covered. As soon as an open track is completely covered, the algorithm proceeds to the next open track by choosing the shortest path through the station connecting both open tracks. Schematically this algorithm is shown in Figure 30.

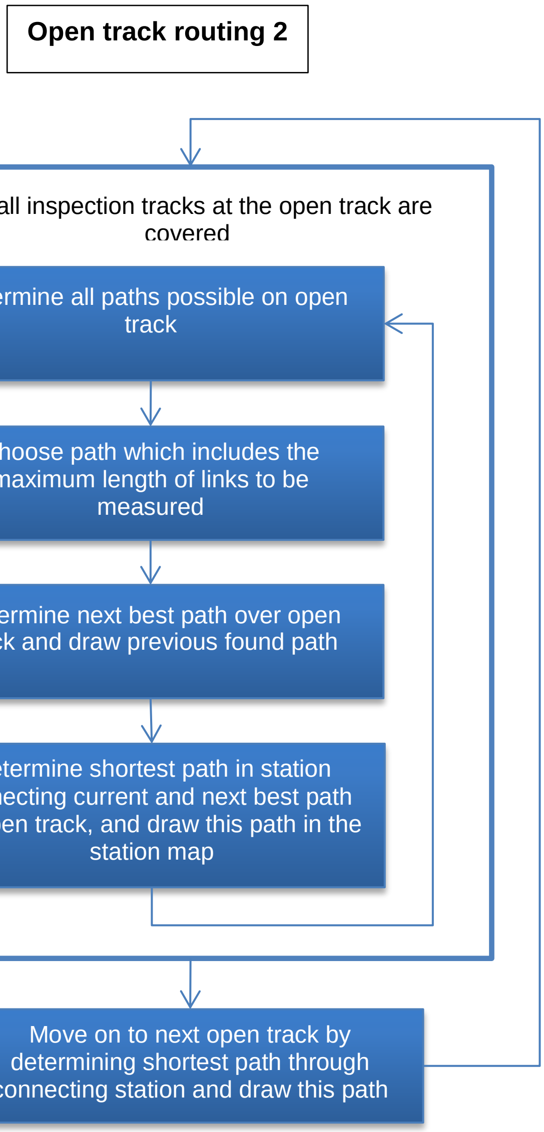


Figure 30: Schematical representation open track routing 2 algorithm

Advantages of the 'Yards first' model algorithm

- Method which can be solved by standard techniques
  (Dijkstra algorithm, assignment map, routing process derived from Euler tour priciple)
- Some sub algorithms can be used on different places in the main algorithm

Disadvantages of the 'Yard first' model algorithm

- Assignment map results in predetermined static routes. In the path creation process another route may seem more logical but is not part of the set selected routes. A dynamic routing algorithm could solve this problem.
- At large stations the calculations may take relatively much time due to the Dijkstra algorithm needed to determine all shortest paths between the nodes.

Choices made in the model
For some problems occurring in the execution of the model, choices were made. In this subparagraph a short description is given of the choices made.

- To find the best combination of connected odd nodes all combinations should be calculated. However in some instances 20 odd nodes were returned, which would mean over 654 million(!) combinations (19x17x…x3x1). This would take too much time to calculate. Therefore the method as described previously was designed. Although this method not necessarily generates the best combination possible, extra train movements caused by this effect have a negligible influence on the efficiency ratio. The extra driven distances are small, because they are located in the stations and not on the open track where the distances would be larger. In the running time estimation the effect may be larger because the extra distance to cover take longer and possibly require extra changes of direction. It is estimated that the extra driven kilometers due to this method are approximately maximal 3 kilometer in the whole model. In this best model the method decreases the efficiency with approximately 0.6%, small enough to accept in order to save calculation time.
- The station routing algorithm needs an specified end node. Keeping in mind the time available for this master thesis research, the choice was made to specify these nodes manually. In a further study an overall optimization method may improve the solution, but it is expected that the improvement will be marginal.
- In the open track routing 2 algorithm all paths over the corridor are determined. In the process of choosing the best path preferred end nodes are used. The choice for a preferred node depends on the driving direction. At the map of Utrecht Central station for example the nodes 78, 79 and 80 are connected with the tracks for the direction towards Amsterdam, the nodes 81 and 82 are the arrival nodes of the opposite direction. These preferred end nodes are used to prevent a train from running a complete corridor in the wrong (standard) driving direction.

5.4.2 Model 2: ‘Corridor routing’

The corridor routing model has many similarities with the yards first model. It uses the open track routing algorithms and the station routing algorithm as well, although they are slightly modified. The schematical representations of the model are presented in Figure 31 and Figure 32.

The model starts with splitting the whole line Utrecht – Alkmaar into two corridors: Utrecht – Amsterdam and Amsterdam – Alkmaar. It is impossible to determine precisely which tracks belong to the one or the other corridor. For simplicity the split is therefore made in the middle of the platforms at Amsterdam Central station near the switches between the platforms. The split is a vertical line dividing the station in two halves (see map 3 in appendix A8).

Next the model determines which paths on the first open track between Utrecht and Amsterdam must be driven, using an assignment map. This map is comparable with the one used in the ‘yards first’ model but here the vertical axis is filled with all possible paths over the open track interconnecting border nodes and buffer stops. It uses preferred end nodes to select the paths that prevent the train from running opposite of the real standard driving direction. The path with the highest efficiency ratio (length tracks to be inspected divided by total path length) is selected and removed from the assignment map. Until all tracks to be measured are removed from the assignment map this process is repeated, generating a list of paths to be driven on the open track.

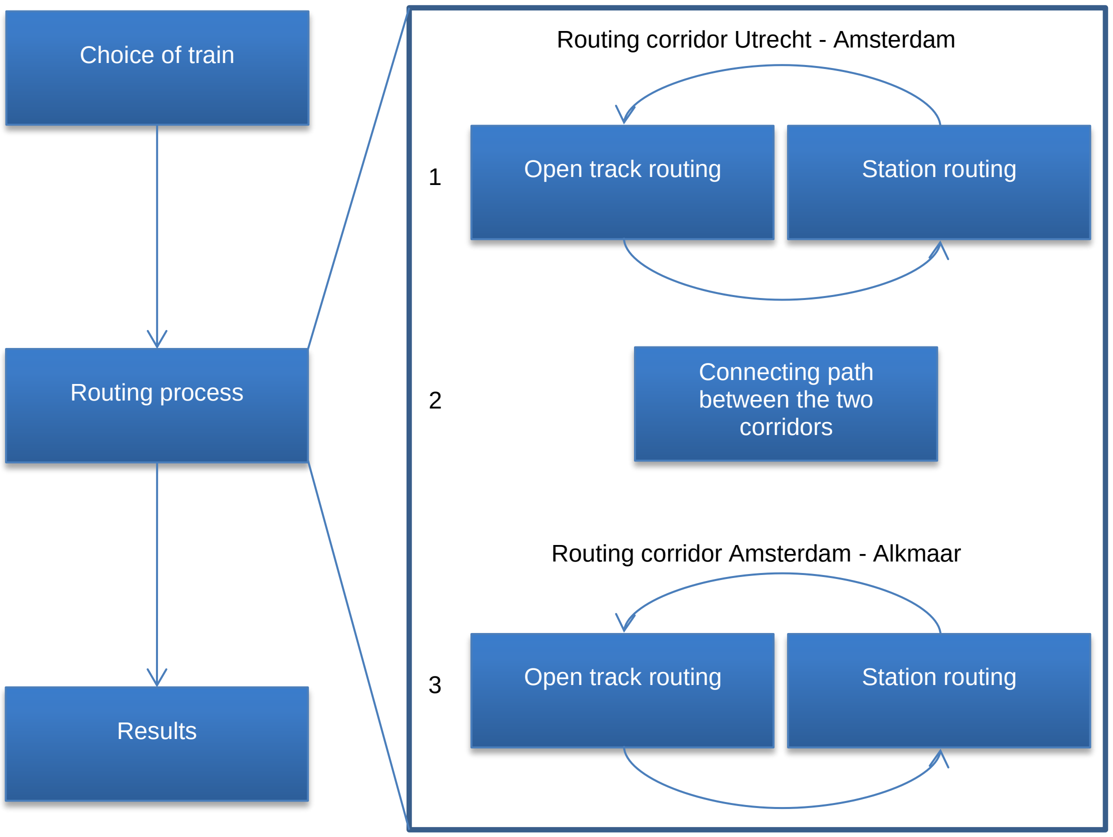


Figure 31: Schematical representation 'corridor' model algorithm

As soon as all paths on the open track are known, the model starts with routing the train over both the stations Utrecht and Amsterdam. Start and end nodes are known from the paths on the open track. The start nodes at the stations form a fixed combination with an end node at a station to speed up the calculations. Creation of the station path is like the process in the 'yards first' model, derived from an Euler tour creation process. Different from the 'yards first' model is that the algorithm in first instance only executes the first step of the path creation process. At the moment only one path on the connected open track remains, the complete path creation process is applied to combine all remaining station tracks to be inspected into a path (see also Figure 28).

When the complete corridor Utrecht – Amsterdam is measured including the station tracks, the same principle is applied at the corridor Amsterdam-Alkmaar. The connecting route between both corridors is the shortest path between the end node of the first and the start node of the second corridor. If the train arrives in Alkmaar the complete station of this city is measured in one run because the corridor between Uitgeest and Alkmaar is only a simple double track line. Crossing it multiple times to measure the tracks in Alkmaar in multiple runs would bring the efficiency ratio down.
Now the model lets the inspection train run multiple times between Uitgeest – Amsterdam until the corridor Zaandam – Uitgeest is covered. Then the model lets the train run several times between Zaandam – Amsterdam to cover the last links.

When all links on this second corridor between Amsterdam and Alkmaar are covered the model creates a path towards the nearest model exit point (see paragraph 5.3, 'assumptions').

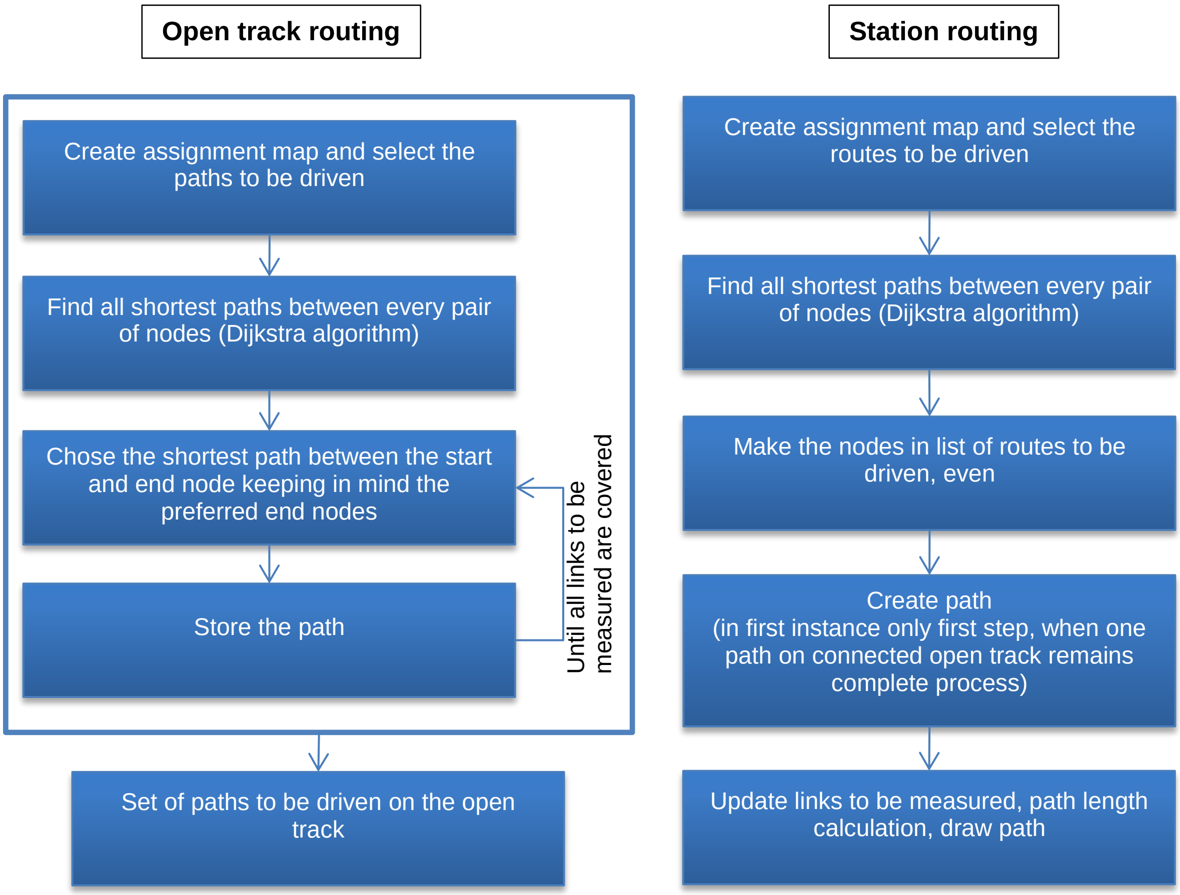


Figure 32: Schematical representation open track and station routing in corridor model

Advantages of the 'Corridor routing' model algorithm

- Model can use algorithms from the 'yards first' model
- Continues paths on the corridor without changes of direction, reducing the train running time

Disadvantages of the 'Corridor routing' model algorithm

- Assignment map results in predetermined static paths. In the routing process another path may seem more logical but is not in the set of paths to be driven
- At large stations the calculations may take relatively long due to the Dijkstra algorithm needed
- Set of corridor paths may end at station where the routing started, while other tracks to be measured are left in another corridor on the other side of the current corridor. Consequently the whole current corridor needs to be driven in transport to reach the other corridor

5.4.3 Mathematical backbone of both models

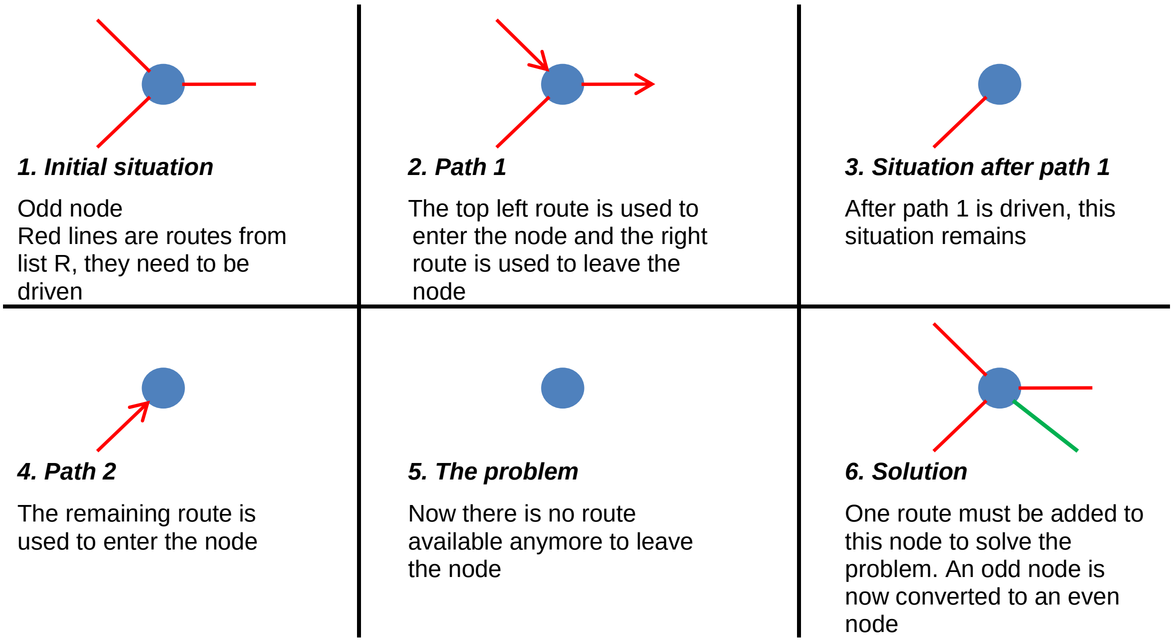
The model setup is too complex to fit into a mathematical representation, due to the fact it is a combinatorial problem based on the graph theory. Therefore the choice is made to describe the different mathematical model steps.

Before the routing algorithm starts, four predetermined lists are loaded:

1. A list containing all links in the network
2. A list containing all routes between every pair of directly coupled nodes
3. A list containing all shortest paths between every pair of nodes in the network, created using the Dijkstra algorithm (Bovy et al. [23]).
4. A list with all the links that have to be measured

With this data the routing algorithm can start. Step one of the routing algorithm is the creation of an assignment map with on the vertical axis all routes between every pair of directly connected nodes (list 2) and on the horizontal axis all links to be measured (list 4). As described in paragraph 5.4.1 under ‘station routing’ and in the example in appendix A9, the assignment map filters the routes that need to be driven. Result is a list of routes containing all links to be measured or in other words: these routes need to be driven to cover all links to be measured. This list is called ‘R’.

Each route in list R contains two nodes: one at each end of the route. The path creation process is a derived version of the Euler tour creation process as also used by Edmonds and Johnson [5]. To create a path based on the Euler tour creation process, all nodes contained in list R (except for the start and end node of the path) need to be connected with an even number of routes. Figure 33 visualizes what an odd node is, why it must be made even and how this can be established.



1. Initial situation

Odd node
Red lines are routes from list R, they need to be driven

2. Path 1

The top left route is used to enter the node and the right route is used to leave the node

3. Situation after path 1

After path 1 is driven, this situation remains

4. Path 2

The remaining route is used to enter the node

5. The problem

Now there is no route available anymore to leave the node

6. Solution

One route must be added to this node to solve the problem. An odd node is now converted to an even node

Figure 33: Odd node problem with solution

All odd nodes except for the start and end node of the path, need to be even. The start and end node need to stay odd, otherwise the path cannot start or end at that node (the opposite situation of Figure 33).

Second step of the routing algorithm is to interconnect all odd nodes in list R. The algorithm does this by first checking which nodes can be directly connected (list 2). The combination of routes that has the shortest overall distance is inserted in a new list ‘AR’. Odd nodes which cannot directly be interconnected remain.

For these nodes, list 3 containing all shortest paths between every pair of nodes is used. Again the combination with the shortest overall distance is selected. The routes included in the selected paths are added to list AR. Because all routes in list AR are routes in which no links have to be measured (all links to be measured are already included in list R), the process of interconnecting the odd nodes selects therefore the combination of routes that has the shortest overall length. The longer the length these routes have, the lower the efficiency ratio becomes (measured distance divided by driven distance).

List 'TR' is made up of lists R and AR, and therefore contains all routes needed to create a path. Third step of the routing algorithm is the path creation process according to the algorithm derived from the Euler tour creation process. As visualized in Figure 28 and in appendix A9 the process begins by selecting the route from list TR connected to the path start node. This route is removed from list TR. The end node of this first route is the next start node. If in list TR a route is available in the same driving direction starting at the next start node, this route is selected and removed from list TR. If not, a direction change have to take place. Because the nodes in list TR are all even (except for the path start and end node) there is always a route available in list TR that connects to the next start node.

This process continues until the path end node is selected. If list TR is empty the path creation process is finished. If not, an insertion point in the established path is searched where a path created from (part of) the remaining routes in TR, can be inserted (taking into account the driving directions).

The insertion process is continued until all routes in TR are used and list TR is empty. Now the inspection path covering all links to be measured is created and the algorithm is finished.

5.4.4 Train running time estimation

When the 'Yards first' algorithm or 'Corridor routing' algorithm are finished, the running time estimation starts. The paths on all maps are known and therefore the required train running time can be estimated. For both the UFM120 and UST02 the short and long turnaround times are the same, for the UST96 this depends whether it the measurement coach has to drive around the flat car (see Table 8). It is assumed that at stations it can change direction without driving around its flat car, except for the last change of direction before leaving the station. If its flat car is at that moment at the wrong side, the long turnaround time is used.

To determine the driving direction the x-coordinates of the signals are used. The x-coordinate of the current position is compared with the x-coordinate of the next signal the path passes. Out of this inequality the driving direction and changes in driving direction can be determined. At the switch between map 2 and 3 (and vice versa) the algorithm automatically changes the driving direction because the maps 3 till 9 are mirrored compared to maps 1 and 2. Cause is that the maps of ProRail also contain this mirroring effect. For recognizability reasons this difference in driving direction is kept in the model. In other words: the train leaves map 2 on the left side and arrives on map 3 at the left side (or vice versa). To correct the driving direction for this situation, the algorithm automatically flips the driving direction.

The maximum track speed a measurement train drives is depending on:

1. The maximum speed allowed on the track
2. The maximum speed during the measurements; if this is lower than the allowed track speed, this becomes the new track speed limit
3. The maximum transport speed; if a track does not have to be measured or has already been measured, the maximum transport speed is used. If it is lower than the allowed track speed, this becomes the new speed limit.

Combining all the data allows to estimate the running times required to drive all paths.

5.5 Calibration

Figure 34: A video-capturing train

Calibration of the models allows to assess the performance of both models. Difficulty in this case is that the models use new routing philosophies, the current inspection paths are not planned according to one of these routing methods for the trains under consideration. However, the Eurailscout video-capturing trains (see Figure 34) use a 'yards first' method to inspect yards. Of all the yards they inspect using this method, only the yard of Amsterdam Central station is present in the line used in the routing models. Calibration of the 'yards first' model can therefore be tested for the VST trains at the yard of Amsterdam Central station.

Currently the VST inspection trains are not planned by Eurailscout itself, but by ProRail directly using an own optimization algorithm. For a few years ago Eurailscout planners developed the paths manually. The model calibration is based on a routebook created by Eurailscout, to assess the performance of the model compared to a manual planned path (routebook from 2008).

The path of the video-capturing train as visualized in the routebook is inserted in MATLAB as a fixed path: MATLAB may not deviate from this path but only draw it on the map and calculate its efficiency plus train running time. In order to calibrate the 'yards first' model, the same start and end point are used as in the routebook path and the tracks to be inspected are filtered out of this path created by the planner (unique links are used as tracks to be inspected). Maximum measurement speed is set to 100 km/h and the turnaround time is set to 2 minutes.

Result of the calibration is that the 'yards first' algorithm comes up with a more efficient path as the path shown in the routebook. The model returns a path with 58.69% efficiency where the routebook paths returns an efficiency of 50.44%, an increase of 8.25% due to the smaller 'transport' distances needed to couple all tracks to be inspected (approximately 6.3 kilometer less). In the estimated train running time a large difference occurs: the routebook path requires in reality 6 hours and 4 minutes where the model path requires approximately 3 hours and 12 minutes. When the required train running time for the routebook path is estimated by the model algorithm, the result becomes 3 hours and 3 minutes. The difference between the calculated train running time of the routebook path and the actual required time can be explained by the fact that in the model no other train traffic is present. In reality the video-capturing train sometimes need to wait before a path through the station is free. Furthermore breaks for the driver are included (approximately 30 to 45 minutes overall). When these waiting times and breaks are filtered out of the actual required time, the train running time drops from 6 hours and 4 minutes to 3 hours and 19 minutes.

Still there exist a substantial difference between the filtered required train running time of the routebook path and the estimated running time of the same path by the model. Cause is the time-loss of acceleration/deceleration from or to a standstill for example. In the models the speed of the train is used without taking into account acceleration or deceleration. To correct for this difference a supplement on the model estimates must be added. This supplement is calculated by dividing the filtered actual needed running time by the estimated running time: $\frac{3:19}{3:03} = 1.084$. As the outcome shows the actual running time is approximately 8.4% larger as estimated. This value is rounded up towards 10% to prevent underestimation of the running times.

With this supplement included in the running time estimation algorithm, the routebook path requires 3 hours and 24 minutes where the created path requires 3 hours and 33 minutes. This difference can be explained by the larger amount of direction changes needed in the model path (75 versus 65).

5.6 Results of the routing models

Outcomes of both routing models are discussed in this paragraph. At first the numerical results of the two models are presented in Table 10 and Table 11. In these tables the professional railway terminology station name abbreviations are used:

Ut:	Utrecht Central station	Utg:	Uitgeest
Asd:	Amsterdam Central station	Amr:	Alkmaar
Zd:	Zaandam		

Table 10: Results Yards first model

Yards first model								
		UFM120			UST96 or UST02			
		Distances [km]			Distances [km]			
Map	Name	Driven	Measured	Efficiency ratio	Driven	Measured	Efficiency ratio	
1	Ut	26.27	9.22	35.09%	36.43	14.52	39.87%	
2	Ut-Asd	151.66	128.02	84.41%	151.66	128.87	84.97%	
3	Asd	39.70	15.34	38.63%	53.73	26.39	49.12%	
4	Asd-Zd	57.75	33.51	58.03%	57.75	33.82	58.57%	
5	Zd	16.44	9.37	56.97%	16.02	8.75	54.59%	
6	Zd-Utg	21.80	19.99	91.69%	21.80	19.99	91.69%	
7	Utg	6.50	3.20	49.22%	10.01	4.85	48.48%	
8	Utg-Amr	28.38	28.38	100.00%	28.38	28.38	100.00%	
9	Amr	3.11	1.24	39.89%	5.76	4.24	73.52%	
	Overall	351.62	248.27	70.61%	381.56	269.83	70.72%	

As Table 10 about the yards first model shows, the overall efficiency ratios of the UFM120 and both ultrasound trains in this model are nearly the same. Remarkable because the driven and measured distances differ substantially (the UST's measure and drive respectively 29.94 kilometer and 21.56 kilometer more). Studying the results more closely, it can be seen that the worst ratios are realized at the larger stations (for the UFM120 also at Alkmaar), and there is one open track (between Uitgeest and Alkmaar) where an 100% efficiency is reached for all three trains under consideration. The latter is caused by the simple track layout of two parallel tracks not connected by switches, on this map (map 8, see appendix A8) where both tracks have to be inspected. All three trains cross this open track once in every direction resulting in a 100% ratio.

The least efficiency ratios can be explained by the fact that the trains have to double cross many track sections to cover all tracks at the large stations of Utrecht and Amsterdam. Comparing the ratios of the UFM120 and both USTs for the maps Amsterdam and Alkmaar, a large difference can be seen. This difference is caused by the small track lengths that need to be inspected by the UFM120 in comparison with the USTs, combined with the scattered position of these tracks across the yards. Consequently the UFM120 needs to drive relatively long transport sections to measure relative short track sections.

Table 11: Results Corridor model

Corridor model							
		UFM120			UST96 or UST02		
		Distances [km]			Distances [km]		
Map	Name	Driven	Measured	Efficiency ratio	Driven	Measured	Efficiency ratio
1	Ut	18.16	9.22	50.78%	29.84	14.52	48.67%
2	Ut-Asd	173.95	128.02	73.60%	173.96	128.87	74.08%
3	Asd	33.51	15.34	45.76%	52.01	26.39	50.75%
4	Asd-Zd	57.75	33.51	58.03%	57.75	33.82	58.57%
5	Zd	13.80	9.37	67.86%	14.81	8.75	59.07%
6	Zd-Utg	36.92	19.99	54.15%	36.92	19.99	54.15%
7	Utg	4.04	3.20	79.17%	8.23	4.85	58.96%
8	Utg-Amr	28.38	28.38	100.00%	28.38	28.38	100.00%
9	Amr	3.11	1.24	39.89%	5.76	4.24	73.52%
	Overall	369.62	248.27	67.17%	407.66	269.83	66.19%
	Corridor Ut-Asd	218.69	149.47	68.35%	236.77	160.63	67.84%
	Corridor Asd-Amr	150.93	98.80	65.46%	170.89	109.19	63.90%

In Table 11 the results of the corridor model are presented. The overall efficiency ratios differ approximately 1% in the advantage of the UFM120. Like the yards first model the worst ratios are scored at the larger stations (Utrecht and Amsterdam and for the UFM120 at Alkmaar). Again the corridor Uitgeest – Alkmaar scores 100% efficiency for the same reason mentioned in the yards first model results.

Regarding the efficiency ratios on the corridors, result of the model is that for all three trains on the corridor Amsterdam – Alkmaar a lower efficiency ratio is reached than on the corridor Utrecht – Amsterdam. This can be explained by the fact that both trains need to make more runs on the corridor Amsterdam – Alkmaar to measure all tracks compared to the corridor Utrecht – Amsterdam. Consequently more transport kilometers have to be made resulting in a lower efficiency ratio.

Comparing both models on overall efficiency it appears that the corridor model performs worse as the yards first algorithm. Furthermore it is remarkable that in the yards first model the efficiency on the open tracks is equal or even better than in the corridor model. This can be explained by the fact that in the corridor model the open tracks are driven from station to station without intermediate stops. In the yards first model an intermediate stop is allowed so the train can change direction on the open track, which is not possible in the corridor model. As a consequence the paths on the open tracks are longer than in the yards first model, decreasing the efficiency ratio.

Besides it can be seen that at stations the opposite is the case: the corridor model is more efficient at the station yards than the ‘yards first’ method. Cause can be found in the driven distances on these yards. In the ‘yards first’ method more transport kilometers need to be made to couple all tracks to be measured. In the corridor model this can be done more efficiently reducing the transport kilometers, increasing the efficiency ratios. Figure 35, Figure 36 and Figure 37 present the data of Table 10 and Table 11 graphically.

In Figure 35 and Figure 36 the red and purple bar do not differ for each inspection train: the distances to measure are (of course) the same in both models. The same two figures show that on the open tracks the 'yards first' model performs better due to the previous elaborated cause. At Utrecht and Amsterdam central station the 'corridor routing' model performs better.

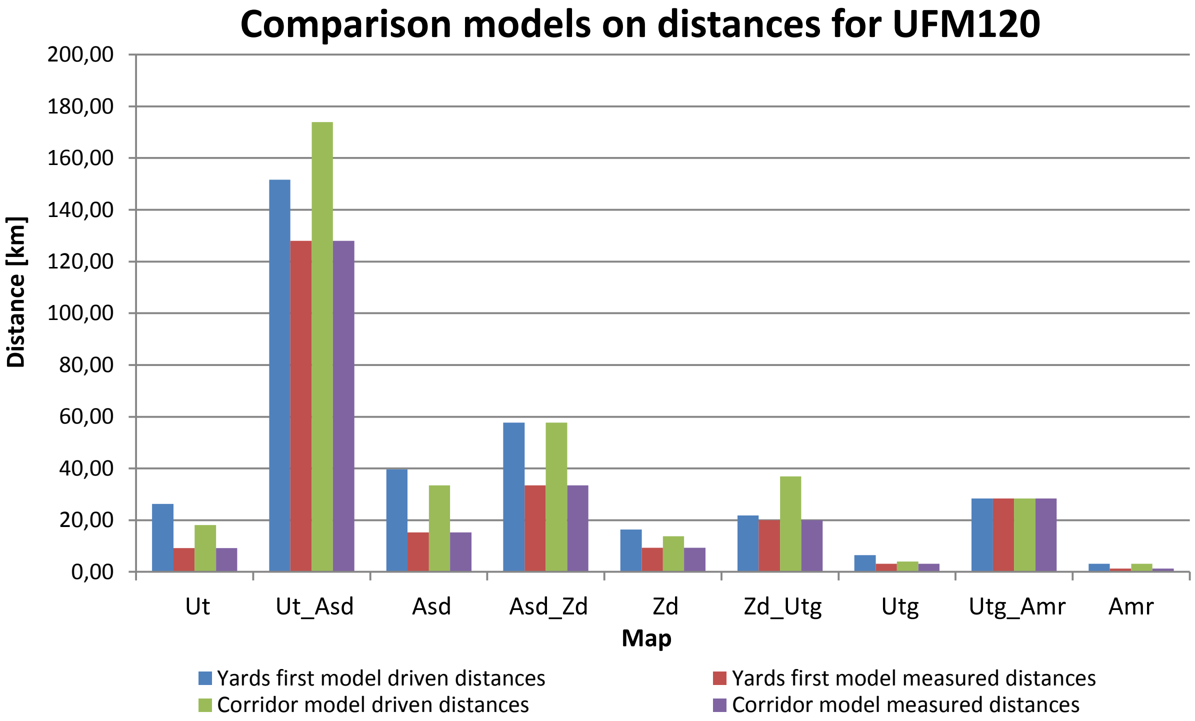


Figure 35: Comparison models on distances for UFM120

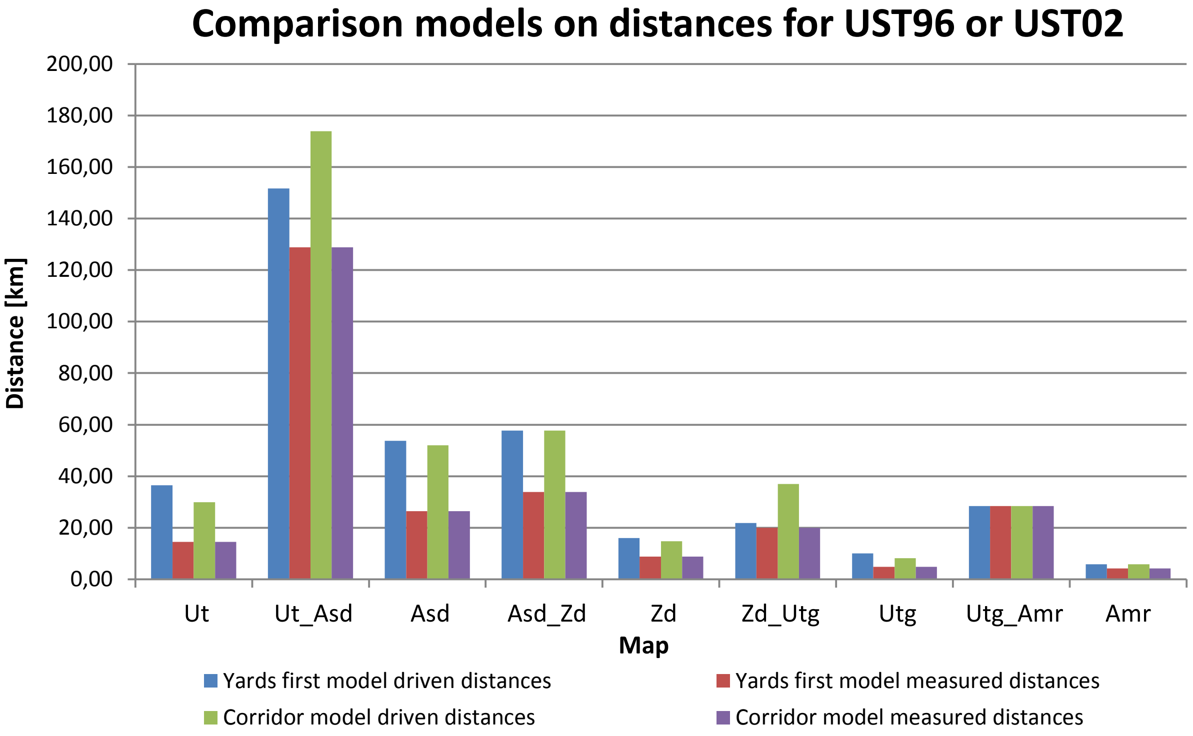


Figure 36: Comparison models on distances for UST96 or UST02

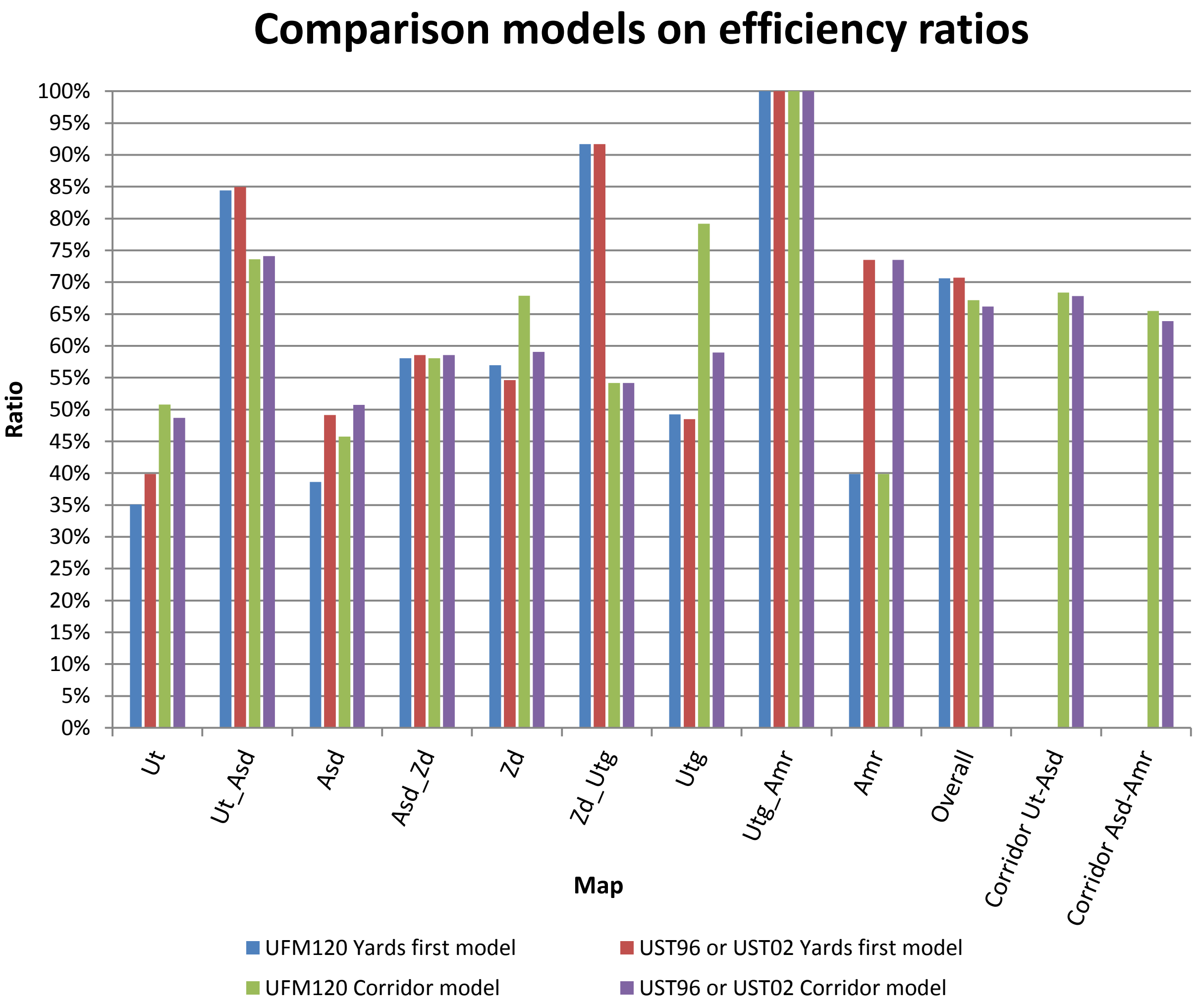


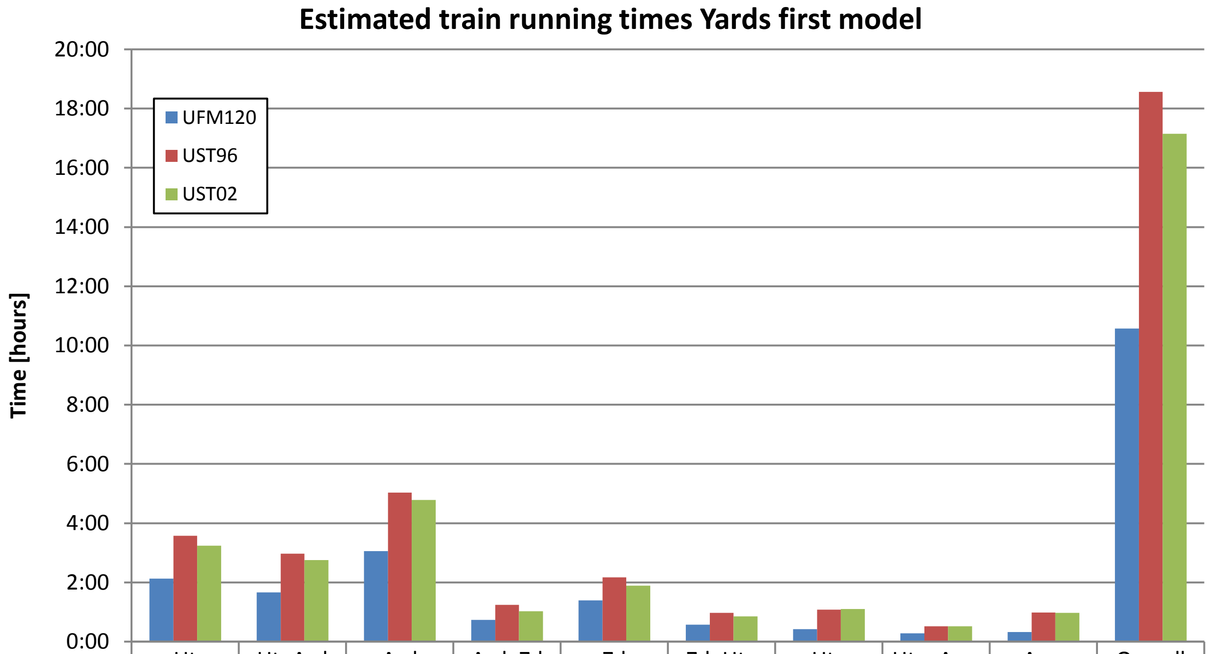
Figure 37: Comparison models on efficiency ratios

The estimated train running times are presented in Figure 38 and Figure 39. Comparing both figures it can be seen that the paths generated by the ‘corridor’ routing method, require less time for all three trains. Expressed in percentages the differences in the overall running times are:

- -23% for the UFM120
- -7% for the UST96
- -5% for the UST02

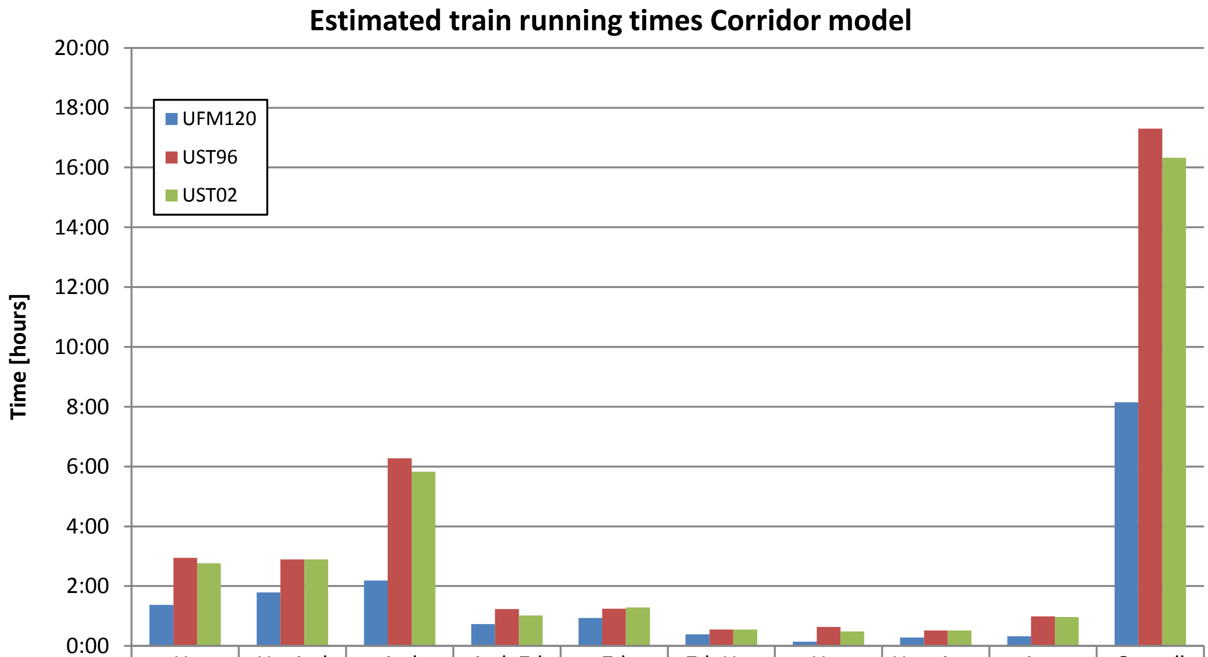
These differences can be explained by the lower number of direction changes needed in the ‘corridor’ routing method compared to the ‘yards first’ method (see Table 12). Especially at the maps Zaandam (5), Zaandam-Uitgeest (6) and Uitgeest (7) the corridor routing method saves time.

Even more remarkable is that the paths resulting from the model generating the highest efficiency ratios (‘yards first’) requires more time to drive for all three trains. Regarding the train running times the ‘corridor’ model scores best due to its lower number of direction changes. Table 13 gives a comparison of the average time needed to measure 1 kilometer of track in both models.



	Ut	Ut_Asd	Asd	Asd_Zd	Zd	Zd_Utg	Utg	Utg_Amr	Amr	Overall
UFM120	2:07:34	1:40:02	3:03:24	0:43:50	1:23:17	0:34:23	0:25:15	0:17:04	0:19:41	10:34:30
UST96	3:34:31	2:58:29	5:02:13	1:14:18	2:10:32	0:58:18	1:04:47	0:31:13	0:59:17	18:33:39
UST02	3:14:31	2:45:29	4:47:13	1:01:18	1:53:32	0:51:18	1:05:47	0:31:13	0:58:17	17:08:39

Figure 38: Estimated train running times 'Yards first' model



	Ut	Ut_Asd	Asd	Asd_Zd	Zd	Zd_Utg	Utg	Utg_Amr	Amr	Overall
UFM120	1:22:21	1:47:10	2:10:54	0:43:49	0:56:06	0:23:24	0:08:15	0:17:04	0:19:41	8:08:45
UST96	2:57:07	2:53:21	6:16:33	1:14:17	1:14:30	0:33:13	0:38:19	0:31:13	0:59:17	17:17:50
UST02	2:46:07	2:53:21	5:49:33	1:01:17	1:17:30	0:33:13	0:29:19	0:31:13	0:58:17	16:19:50

Figure 39: Estimated train running times 'Corridor' model

Table 12: Number of direction changes per map

		UFM120			UST96			UST02		
	Model	Yards first	Corridor	Δ	Yards first	Corridor	Δ	Yards first	Corridor	Δ
Map	Name	Direction changes			Direction changes			Direction changes		
1	Ut	18	11	-7	20	17	-3	20	17	-3
2	Ut_Asd	1	0	-1	1	0	-1	1	0	-1
3	Asd	26	17	-9	30	39	+9	30	39	+9
4	Asd_Zd	1	1	+0	1	1	+0	1	1	+0
5	Zd	14	9	-5	14	9	-5	14	9	-5
6	Zd_Utg	4	0	-4	4	0	-4	4	0	-4
7	Utg	4	1	-3	8	3	-5	8	3	-5
8	Utg_Amr	0	0	+0	0	0	+0	0	0	0
9	Amr	3	3	+0	7	7	+0	7	7	+0
	Overall	**71**	**42**	**-29**	**85**	**76**	**-9**	**85**	**76**	**-9**

Table 13: Average train running time needed per kilometer of track to be measured

		UFM120			UST96			UST02		
	Model	Yards first	Corridor	Δ	Yards first	Corridor	Δ	Yards first	Corridor	Δ
Map	Name	[time/km]			[time/km]			[time/km]		
1	Ut	0:13:50	0:08:56	-35.4%	0:14:46	0:12:12	-17.4%	0:13:24	0:11:26	-14.6%
2	Ut_Asd	0:00:47	0:00:50	+7.1%	0:01:23	0:01:21	-2.9%	0:01:17	0:01:21	+4.8%
3	Asd	0:11:58	0:08:32	-28.6%	0:11:27	0:14:16	+24.6%	0:10:53	0:13:15	+21.7%
4	Asd_Zd	0:01:18	0:01:18	+0.0%	0:02:12	0:02:12	+0.0%	0:01:49	0:01:49	+0.0%
5	Zd	0:08:54	0:05:59	-32.6%	0:14:55	0:08:31	-42.9%	0:12:59	0:08:52	-31.7%
6	Zd_Utg	0:01:43	0:01:10	-31.9%	0:02:55	0:01:40	-43.0%	0:02:34	0:01:40	-35.3%
7	Utg	0:07:53	0:02:35	-67.3%	0:13:21	0:07:54	-40.9%	0:13:33	0:06:02	-55.4%
8	Utg_Amr	0:00:36	0:00:36	+0.0%	0:01:06	0:01:06	+0.0%	0:01:06	0:01:06	+0.0%
9	Amr	0:15:52	0:15:52	+0.0%	0:13:59	0:13:59	+0.0%	0:13:45	0:13:45	+0.0%
	Overall	**0:02:33**	**0:01:58**	**-23.0%**	**0:04:08**	**0:03:51**	**-6.8%**	**0:03:49**	**0:03:38**	**-4.7%**

In Table 13 it can be seen that most running time is saved in the corridor routing method at the maps 1, 5, 6 and 7 due to the lower number of direction changes. At the maps 2 and 3 the corridor routing model sometimes shows a longer running time. This can be explained by the requirement that trains can only change direction at a station at one of the ends of an open track. As a consequence the train needs to drive more kilometers in total to cover all tracks to be inspected, causing a higher total running time. Divided over the track length to be measured this results in a higher ratio.

5.7 Conclusions on the models

Both the yards first and corridor model return a most efficient path for an inspection train according to the routing philosophy of that model. The yards first model is a theoretical model, the corridor model is more related to reality. Outcomes show that the yards first model is the most efficient in minimizing the total kilometers driven. Especially because of the more efficient routing on the open tracks. In the corridor routing model the trains are forced to continue to a station at one of the open track ends before changing direction. As a consequence the path on an open track is longer, decreasing the efficiency ratios. The efficiency ratios reached range from 35% at large stations to 100% on an open track. On average an efficiency ratio of approximately 70% can be reached using the yards first method, a ratio of 66% can be reached using the corridor routing method for the line Utrecht – Amsterdam.

Regarding the train running time minimization criterion, the corridor model gives the best result. In the paths generated by this model less direction changes have to be made compared to the yards first paths. Direction changes cost at least 5 minutes (depending on the inspection train selected), time saved by reducing the number of direction changes.

Of course both models are theoretical. Converting the results into reality will result in lower efficiency ratios and longer running times due to other train traffic, routing restrictions, direction change location restrictions, track measuring frequencies, etc. Especially at stations this will affect the results.

Estimated train running times show that when assuming a maximum train crew shift length of 10 hours, only the measurements of the UFM120 can theoretically be executed in one shift. In this theoretical both the UST96 and UST02 already require multiple shifts to execute the measurements. Converting the model outcomes to reality will result in even longer running times and therefore the paths as determined in the models need multiple shifts to execute.

6 Efficiency improvement recommendations

In the previous chapters possibilities for efficiency improvements were identified. During working at the office, other efficiency improvements also were identified. Because these latter recommendations are not studied in detail they are discussed in a separate paragraph.

Studied recommendations are elaborated in paragraph 6.1. Part of the improvements can be executed by Eurailscout, for the other part Eurailscout is dependent on other parties. Therefore this paragraph is split in two: subparagraph 6.1.1 includes improvements that can be executed by Eurailscout, subparagraph 6.1.2 presents improvements laying beyond the direct influence of Eurailscout. Paragraph 6.2 discusses recommendations that could not directly be related to the analyzed disturbances or models from chapters 4 and 5. These recommendations are not studied in detail but are identified during the execution of this research at the office. The last paragraph (6.3) discusses the estimated effects the recommendations will have. All improvements can be implemented or requested, in the short or long term. The expected results of the improvements are however difficult to estimate due to the complex interconnection of processes in railway operations. The many involved external parties in the process of railway planning and operation make it even more complex.

As mentioned in paragraph 1.2 Eurailscouts efficiency is measured by ProRail in the number of deployment days they will pay for, and internally in Eurailscout by the efficiency ratio of measured kilometers divided by total driven kilometers in a deployment. In this chapter improvements are described that can raise the efficiency according to both criteria.

6.1 Studied recommendations

In this paragraph the studied efficiency improvement recommendations are presented. First subparagraph 6.1.1 presents the improvements Eurailscout can directly initiate. Subparagraph 6.1.2 presents the recommendations in which Eurailscout is dependent on other parties.

6.1.1 Improvements Eurailscout can initiate

First the improvement recommendations that can be executed by Eurailscout are explained. They are arranged at random.

- **Improving the reliability of the inspection trains**
  As shown in chapter 4.3, for both the UFM120 and the UST trains a large share of the disturbances in the execution of the measurements, is related to failing measurement systems or even worse a whole train. For the UFM120 this is approximately 41% of all disturbances, for both UST’s together approximately 53%. Especially the UFM120 is sensitive for failing measurement systems, because it uses more than 10 systems at the same time. When one of these fail, most of time a remeasurement run needs to be made to cover the ‘missed’ tracks. Although a failure rate of 0% is not realistic (the measurement systems and trains are mechanical systems which sooner or later will fail even with excellent maintenance), improving the reliability is a possibility to increase the efficiency in the short term.

- **Implement ‘yards first’ or ‘corridor routing’ philosophy**
  As shown in chapter 5 the ‘yards first’ modeling principle is overall the most efficient of the two researched routing principles. Although it requires more time to drive the generated paths compared to the paths generated by the corridor model, the advantage of the ‘yards first’ principle is that the tracks to be inspected at a yard are covered first. When on a later moment the same yard is visited, it does no longer matter which track is driven. Applying (one of) these philosophies will result in a more systematical approach to the inspection path creation process.

- **Increase the headway time of subsequent trains**
  From paragraph 4.3 and appendix A7 it can be seen that especially the considered ultrasound inspection trains are not always able to drive according to their assigned timetable. Cause is the lower actual measurement speed than the speed used for timetable determination. As a solution the headway times of trains behind the inspection train can be increased. Goal is to create space to absorb deviations from the planned timetable. Space to absorb the deviations will cause less hindrance for the other train traffic. With the new planning system 'DONNA' (see chapter 3.5) implemented, the consequences of larger headway times for trains behind the inspection trains can more easily be determined than in the old VPT-Planning. DONNA is capable of automatic conflict detection between planned trains, allowing planners to determine the consequences of the changes more easily.

- **Add more buffer time to the timetables**
  In addition to the recommendation of increasing the headway times for subsequent trains of the ultrasound inspection trains, adding more buffer time at strategic locations increase the ability to absorb more small deviations in the measurement run. Advantage is that the chance later paths have to be adapted decreases, increasing robustness and an increased guarantee that the planned tracks can be driven. Adding more buffer time needs to be arranged by NS Dagplan and/or NS Lokaalplan.

- **Position the person of Eurailscout with the 'control' task at the OCCR**
  As presented in the analysis of the current performance a large share of the disturbances in the execution of the measurements are caused by dispatchers. For the UFM120 and both ultrasound trains respectively 29% and 20% of the occurred disturbances can be related to decisions made by dispatchers, see paragraph 4.3. Currently Eurailscout tries to decrease the risk of disturbances caused by dispatcher actions, by sharing their routebooks and direct communication of the train drivers and planning department with the dispatchers.

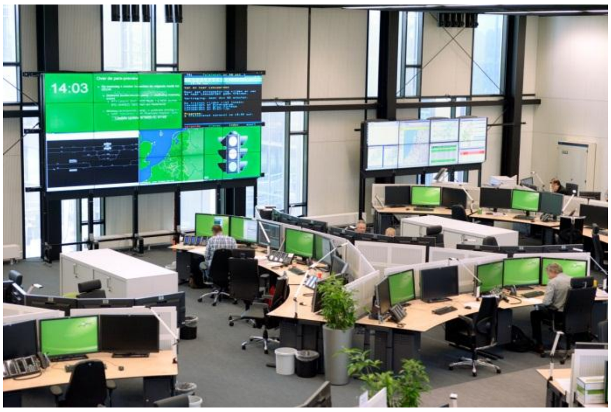
  

  Figure 40: OCCR control room (source [24])

  Apart from improvements Eurailscout can request at ProRail (see paragraph 6.1.2), there is another possibility they can initiate to improve the dispatcher decisions in their advantage: positioning of the Eurailscout 'control' department at the OCCR.

  The OCCR – Operational Control Center Rail [24] – is a control center where the national railway traffic is 24/7 monitored. In this center disruptions, weather situation and calamities are monitored and if necessary action is taken. Furthermore the train traffic, dispatchers and train traffic controllers are monitored. The organization behind it is a special collaboration of railway related companies; participating are among others ProRail, NS (Dutch national railway company), other passenger train operating companies, freight train companies and railway contractors.

  The trains of Eurailscout are special trains with specific requirements as described in chapter 1. Advantage of positioning the 'control' department of Eurailscout at the OCCR is that the progress of the trains can be monitored in detail (track level).

Furthermore direct (face to face) connections with national train traffic control and dispatchers are available and disruptions can be dealt with more easily because the forecasts and updates can be received first-handed. Taking part in the OCCR may result in higher efficiency ratios for Eurailscout, because of the fact that their trains can be monitored in detail and the actions/decisions of dispatchers or national train traffic control can be checked and steered, reducing disturbances caused by dispatchers.

- **Request Eurailscout line closures**
  In the daily practice of planning the measurement trains, the Eurailscout planners run into problems with line closures (due to track maintenance in both short and long term). The analysis results in paragraph 4.3 and appendix A7 show that for both ultrasound trains 6% and for the UFM120 10% of the disturbances are related to track closures. Although the occurrence frequency is not that high, the affected distances are substantial as presented in appendix A7. The disadvantages of line closures in the current situation can however be converted into an advantage. On the increasingly utilized Dutch railway network it becomes harder to measure tracks between the normal train traffic. Especially for the 'slow' measuring ultrasound inspection trains (measurement speed approximately 60 km/h) it becomes more difficult to run during day time (the other trains can measure with higher speeds and can therefore blend in more easily with the regular train traffic).Requesting 'Eurailscout track closures' can therefore be advantageous.

Another advantage of Eurailscout line closures is that it becomes possible to combine the measurements of the trains with the manual ultrasound measurements. Due to the stringent health and safety regulations, these manual inspections may no longer be executed in tracks being in service but only in tracks out of service (see chapter 1). Combining the line closures for the Eurailscout trains with the manual ultrasound inspections may increase the return on investment.

Assuming data processing can be executed fast (in a time span of hours) the following example situations can be executed:

1. *The UST train drives along the closed track. When the run is finished the data is processed and analyzed. From the analyses is determined where manual inspections are necessary. Now the colleagues with the manual equipment can be sent to the right location.*
2. *A large station (Utrecht, Amsterdam, Rotterdam, etc.) is closed partly or complete for inspections. When the measurements of one of the UST trains is combined with the UFM120 and/or manual inspections, maximal return on investment can be achieved.*

Advantages:	no hinder from other train traffic, safe working environment for the manual ultrasound inspections, fast track coverage. Current safety regulations prescribe that manual ultrasound inspections may only be executed in closed tracks. A 'Eurailscout track closure' provides an empty track where just their own inspection trains may/could run. Another advantage is that when track closures are only used for the inspection trains, the time the tracks need to be closed does not have to be long. It is not necessary to close a track during a whole night to execute the inspections. As soon as the inspections are finished the track can be opened again.

Disadvantages:	night shifts are expensive on labour, requesting track closures is a long procedure. In case multiple inspection trains are used, the closed track sections must be large enough to accommodate multiple trains without hampering each other.
Requirements:	fast data processing onboard the train or along the trackside to guide the manual inspections to the right locations.

Implementation of the Eurailscout track closures have to take place in the track capacity request, one year in advance of the actual year the inspections have to take place. By doing so the track closures are included into the national railway timetable BHP (‘Basic Hour Patern’). Advantage is then that the track closure is fixed in the railway timetable and is always free (at least it should be) for Eurailscout. Before implementation among others an economic trade-off needs to be made whether the higher personnel costs and line closure costs outweigh the benefits of applying this method.

6.1.2 Improvements outside Eurailscout

Paragraph 6.1.1 presented recommendations for efficiency improvements Eurailscout itself can initiate. There are however improvement recommendations that lay beyond the direct influence of Eurailscout. Results of the current performance analysis in paragraph 4 show that 35% to 50% of the disturbances in the execution of the measurements can be related to the external party ProRail. Therefore the recommendations in this paragraph suggest improvements that need to be requested at ProRail:

- **Request permission for priority over other trains**
  ProRail takes a special position in the execution of the measurements: at one side they are the client, whilst on the other side they guide the trains over the network (dispatchers and train traffic control). This situation makes it strange that the Eurailscout trains are set aside when other trains are given priority. If Eurailscout can request and receive priority over other trains, the efficiency can increase and the number of remeasurement deployments may decrease.

- **Request ProRail to increase awareness by dispatchers**
  If Eurailscout can convince ProRail to increase the awareness of train dispatchers concerning the importance of the inspection runs, it will improve the decisions made by train dispatchers in favor of Eurailscout.

- **Request own train category**
  In both the VPT-Planning and the new ‘DONNA-SD’ planning systems there are three train categories used: passenger, freight and other trains. The inspection trains are classified in the latter category. Problem here is that on the displays of the dispatchers also only these three categories can be distinguished. Inspection trains are therefore not immediately recognizable for the dispatcher. The measurement trains can only be identified by their train number. It would be better to extended the train categories with an fourth category. For example: passenger, freight, inspection/work and other trains. Adding this fourth category may increase the recognizability of the inspection trains on the screen of the dispatcher. Consequently dispatchers may be better able to route the inspection train according to the planned path, with as result less deviations from the planned inspection paths.

6.2 Recommendations not studied in detail

During the research some other possible improvements were identified. These improvements however are not directly related to the analyses in chapter 4 or the developed models in chapter 5. Therefore they are not studied in detail, but only mentioned in this separate paragraph of recommendations for improving efficiency.

- **Use DONNA to determine track sections with 'critical' capacity**
  In the new introduced railway scheduling system 'DONNA' an internet application is integrated which can be used by Eurailscout and other parties. It contains among many other elements time-distance diagrams of the BHP of the national railway timetable. Selecting a train in this diagram shows the precise tracks it is scheduled on according to the BHP. By analyzing these occupations it becomes visible where track sections with little remaining capacity are located in the BHP. These locations can cause problems for the inspection trains when these tracks need to be measured. In the BHP there is then already very little capacity left for the inspection trains at these locations. If Eurailscout requests capacity for these tracks in the annual track capacity request at ProRail, the Eurailscout trains are also inserted in the BHP for these track sections. A fixed capacity at these bottlenecks is now reserved for the inspection trains. Otherwise track closures can be requested to guarantee the availability of these tracks for inspections.

- **Long term planning vs. short term planning**
  At the moment the Eurailscout planners already use a long and short term planning. However as also proposed by Peng et al. [3] a long term planning should only be used for resource planning (annual horizon) and the short term (3 months) planning only for detailed planning. In the long term planning the campaigns, train maintenance, train personnel instruction days and holidays must be planned. In the short term planning the detailed routing, timetable and personnel must be planned. The inspection trains have many deployments for several customers, in The Netherlands but also in foreign countries. These so called 'campaigns' (all measurements performed for one client) are therefore planned with short intervals. Consequently there exists a large pressure to finish on time and to get the trains at the start location for the next campaign. A delay in for example the transport of an inspection train from Denmark back to The Netherlands can cause problems for the start of the next campaign. Planning the campaigns with longer intervals slightly releases the pressure to finish on time and allows to absorb delays or unforeseen circumstances.

- **Use the available communication networks to update the dispatcher**
  By using GPS an inspection train can communicate by itself with dispatcher when it is approaching his control area. The train automatically updates its status (current position, expected time of arrival, path to be driven, etc.) towards the train traffic controller, for example one hour before arriving in his control area. With this system the dispatcher is alerted of the oncoming inspection train. In case a complete measurement deployment is cancelled this can automatically be communicated by the train (besides the 'control' department of Eurailscout removing the timetable from the national train timetable database). Currently the train driver or the 'operator' (the person leading the measurements) has to do this manually. Advantage of GPS is that the train driver or operator is no longer disturbed by this task. Furthermore it may increase the awareness of train dispatchers about the oncoming measurement train, causing less deviations of the planned path. In the end this will increase the efficiency ratio, which in turn may help to reduce the number of deployment days.

- **Increase the number of parking locations for the inspection trains**

  Figure 41: Eurailscout UFM120 and Strukton engine 'Carin' parked at Rotterdam CS

  Currently Eurailscout tries to return their trains to the depot in Amersfoort at the end of an inspection run. This is done because of the water/fuel intake facilities and the availability of electricity connections (to keep the measurement systems free of freezing or condensation) at the yard in Amersfoort. As a consequence the trains make many transport kilometers and loose time during these transports. In case the number of parking locations with the required facilities increases, a reduction in the number of transport kilometers can be established. Furthermore the time otherwise spent on the transport can be used for measurements.

- **Working in shifts**
  ProRail measures Eurailscout's efficiency in the number of deployment days necessary to measure the tracks specified in the contract. Currently the measurements are planned with one shift a day (or night). Increasing the number of shifts reduces the number of required deployment days, which in turn will improve the efficiency as measured by ProRail. Implementing working in shifts requires multiple train crews able to work on a train. Furthermore it requires good coordination about the location and time the next crew has to take over the inspections, especially in case of disturbances affecting the original planned timetable. Switching of train crews can take place at a central location (most logically at the home base Amersfoort). When spare time is included, for example an hour, delays in the runs of the first crew do not influence the departure time of the next crew. Disadvantage of this recommendation is the increase in labor costs. An economic trade-off is necessary to determine whether the benefits outweigh the investment.

- **Train operating crews able to work on multiple trains**
  When the train crews are able to operate on multiple inspection trains, the flexibility in the planning increases. Especially when the improvement 'working in shifts' is applied, flexibility of train crews to operate on multiple inspection trains is a necessity to execute the measurements fluently.

- **Further improve the strategic planning**
  At the moment the planning of the measurements is completely based on the track inspection frequencies and remeasurement deadlines. When for example for every 10 days of measurements one spare day is reserved, this reserve day can be used for runs covering 'missed' track sections in previous runs. Depending on the available time before this remeasurement run, the timetable can be requested in the regular way or the train must be planned manually by the 'control' department of Eurailscout on the day itself in cooperation with dispatchers. If this run is not necessary the train crew can use this day to drive the train back to Amersfoort, towards the next start location, or they can update their route knowledge on the railway network.
  Advantage of planning with this method is that there is always a spare day available which can be used for remeasurements. When this day is not needed it can be used for updating/extending the route knowledge of the crew.

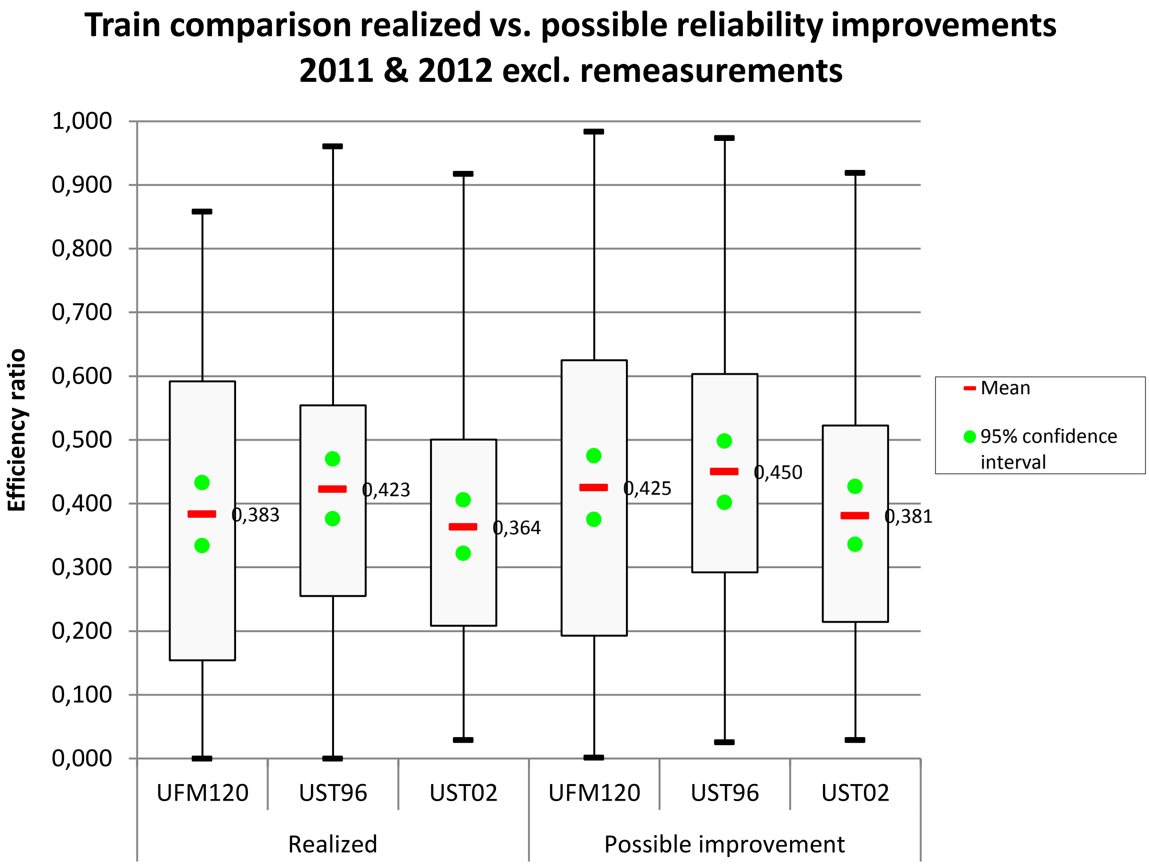
- **Use the software application ‘TOON’ to determine the exact paths of an inspection train afterwards**
  During inspection runs the train crew needs to report changes from the planned path manually, apart from their measurement tasks. With the software application ‘TOON’ – provided by ProRail – the driven path can be retrieved afterwards. In ‘TOON’ (replacing ‘TNV-Replay’ which had the same possibilities but was connected to the replaced VPT-planning system) the exact paths of all train movements of the day before can be visualized schematically. Filtering on train number allows to collect the measurement trains and visualize their exact driven paths. Using ‘TOON’ the number of tasks for the train crew will reduce and during data processing the exact driven path is already known and does not have to be filtered out of the notes on the planned path. In the future this process may also be done with a GPS system.

6.3 Estimated effects

In the previous two paragraphs recommendations for improvements were presented. This paragraph elaborates on the estimated effects of these improvements.

Improving reliability
Increasing the reliability of the measurement systems and trains is one of the suggestions given. To determine the effect of improved equipment reliability a calculation was made based on the efficiency analysis from chapter 4.2. For this calculation the efficiency data of the realized runs without remeasurements is used. It is assumed that with improved reliability 80% less kilometers of missed track sections can be achieved. Or in other words: if due to failing equipment, in the current efficiency analysis 10 kilometer of track could not be measured, the situation with improved reliability assumes that only 2 kilometer of track could not be measured. The dataset without remeasurements is used. Remeasurement runs are used to cover multiple missed track sections. It is possible to determine in which of these runs a missed track section is driven and thus the distance that can be removed from this run in the improved situation. However it is not easy to determine how many transport kilometers can/need to be removed from this remeasurement run. Therefore the dataset without remeasurements is used.

Figure 42 presents the efficiency ratios with improved reliability compared to the currently realized ratios. It shows that for the UFM120 approximately 4% efficiency improvement can be reached, for the UST96 approximately 3% and for the UST02 approximately 2%. The size of the boxes and the confidence intervals stay more or less the same. Furthermore reducing the mechanical failures reduces the number of remeasurement runs necessary. In both 2011 and 2012 respectively the UFM120, UST96 and UST02 had 32,16 and 11 remeasurement deployments (see Table 3). If approximately 80% reliability improvement can be reached, it is expected that 20% less remeasurement deployments are necessary. This would mean that a reduction in deployments of in total 6 days for the UFM120, 3 for the UST96 and 2 for the UST02.



	Realized			Possible improvement		
	UFM120	UST96	UST02	UFM120	UST96	UST02
# Arg	96	98	80	94	98	79
Min.	0,000	0,000	0,029	0,001	0,025	0,029
25th percentile	0,154	0,255	0,208	0,195	0,292	0,215
Median	0,366	0,440	0,366	0,461	0,444	0,386
75th percentile	0,592	0,554	0,501	0,621	0,603	0,522
Max.	0,858	0,961	0,917	0,940	0,973	0,919
Mean	0,383	0,423	0,364	0,425	0,450	0,381
95% CI low	0,334	0,376	0,322	0,375	0,402	0,336
95% CI high	0,433	0,470	0,406	0,475	0,498	0,427
St. dev	0,241	0,233	0,187	0,242	0,238	0,201

Figure 42: Possible efficiency improvement due to improved reliability equipment

Applying ‘yards first’ or ‘corridor routing’ philosophies

Next recommendation in paragraph 6.1.1 is to implement a more systematical approach to the planning of the measurement run paths. As shown in paragraph 5.5 about the calibration of the models, the (only possible) test with the ‘yards first’ algorithm revealed an improvement of approximately 8%. Difficulty in this case is that this is the only calibration possible because currently neither of the measurement trains under consideration are planned according to one of the studied routing methods. Therefore it is not possible to determine the exact expected efficiency improvement when applying this recommendation. The best test that can be executed to determine a bandwidth in which the expected improvement percentage will lay, is to compare the overall efficiency ratios reached by the models with the current mean planned ratios of chapter 4 (see Table 14).

Table 14: Comparison actual planned efficiency with results models

	UFM120	UST96	UST02
Current planning efficiency	42.4%	46.5%	38.2%
‘Yards first’ model	70.6%	70.7%	70.7%
Difference with current efficiency	+28.2%	+24.2%	+32.5%
‘Corridor routing’ model	67.1%	66.1%	66.1%
Difference with current efficiency	+24.7%	+19.6%	+19.6%

Regarding the data presented in Table 14 a few things have to be kept in mind. First of all the current planning efficiency is determined over many inspection runs, where the model efficiency concerns only one run on one line. Furthermore the planned paths are adapted to reality. The model paths are theoretical and therefore not one on one comparable. Calibration of the ‘yards first’ model with a real driven path by a video capturing train showed an improvement of only 8% instead of the 19%-32% as shown in Table 14. Therefore the overall estimated effect of implementation (one of) the studied routing methods is expected to be in the bandwidth of 5% to 15% improvement compared to the current planned paths.

Calibration of the ‘yards first’ model shows that basically this method requires more time to drive as the real planned path due to a higher number of direction changes. At the same time the paths developed by the routing method ‘corridor routing’ require less time than the ‘yards first’ model. Decreasing the required running time in a current deployment allows to increase the distance of measured tracks in these runs, saving on the number of deployments. Assumed it saves 5% of the runs, the number of deployment days drops for the UFM120, UST96 and UST02 as shown in Table 15.

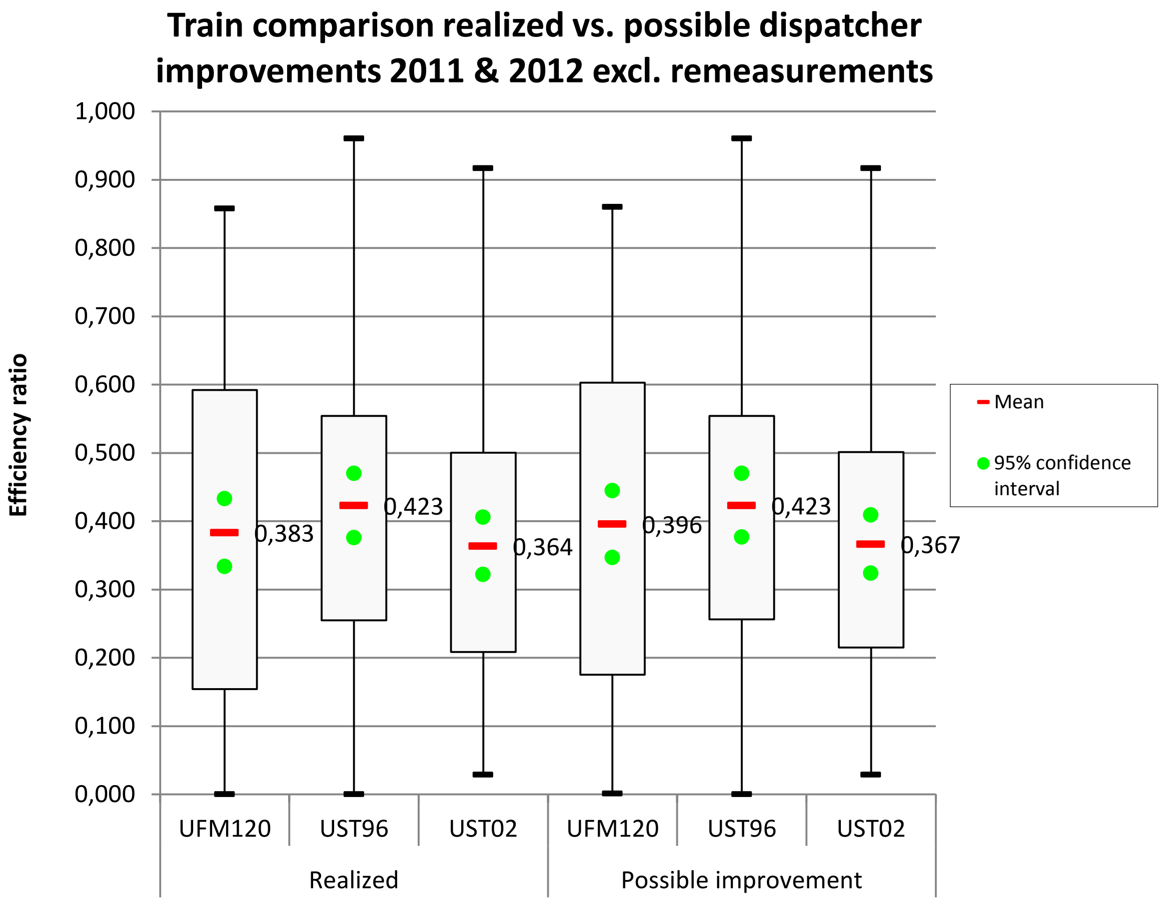
Table 15: Estimated saved deployments due to applied model routing methods

	UFM120	UST96	UST02
In 2011 and first half 2012 realized number of normal runs	96	98	90
5% saving	-5	-5	-4

Improvements by dispatchers

In paragraphs 6.1 and 6.2 several recommendations for improvements were given, related to ProRail dispatchers. As Table 23 and Table 24 in appendix A7 show, disturbances caused by actions of dispatchers relate to relatively small influenced distances of tracks to be measured. This is also shown in Figure 43, where it assumed that all mentioned recommendations will reduce the length of missed track sections by 50%. The largest improvement in the mean performance occurs by the UFM120, although still relatively small: approximately 1.3%.

However, if it is possible to reduce the length of missed track sections due to actions of dispatchers, a saving in the number of remeasurement deployments can be established. Assuming the same reduction percentage (20%) as used in the calculation for the reliability improvement can be realized, this would decrease the number of remeasurement deployments by 6 days for the UFM120, 3 days for the UST96 and 2 days for the UST02.



	Realized			Possible improvement		
	UFM120	UST96	UST02	UFM120	UST96	UST02
# Arg	96	98	80	94	98	79
Min.	0,000	0,000	0,029	0,001	0,000	0,029
25th percentile	0,154	0,255	0,208	0,175	0,256	0,215
Median	0,366	0,440	0,366	0,389	0,440	0,376
75th percentile	0,592	0,554	0,501	0,603	0,554	0,501
Max.	0,858	0,961	0,917	0,860	0,961	0,917
Mean	0,383	0,423	0,364	0,396	0,423	0,367
95% CI low	0,334	0,376	0,322	0,347	0,377	0,324
95% CI high	0,433	0,470	0,406	0,445	0,470	0,409
St. dev	0,241	0,233	0,187	0,239	0,233	0,187

Figure 43: Possible efficiency improvement due to improved actions of dispatchers

Other improvements

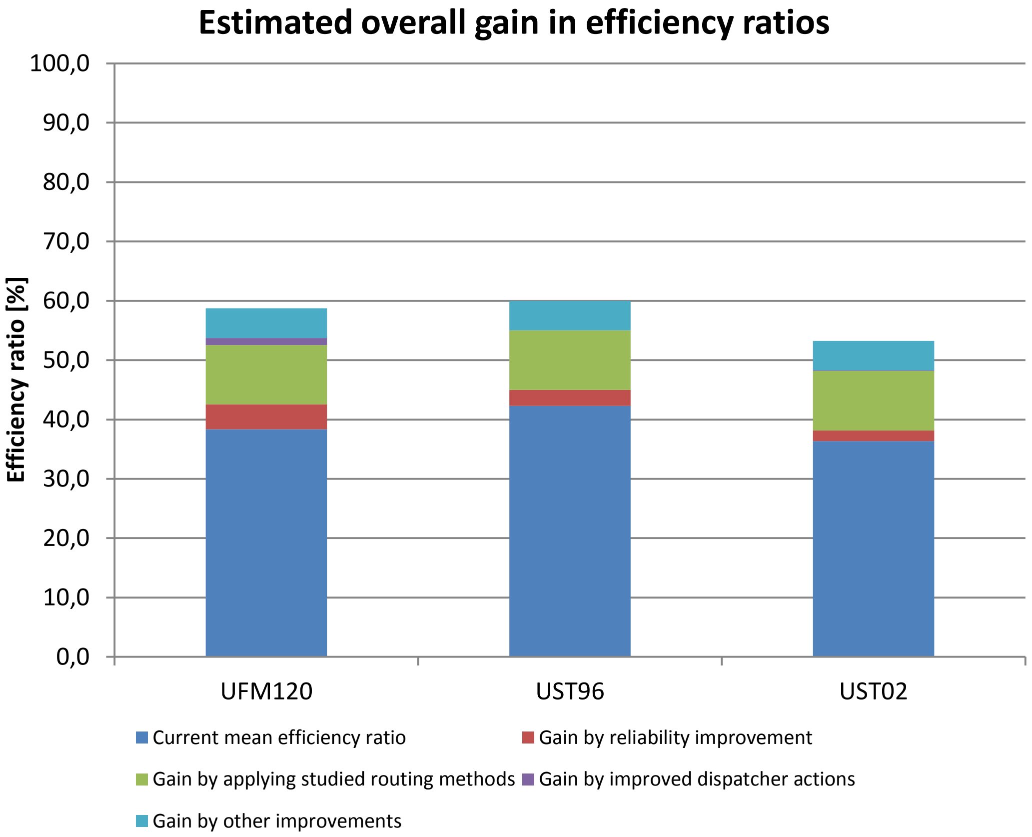
Besides the previous mentioned improvement recommendations, several other suggestions were discussed in paragraphs 6.1 and 6.2. Determining the exact effects these recommendations will have is even harder because not all suggestions can be related to the disturbances or the developed models. Therefore the assumption is made that the remaining recommendations will reduce the number of deployment days by 10%, especially when working in shifts is introduced. Efficiency ratios will increase by an estimated 5% due to increased availability of tracks (e.g. by ‘Eurailscout line closures’).

6.3.1 Combined estimated effects of the recommendations

Combining all recommendations and summing the estimated effects they will generate, results in the figures as visualized in Table 16 and Figure 44.

Table 16: Estimated gain in deployment days by recommendations

	UFM120	UST96	UST02
Deployments in 2011 and first half 2012 (incl. remeasurements)	127	114	100
Saved deployments by recommendations:			
Improving reliability	6	3	2
Applying studied routing methods	5	5	4
Improvements dispatcher actions	6	3	2
Other improvements	12	11	10
Total gain in deployments	29	22	18
Gain in efficiency (saved deployments/total deployments)	22.8%	19.2%	18.0%



	UFM120	UST96	UST02
Current mean efficiency ratio	38.3%	42.3%	36.4%
Gain by			
Improving reliability	4.2%	2.7%	1.8%
Applying studied routing methods	10%	10%	10%
Improving dispatcher actions	1.2%	0%	0.1%
Improvements by other recommendations	5%	5%	5%
Improved efficiency ratio	58.7%	60.0%	53.3%
Gained	20.4%	17.7%	16.9%

Figure 44: Estimated gain in mean efficiency ratios

Most important for answering the main research question is the gain in deployment days needed to inspect the rail network as agreed in the contract with ProRail. Table 16 presents this gain. Although it is an estimate, it indicates that improvements are possible. The estimated improvements range from approximately 18% to 23%. These results imply that increasing the efficiency measured by the number of deployments by 10% annually, is possible in at least the first year. For subsequent years the10% annual improvement is harder to establish because the current performance of the Eurailscout measurement trains are good already.

The efficiency ratios as internally used by Eurailscout also improves by the recommendations. As Figure 44 presents, improvements in the mean efficiency ratios range from approximately 17% till 20%, depending on the measurement train under consideration.

7 Final conclusions and recommendations

Paragraph 7.1 of this chapter presents the conclusions that can be drawn from the executed analyses and model results. The main research question is answered and the conclusions are underpinned with the established results. Paragraph 7.2 discusses recommendations for further research about topics that could not be studied as far as desirable or felt beyond the scope of this research.

7.1 Conclusions

Regarding the results of the current practice analysis in chapters 3 and 4 and the routing models results in chapter 5, it can be concluded that efficiency improvements in the planning and execution of the measurements by the UFM120, UST96 and UST02 trains, are possible.

In this research two expressions of efficiency are used. The first method is used by ProRail and measures efficiency by the number of deployments necessary to execute the measurements. The second method is the ratio Eurailscout uses internally, calculated by dividing the measured kilometers of track by the total driven kilometers in a deployment. For both efficiency expressions improvements were searched.

Analysis of the current planned and realized efficiencies in chapter 4 show that on the highly utilized Dutch train network, the current performance is good already. The realized mean efficiency ratios range from approximately 34% till 41%, the planned mean efficiency ratios range from approximately 38% till 47% for the trains under consideration. For all three trains the realized efficiency ratios are lower than the planned ratios, but the differences are insignificant. The affected measurement kilometers however can be substantial, reason why the causes for the disturbances are investigated.

A range of disturbances occurring in the realization phase cause the occurring differences between the planned and realized efficiencies. Main causes for all three trains are failing measurement systems (37%-43%) and dispatchers assigning wrong paths (19%-29%). Eurailscout itself and ProRails dispatchers are the main parties the disturbances can be assigned to. Based on the information source used for this analysis, relatively few disturbances can be related to the planning phase; most disturbances occur in the realization phase. The analysis indicated some possible improvements to increase the efficiency ratios, as further on elaborated.

Because the differences between the planned and realized efficiency ratios are not significant, the study focused on the planning of the measurement trains. improvements were searched in the way the trains are planned. Several routing philosophies exist to route the measurement trains over the railway network. Currently the planners are creating the paths heuristically based on previous runs, knowledge and experience of the planners as explained in chapters 3 and 5. The routing models were built with the purpose to determine whether a more systematic approach might improve the efficiency.

For the line Utrecht – Alkmaar: a ‘yards first’ model and a ‘corridor routing’ model were built. They show that the efficiency can be further improved when a more systematic inspection path creation approach is used. Outcomes of both models show that the mean theoretical possible efficiency ratios lay approximately around 70%. At large stations with complex track layouts, the theoretical reached efficiency ratios are approximately 38%. On a simple track layout consisting of just an open track (two parallel tracks not interconnected with switches) may even reach 100% efficiency. Compared with the current mean efficiency ratios, the models improve these values with approximately 17%-20%. Converting the model results to reality will reduce the possible efficiency ratios, due to limitations in the models (e.g. absence of other train traffic).

The calibration executed in chapter 5.5, result in a 8% more efficient inspection path generated by the model compared to an actual driven path. Based on the theoretical model results and the calibration it is estimated that a more systematic approach to the path creation process will improve current efficiency ratios by 5%-10%. Although the required train running times are estimated by the models in a simple way, they show that in the theoretical situation the generated paths on the line Utrecht – Alkmaar already require two shifts.

Due to the limitations and assumptions used to make the calculation of the optimal paths possible and the complexity of the problem as studied, the model outcomes are theoretical and approach an optimal situation. Both models can be used to help the planners in creating inspection paths in a more systematic way or they can be used to determine an optimal inspection path on a closed line in which no other train traffic is present. Furthermore they can be used as a basis to look at where further improvements can be sought, see the recommendations for further research in paragraph 7.2.

Chapter 6 discussed efficiency improvement recommendations. Two categories divide the recommendations into suggestions that can be related to the performed analyses or to the models built and suggestions that were identified during the research that cannot directly be related to the analyses or models. In the former category two subclasses are used: recommendations Eurailscout can initiate and suggestions they are dependent on other parties. The exact effects the recommendations will have are hard to determine due to the complex interconnected processes in railway operation planning, scheduling and execution as discussed in chapter 3. The effects the improvements will have are estimated with a bandwidth in which the expected improvement will lay.

In the category of studied recommendations Eurailscout can initiate, improving the reliability of the equipment and applying a routing philosophy as used in the models are the most effective. Further improving reliability with 80% increases the efficiency ratios with approximately 3% and saves an estimated 2-6 deployment days. Implementing one of the studied routing philosophies as analyzed in the developed routing models, will improve efficiency ratios by 5%-10% and save an estimated 4-5 deployment days.

In the second category in which Eurailscout is dependent on other parties the main improvements are increasing the awareness of dispatchers about the importance of the measurements and requesting an own train category. These suggestions have an negligible effect on the efficiency ratios but save the same amount of deployment days as the increased reliability.

Recommendation not studied in detail are among others working in shifts, increasing the number of parking locations and the usage of DONNA to determine track sections with critical capacity.

Combining all recommendations an estimated improvement in efficiency ratios of 17%-20% is possible and a reduction in the deployment days of approximately 18%-23% as well. All improvement recommendations can be applied, both in the short, mid or long term. Before implementation an economic trade-off needs to be made to determine whether the investment to implement a recommendation outweigh the expected benefits.

Main research question of this master thesis was: '*How to establish an annual 10% efficiency improvement after the year 2013 in the planning and deployment of the Eurailscout measurement trains, given the limitations imposed by the measurement trains, the tracks and scheduling?'*. The answer to this question lays in the recommendations presented. Improvements are possible both in the planning and execution according to the two used definitions of efficiency. Most important for Eurailscout regarding their contractual obligation with ProRail, is the reduction of deployment days. The combined estimated effects of the presented recommendations show improvements larger than 10%.

Final conclusion is that an annual 10% reduction in the deployment days is possible, at least in the first year. For subsequent years it will become harder to establish the same percentage of improvement, due to the already good current performance.

Eurailscout is one of the very few train operating companies requesting paths in which specific tracks need to be driven. Additionally the inspection trains have many special requirements. These characteristics generate many challenges in the planning, scheduling and execution of the measurements. Especially with the current increase in rail traffic.

Track inspections are and will stay very important for the safety level of rail transportation. Efficient inspection schemes provide the customer with detailed overviews of the tracks, with minimal hindrance for other rail traffic. This research helps Eurailscout to reach their target set and to improve their efficiency both on the busy Dutch railway network as on foreign railway networks for other (international) customers.

7.2 Recommendations for further research

Due to the complexity of the examined problem not all subjects could be studied as far as desirable. Therefore the following suggestions for further research are made.

In the efficiency analysis of chapter 4 the causes for disruptions were discussed. Possible extension of the study can be to determine whether disturbances in the execution of the measurements are caused by errors made in the planning/scheduling, or whether measurement paths do not correspond to the real track layout. To do so, more detailed information about the exact (location in the planning process of the) disturbance causes must be collected.

Chapter 5 discussed the two routing models developed in this master thesis. To build these models several assumptions and decisions were made. In further researches the models as presented may be improved/extended with the following suggestions:

- ***Path optimization over all maps***
  The presented algorithms search for the optimal path on each map individually. Extending the model towards an overall algorithm capable of assessing the complete line instead of the maps individually may further increase the results. Negative effect of this suggestion is the (exponential) increase in computation time. A trade-off between the estimated gain and the time and effort needed to calculate the improved situation, gives an answer whether it is worth the investment
- ***Adding directed links to the network***
  Not all real track sections may be driven in both directions. Inserting directed links converts the network to a more realistic representation. As a consequence the path finding process must be adjusted because the used algorithm only functions on undirected networks
- ***Restrict the number of possible paths to the real possible paths***
  In both MATLAB models it is assumed that all paths in the network between any pair of nodes is possible. However in reality it may occur that there are system limitations restricting the number of possible paths to a lower number than the infrastructure allows. Adding these limitations will result in a model better representing reality
- ***Make the running time estimation more precise***
  The running time is estimated by simply dividing the track length by the speed limit supplemented with 10% to correct for acceleration/deceleration and speed deviations of the train. When the acceleration and deceleration values of the trains can be included in the running time estimation, the outcome becomes more precise. Furthermore if the locations where the UST96 is able to drive around its flat car are precisely located, the running time of the UST96 can be more precisely estimated.

- ***Adding other train traffic***
  Difficult to realize but if possible it would result in a better representation of reality. Possibly a coupling can be made with the DONNA planning application to see the availability of tracks
- ***Improve the method to connect odd nodes***
  As mentioned in subparagraph 5.4.1 under ‘choices made’ the used method to connect odd nodes saves the calculation of, in the worst case, approximately 654 million combinations. It however does not guarantee the best combination of connected odd nodes, it approximates the optimal solution. Therefore a better method to connect all odd nodes may result in a better solution of the model. However the expected improvement of this more optimal method is small. As estimated in the same subparagraph improvement in the overall efficiency ratio is approximately 0.6%.

Chapter 6 presented recommendations for efficiency improvements. Estimates about the effects of the improvements are presented in a bandwidth in which the expected value of improvement will lay. In another research the precise effects of the suggestions may be studied. This study then allows to make a better economic trade-off whether the investment for improvement outweigh the expected benefit. Due to the complexity of the studied problem, the exact effects could not be examined in detail.

Another recommendation for further research is to determine the effects on the measurements of the plans of the Dutch government and ProRail to improve the robustness of the Dutch railway network (ProRail, [25]). Improving the robustness reduces the flexibility available in the rail network. This will have direct consequences for the execution of measurements by the Eurailscout inspection trains. The flexibility to schedule these trains between the regular trains will be further reduced, apart from the reduction by the growing rail traffic. Determining the exact effects allows to develop a long-term strategy for the planning and execution of the measurements.

Last recommendation for further research is to study whether it is an option to let the Eurailscout planners directly schedule the measurement trains. With the new planning and scheduling application DONNA, it is for the planners possible to schedule trains. Advantage of the direct scheduling by Eurailscout planners is that they know best: which path the train needs to drive, the limitations and requirements the trains have and where trains can be parked after a deployment. Direct scheduling removes a party in the planning process, reducing the chance of miscommunication. Disadvantages are that the Eurailscout planners are not allowed to reschedule passenger trains and they have to follow a course in scheduling trains in DONNA.

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Other consulted information sources:

www.eurailscout.com	website Eurailscout Inspection and Analysis
www.prorail.nl	website Dutch rail infrastructure manager
www.infrasite.nl	Dutch website with infrastructure related news
www.marcrpieters.nl	website of Eurailscout colleague about railway signaling

Used software packages:

- Microsoft Office 2010 (Word, Excel, Powerpoint)
- EB-ViCoP
- MATLAB R2010b SP1
- IBM SPSS Statistics 19
- Google Earth, version 6.1

9 Woordenlijst Engels – Nederlands

Engels →	*Nederlands*
Application	Aanschrijving (meetrit aanvraag + dienstregeling)
Basic Hour Pattern (BHP)	Basis UurPatroon (BUP)
Buffer stop	Stootjuk
Catenary	Bovenleiding
Control (railway-)	Bijsturing
Corridor	Traject
Deployment	Inzet
Dispatcher	Treindienstleider
Headway time	Opvolgtijd
Infrastructure manager	Infrabeheerder
Kilometer ‘jump’	Kilometer sprong
Knock-on delays	Opvolg vertraging
Line closure	Buitendienststelling
Main line	Hoofdbaan
Maintenance window	Onderhoudsrooster
Measurement script	Meetrit aanvraag
Measurement coach	Meetrijtuig
Open track	Baanvak
Railway line	Spoorlijn
Route book	Draaiboek
Route knowledge	Wegbekendheid (van machinist)
Run	Inzet
Siding	Rangeer-/opstelterrein
Signal aspect	Seinbeeld
Slot	Pad (in tijd en ruimte)
Parking location	Opstellocatie
Track superstructure	Bovenbouw (spoorstaaf, bevestiging, dwarsliggers, ballastbed)
Train traffic control	Verkeersleiding (landelijke)
Turnaround time	Keer tijd (= kopmaak tijd)
Ultrasound	Ultrasoon
Video capturing	Videoschouw
Yard	Emplacement

A. Appendixes

A1. Organogram Eurailscout

A2. Schematical representation current planning process

A3. Schematical representation of locations where disturbances occur in planning process

A4. Details of scheduling by NS Dagplan

A5. Adjustments dataset current efficiency analysis

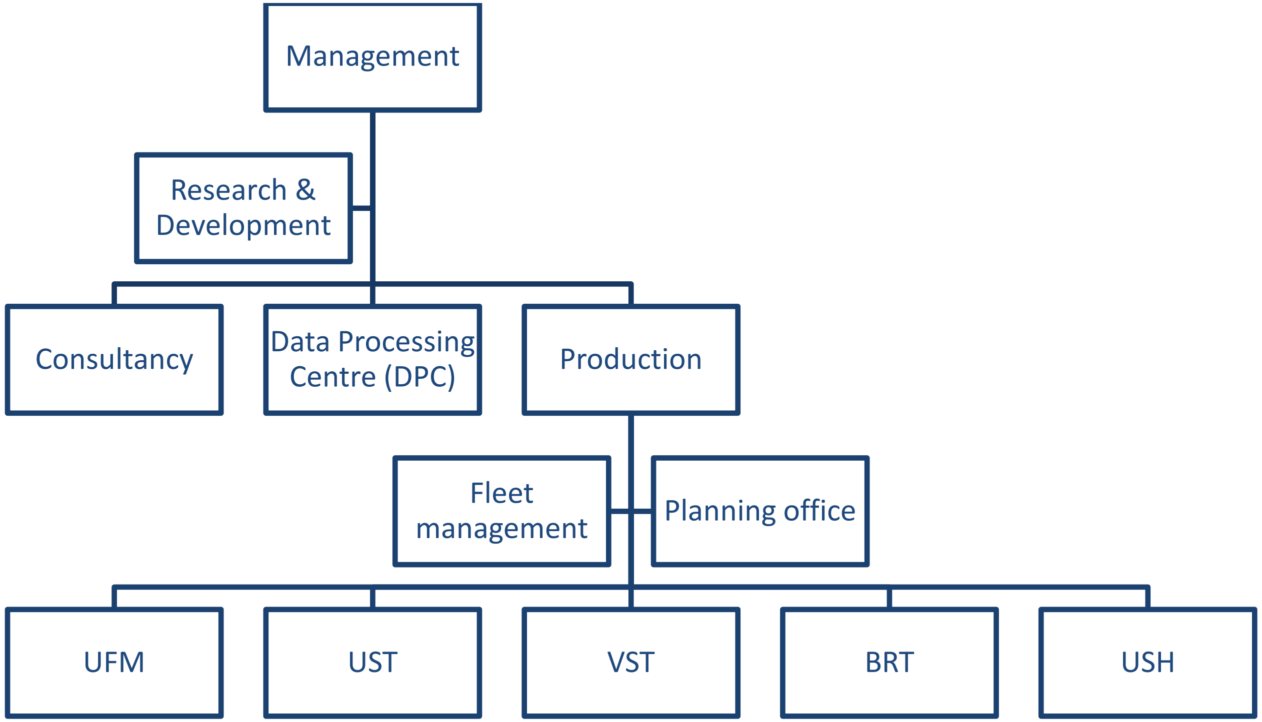
A6. Inspection train specific efficiency performances

A7. Details inspection train measurement disturbances

A8. MATLAB network maps of railway line Utrecht – Alkmaar

A9. Example of path creation process
    - Assignment map creation and filtering
    - Making the nodes in the list of routes to be driven, even
    - Path creation

A1. Organogram Eurailscout



UFM = Universal measurement trains (multiple measurement systems)

UST = Ultrasound measurement trains

VST = Video capturing trains

BRT = Safety system control trains

USH = Handheld ultrasound inspection teams

The SIM, ODT and UMR trains are most of time planned by one of the UFM, UST or VST planners

A2. Schematical representation current planning process

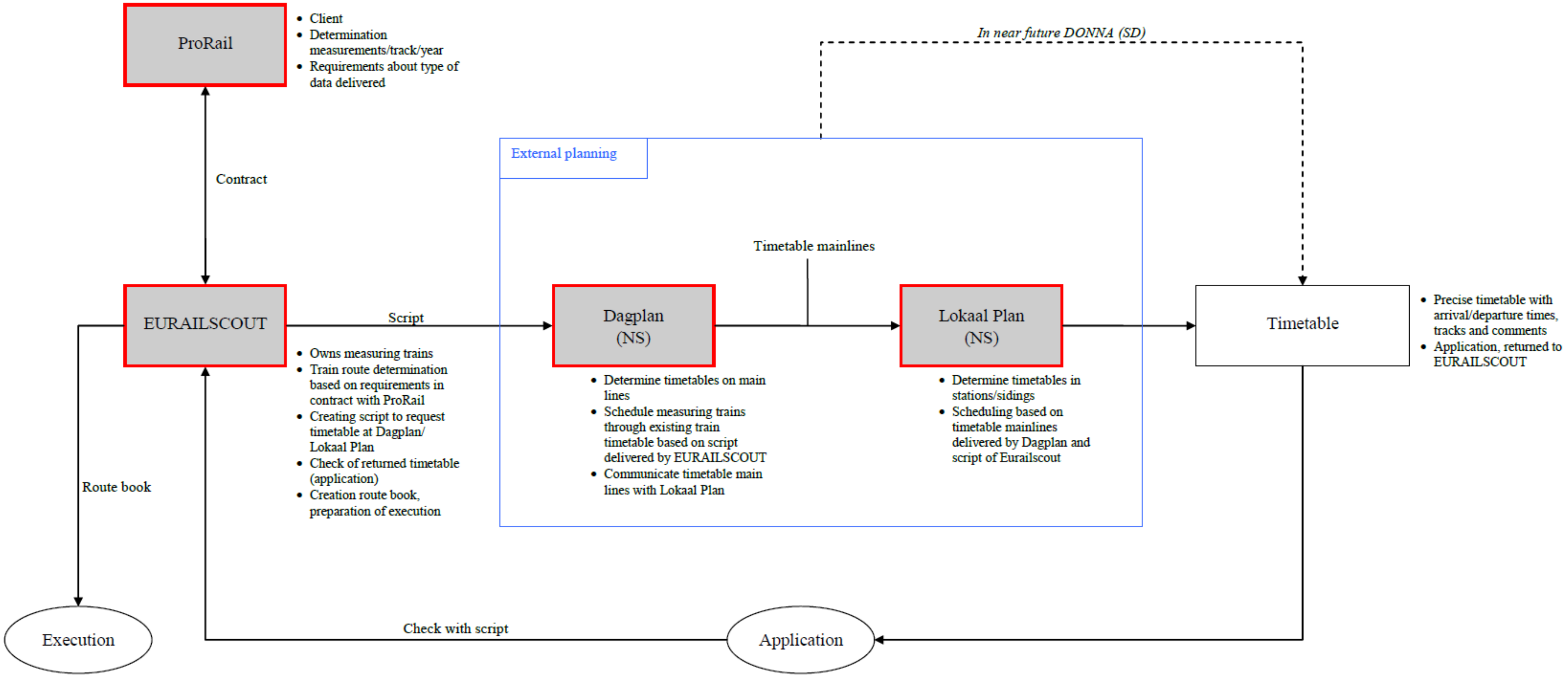


Figure 45: Schematization current planning process Eurailscout measurement trains

A3. Schematical representation of locations where disturbances occur in planning process

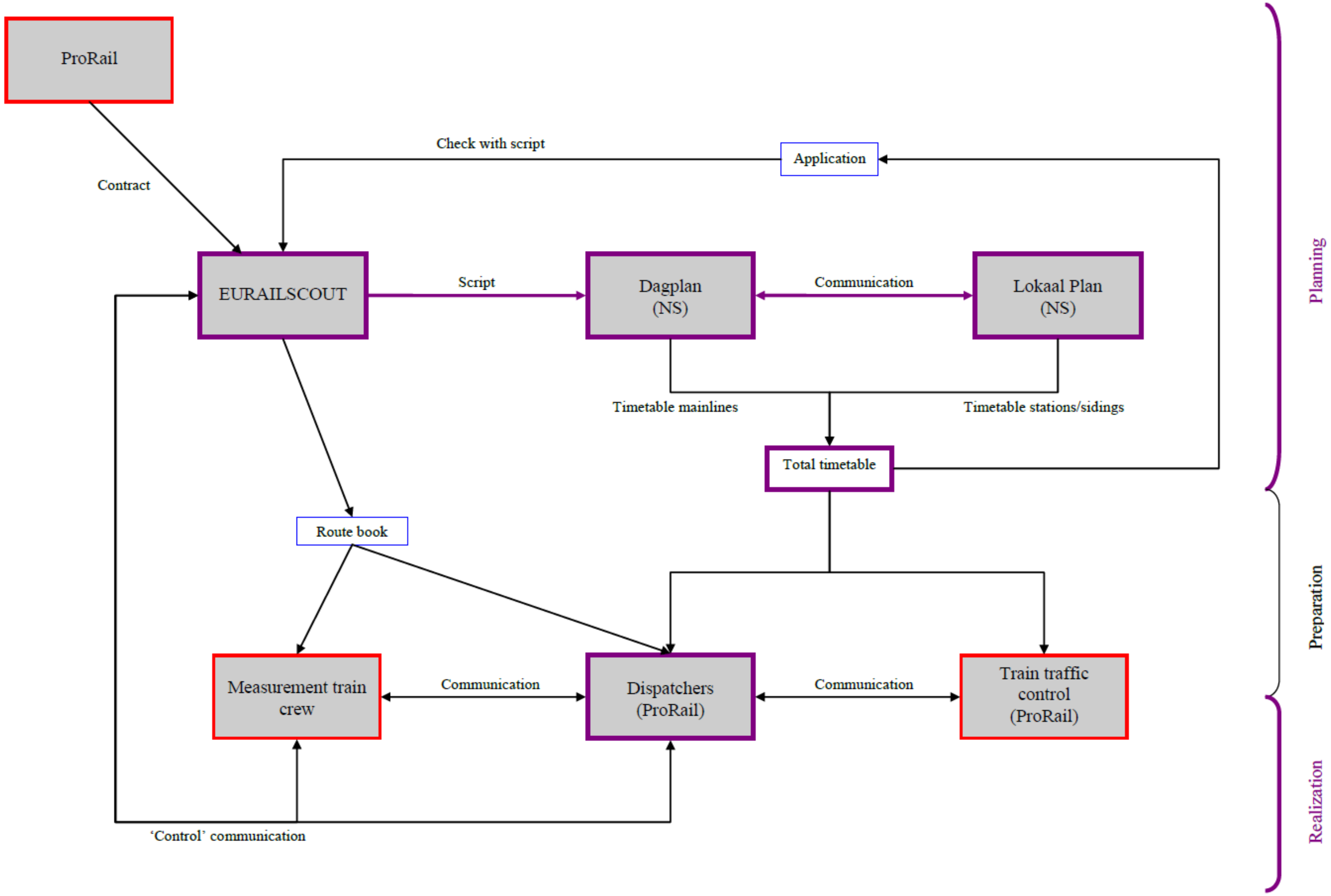


Figure 46: Overview process from planning to execution of measurement runs
In purple are locations of possible disturbances shown.

A4. Details of scheduling by NS Dagplan

As mentioned in paragraph 3.2, NS Dagplan schedules the inspection trains in VPT-Planning. In VPT-Planning the planners of Dagplan schedule trains using time-distance diagrams (see for an example time-distance diagram Figure 47).

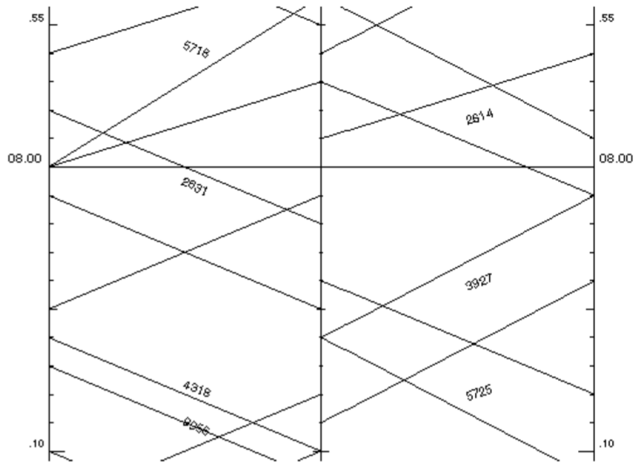


Figure 47: Example of a time distance diagram (source: [22])

Time-distance diagrams graphically show the location of trains at each time moment. In Figure 47 the diagram shows on the vertical axis time, on the horizontal axis distance. The diagonal lines with numbers on it represent trains, the angle of the diagonal line represents the speed of the trains (distance/time = speed). The VPT-Planning system shows the Basic Hour Pattern (BHP) of the national railway timetable. A basic hour pattern is an hourly repeating sequence of trains.

Furthermore it can show ‘constraints’ in the railway network like for example the opening times of moveable bridges. It provides the Dagplan planners a graphical overview of the available spaces between trains, which is used for determination of gaps between consecutive trains large enough for inserting the measurement train, taking into account its specific requirements.

Relevant parameters are the train its maximum speed (during measurement and transport), vehicle type, weight and length. These parameters combined with a predetermined train number, allow Dagplan to determine a timetable based on the script received from Eurailscout.

When a gap large enough is found, the measurement train is inserted by creating a timetable. This timetable consists of arrival and departure times at stations, signals or other infrastructure elements. Furthermore the specific tracks the route will cover are mentioned. In the time distance diagram the line representing the measurement train is immediately visible. A gap between two consecutive trains is considered large enough as soon as the headway time is 3 minutes or more, in case of a cross-over the gap between two consecutive trains must be 4 minutes or more (respectively situation 1 and 2 in Figure 48). After implementation of DONNA the headway time is increased to 4 minutes or more and the cross-over time are increased to minimal 6 minutes.

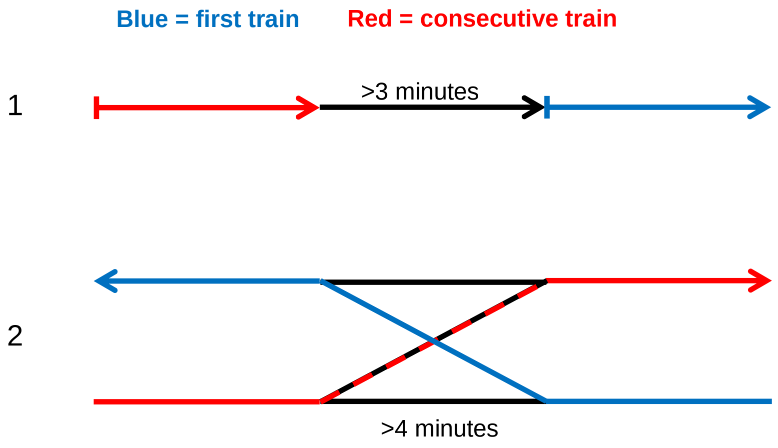


Figure 48: Headway times in two situations

Conflicts may not arise with the already planned trains. May these conflicts arise and another path in the timetable is not available or possible for the measurement train, Dagplan has the authorization to reroute other (passenger) trains if this will solve the conflict. Because Dagplan is part of the Dutch national railway company it is authorized to reschedule passenger trains. Therefore they are included into the measurement train planning chain to warrant the availability of specific mainline tracks for Eurailscout as much as possible (no complete guarantee can be given, see paragraph 3.4).

A5. Adjustments dataset current efficiency analysis

The dataset as exported by EB-ViCoP contains distances with an accuracy of three decimals. However there are some points that have to be corrected/kept in mind by analyzing the results:

- At some places in the railway network kilometer ‘jumps’ exists. This is a situation where the actual distance difference between two kilometer markers does not correspond to the difference between the figures on the markers. For example the actual distance between two markers is 500 meter while the distance according to the numbers on the markers is 2.5 kilometer (Figure 49). In the digital maps provided by ProRail the same differences occur. Consequence is that some automatically generated distances of the measured and transport sections are too long or too small compared to the actual covered distances.

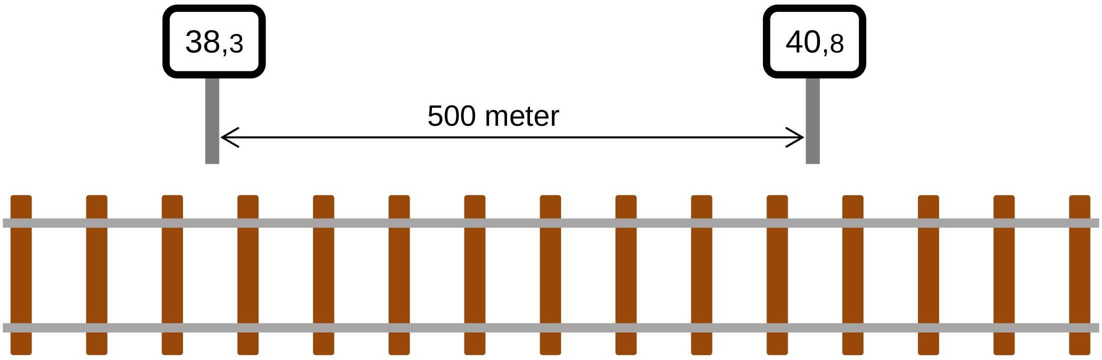


Figure 49: Example of a kilometer ‘jump’
The actual distance is 500 meter while the distance markers imply a distance of 2.5 kilometer. Also the other way around occur.

Days where ‘obvious’ kilometer jumps occurred were removed from the dataset because the kilometer data of these days are not reliable. Obvious in this case means clearly visible in the dataset. Days on which in total over 500 kilometers were driven, are manually checked on kilometer jumps. For example a day where a in a train movement of 20 minutes over 3000kilometer was travelled, was completely removed from the dataset. The occurrence frequency is however low and therefore the impact on the data is also marginal, especially when the obvious kilometer ‘jumps’ are removed from the dataset.

- EB-ViCoP is filled with input from the planners. Although they work as precise as possible, faults (like selecting wrong tracks, path determination on network maps not being updated to a new situation, etc.) may occur. These faults cannot be checked by the software and therefore have an effect on the generated lists. However these faults are accepted as possibly present in the dataset and assumed to have a negligible effect on the efficiency ratios.

- The distances on the maps can differ from the distances in the real situation. Because both the planned and realized data are extracted from the same maps, any fault generated cancels itself out.

- In the evaluation of planning efficiency the timetable as generated by Dagplan and Lokaal Plan is used. It is possible that this timetable already includes detours due to tracks being out of service for example caused by maintenance works. The automatically generated efficiency overviews therefore may include detours or reroutings compared to the initial planned path determined by the Eurailscout planners. This may frequently occur but does not have an effect on the outcomes, because the planning data also contains these deviations. The planning data consist of the data which can also be seen in a route book (which is the script supplemented with the timetable).

- A drawback of the compare tool included in EB-ViCoP is that when evaluating executed measurements, the tool does not take into account parts of the total run where no measurements were executed (‘transport’ sections). For example consider the following case. A Eurailscout train drives in ‘transport’ from Amersfoort to Utrecht to execute measurements between Utrecht and Gouda. When evaluating this trip in EB-ViCoP, the section between Amersfoort and Utrecht will not be included in the overview. In the planning overview this problem is not occurring.

  Comparing the realized efficiency with the planned efficiency, without correcting for this problem, would give a wrong bias to the outcomes (realized efficiency would be much better than planned performance). To solve this problem the sections of ‘transport’ excluded in the realized efficiency overviews are copied from the planning overview. This solution introduces also an error in the data because the actual driven ‘transport’ kilometers may substantially differ from the planned ‘transport’ kilometers. However this fault is accepted because the solution procedure allows comparing planned and realized efficiency.

- Days with 100% efficiency were removed from the data set because these days were planned via the ‘control’ department. EB-ViCoP includes only the measurement lengths in that case and therefore return a 100% efficiency ratio. Including these days in the dataset would give a wrong bias to the data.

- The dataset covers the whole year 2011 and the first half of 2012. As a consequence a whole winter period is included, in which weather circumstances could negatively influence the outcomes. However these disturbances cannot be assigned to any party and can be seen as circumstances beyond anyone’s control. Furthermore only the UST trains had in total eleven days in which complete runs were cancelled due to winter weather. Therefore the data is not corrected for the winter period.

The above listed points were applied/changed/removed from the dataset before the actual analysis was applied. Paragraph 4.2 presents the results obtained from the analysis.

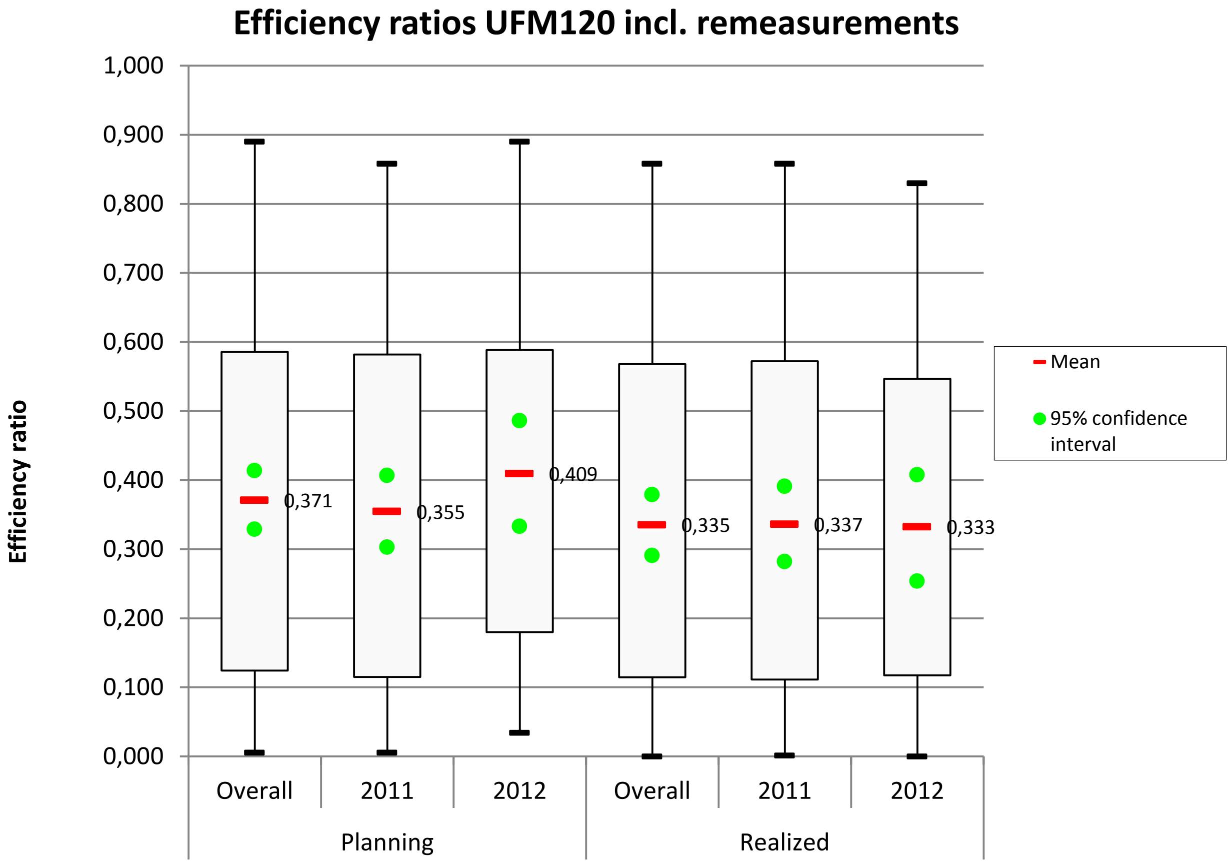
A6. Inspection train specific efficiency performances

To assess the train specific performance, the data of 2011 and first half of 2012 are compared to each other and to the overall performance (2011 plus first half of 2012), using Microsoft Excel and IBM SPSS Statistics 19. The data is visualized in so called ‘boxplots’. A boxplot shows the total range of the dataset with the box marking the middle 50% of the data.

All distributions are tested on normality and (student) t-tested with significance level 0.05 (5%) to check for significant differences between the distributions. Any p-value (chance) larger than 0.05 means the difference is not significant, any p-value smaller means there is a significant difference between two distributions. The shown confidence intervals are based on the means of the distributions.

UFM120
In Figure 50 the data of the UFM120 is shown in the boxplot. All datasets are normally distributed except for the set ‘realized-overall’. A slight difference between the mean planning efficiency and realized efficiency caused by disturbances occurred in the execution of the inspections is visible. The mean planning efficiency in the first half of 2012 is larger than the overall planning mean, although the difference is not significant (p-value (two sided) of 0.38, see Table 17). No cause can be found in the data and a check by the UFM planner learned that there are no changes in the way of planning applied. A possible cause is changes in the infrastructure, but this cannot be checked.

The comparison between the overall planning efficiency and the overall realized efficiency shows that there is no significant difference between them (p-value (two sided) of 0.25, see Table 17). Looking to the confidence intervals of the mean it can be seen that there are many ‘outliers’ in the data, or in another way: the spread in the data is relatively large.



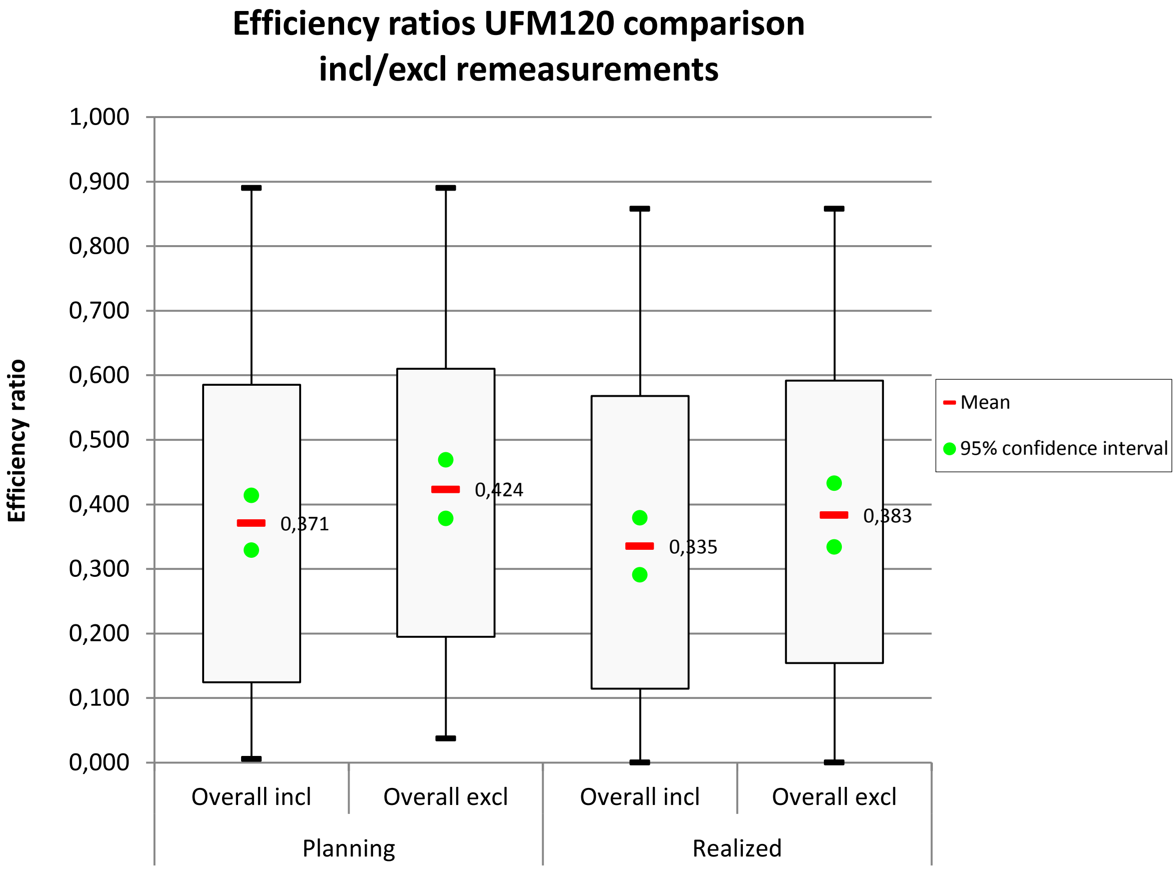
	Planning			Realized		
	Overall	2011	2012	Overall	2011	2012
# Arg	137	96	41	127	88	39
Min.	0.006	0.006	0.034	0.000	0.001	0.000
25th percentile	0.124	0.115	0.180	0.114	0.111	0.117
Median	0.325	0.311	0.455	0.297	0.274	0.306
75th percentile	0.585	0.582	0.588	0.568	0.572	0.547
Max.	0.890	0.858	0.890	0.858	0.858	0.830
Mean	0.371	0.355	0.409	0.335	0.337	0.333
95% CI low	0.329	0.303	0.333	0.291	0.282	0.254
95% CI high	0.414	0.407	0.486	0.379	0.391	0.408
St. dev	0.251	0.255	0.238	0.250	0.256	0.235

Figure 50: Boxplot UFM120 incl. remeasurements

Table 17: (Two sided) p-values datasets UFM120

	Planning Overall	Planning 2011	Planning 2012	Realized Overall	Realized 2011	Realized 2012
Planning Overall		0.63	0.38	0.25		
Realized Overall	0.25				0.97	0.95

Comparing the overall planning and realization for the data inclusive and exclusive remeasurements gives the boxplot as shown in Figure 51. Now it is clearly visible that excluding the remeasurements of the data improves the mean performance but the differences are not significant (see Table 18).



	Planning		Realized	
	Overall incl	Overall excl	Overall incl	Overall excl
# Arg	137	106	127	96
Min.	0.006	0.037	0.000	0.000
25th percentile	0.124	0.195	0.114	0.154
Median	0.325	0.462	0.297	0.366
75th percentile	0.585	0.610	0.568	0.592
Max.	0.890	0.890	0.858	0.858
Mean	0.371	0.424	0.335	0.383
95% CI low	0.329	0.378	0.291	0.334
95% CI high	0.414	0.469	0.379	0.433
St. dev	0.251	0.236	0.250	0.241

Figure 51: Boxplot UFM120 comparison incl/excl remeasurements

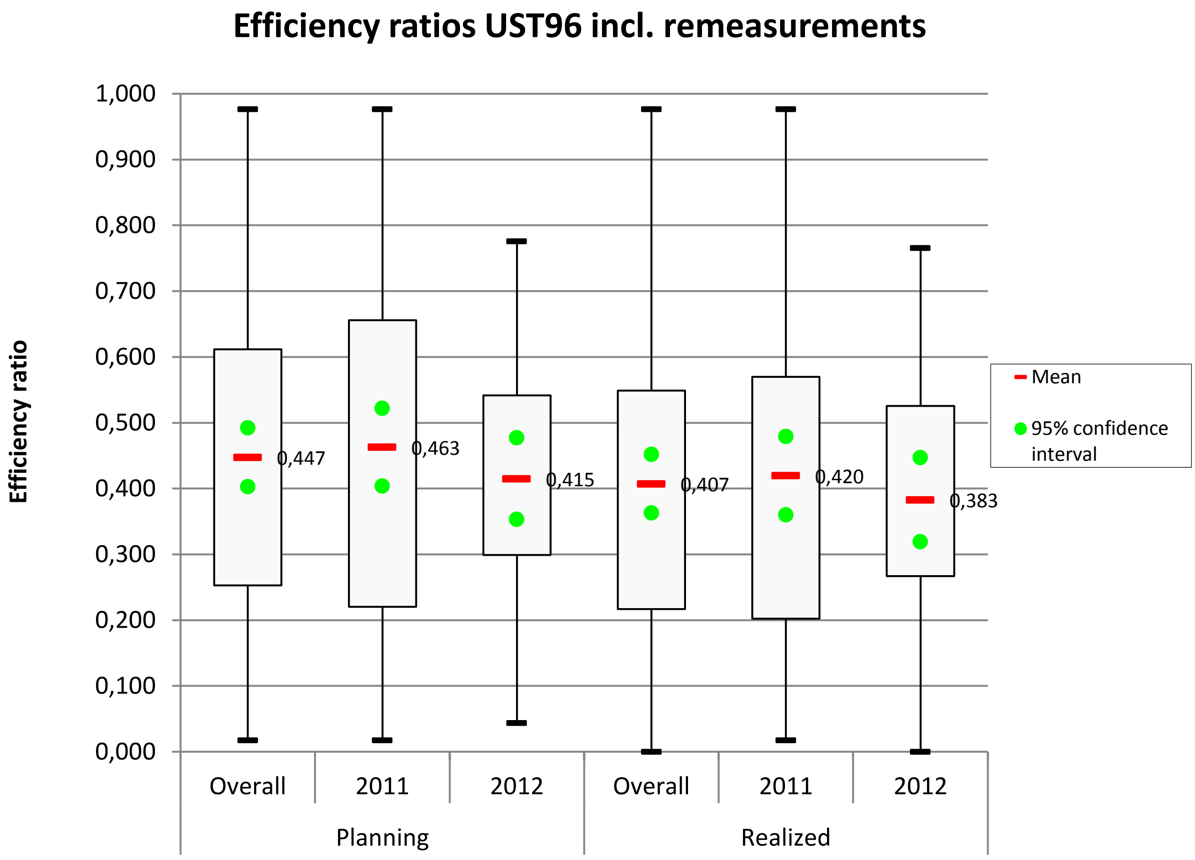
Table 18: (Two sided) p-values datasets incl/excl remeasurements UFM120

	Planning Overall excl	Realized Overall excl
Planning Overall incl	0.10	
Realized Overall incl		0.15

UST96

Figure 52 presents the boxplot of the UST96. All the datasets are normally distributed. Looking to the mean values of the planning compared to the realized means, it can be seen that the planned mean ratios are higher. Remarkable is the difference between the planning and realization in 2012 compared to 2011. The spread in data is smaller and the mean of the efficiency ratios is also smaller in 2012. A cause can be found in the higher number of occurred disturbances in the first half of 2012 (see paragraph 4.3). The differences between the datasets however are not significant as can be seen in Table 19.

When comparing the data of the UST96 with and without the remeasurements generate a figure as shown in Figure 53. Like with the UFM120 excluding the remeasurements from the dataset increases the mean efficiency ratio, implying that the remeasurements have a lower efficiency ratio than the normal measurements. Table 20 shows however that the differences between the datasets are not significant.

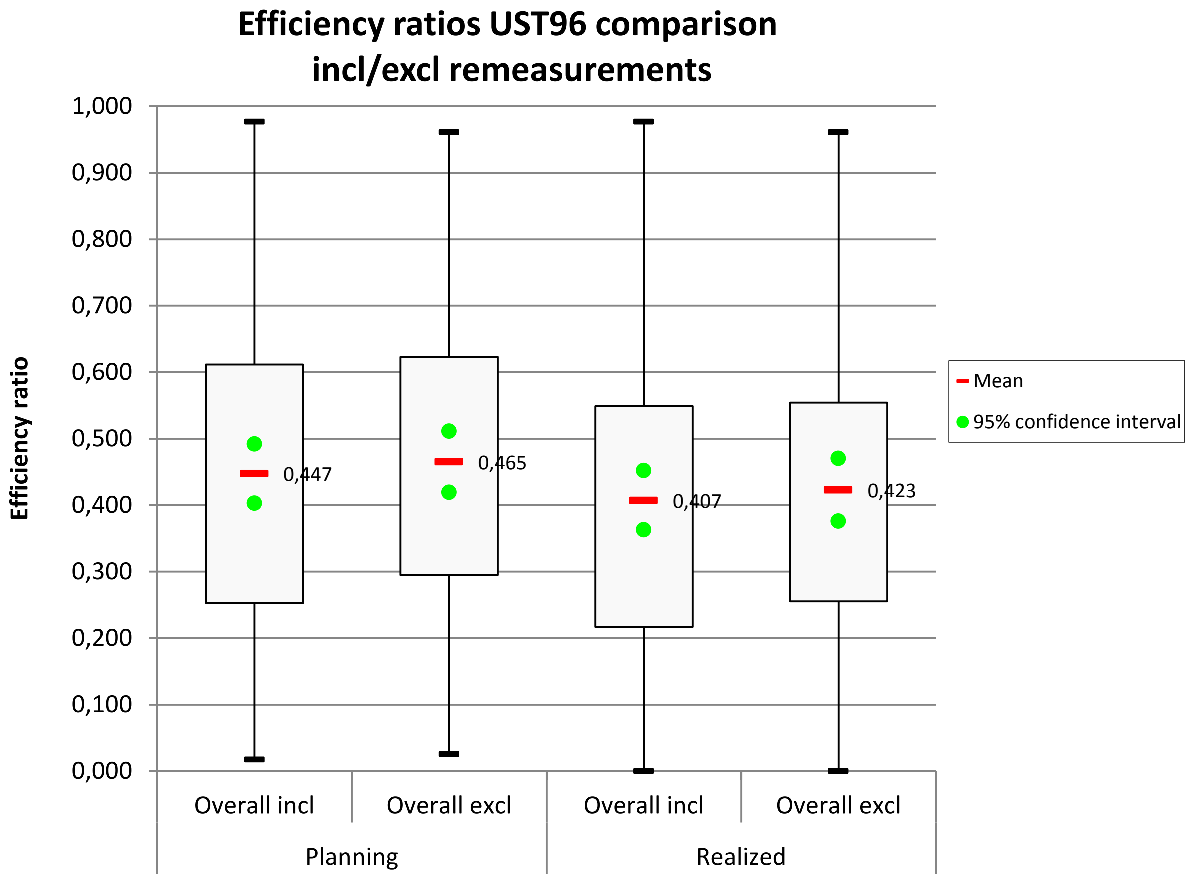


	Planning			Realized		
	Overall	2011	2012	Overall	2011	2012
# Arg	125	85	40	114	76	38
Min.	0.017	0.017	0.044	0.000	0.017	0.000
25th percentile	0.253	0.220	0.299	0.217	0.202	0.267
Median	0.457	0.457	0.455	0.421	0.410	0.429
75th percentile	0.611	0.656	0.542	0.549	0.570	0.526
Max.	0.977	0.977	0.775	0.977	0.977	0.765
Mean	0.447	0.463	0.415	0.407	0.420	0.383
95% CI low	0.403	0.404	0.353	0.363	0.360	0.319
95% CI high	0.492	0.522	0.477	0.452	0.479	0.447
St. dev	0.249	0.270	0.191	0.240	0.260	0.192

Figure 52: Boxplot UST96 incl. remeasurements

Table 19: (Two sided) p-values datasets UST96

	Planning Overall	Planning 2011	Planning 2012	Realized Overall	Realized 2011	Realized 2012
Planning Overall		0.68	0.39	0.21		
Realized Overall	0.21				0.74	0.53



	Planning		Realized	
	Overall incl	Overall excl	Overall incl	Overall excl
# Arg	125	109	114	98
Min.	0.017	0.025	0.000	0.000
25th percentile	0.253	0.295	0.217	0.255
Median	0.457	0.470	0.421	0.440
75th percentile	0.611	0.623	0.549	0.554
Max.	0.977	0.961	0.977	0.961
Mean	0.447	0.465	0.407	0.423
95% CI low	0.403	0.419	0.363	0.376
95% CI high	0.492	0.511	0.452	0.470
St. dev	0.249	0.242	0.240	0.233

Figure 53: Boxplot UST96 comparison incl/excl remeasurements

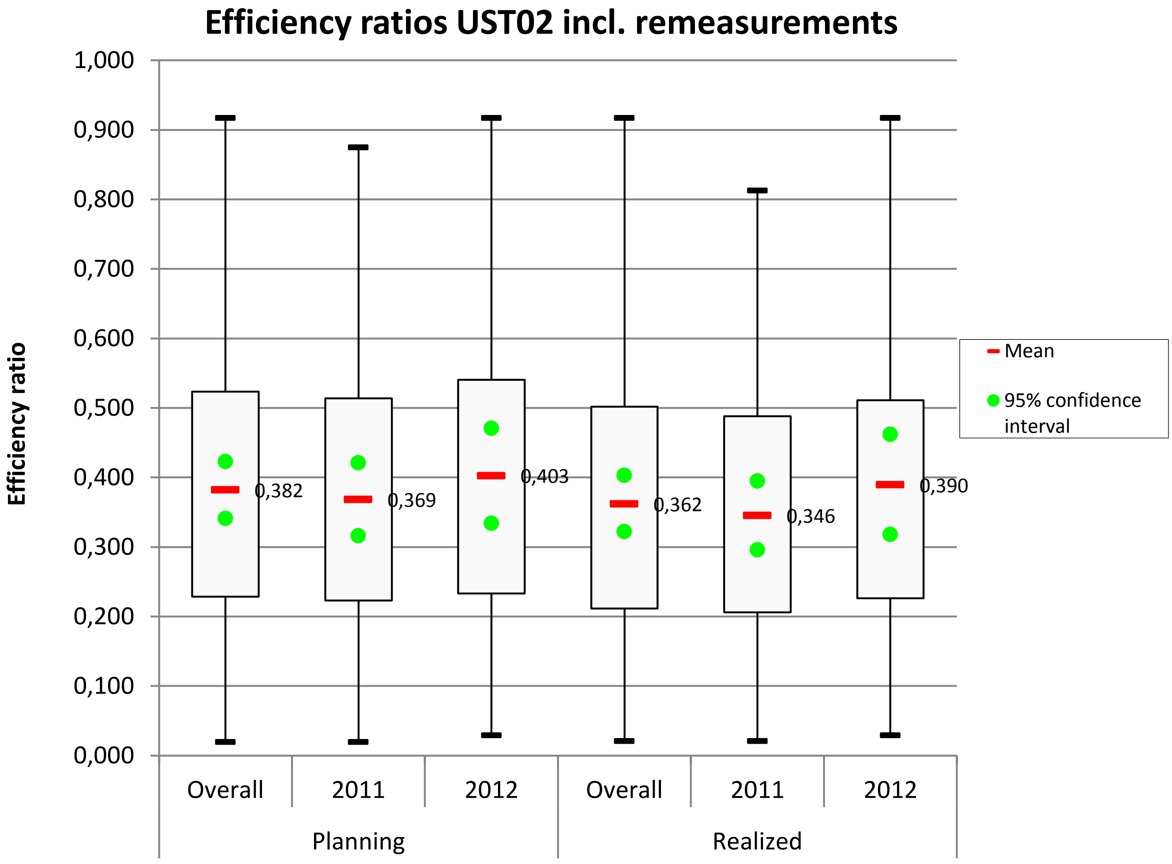
Table 20: (Two sided) p-values datasets incl/excl remeasurements UST96

	Planning Overall excl	Realized Overall excl
Planning Overall incl	0.58	
Realized Overall incl		0.63

UST02

In Figure 54 the boxplot demonstrates the efficiency performance data of the UST02. All datasets have a normal distribution. Like the UFM120 and the UST96 the planning efficiency ratios means are slightly higher than the means of the realized efficiencies. The differences between the datasets are not significant as shown in Table 21. The 95% confidence interval shows that there are many outliers in the data, the confidence interval is concentrated around the means. Remarkable is that the mean efficiency ratios are quite constant and the differences between planning and realization are small.

Shown in Figure 55 is the boxplot comparing the planning and realization with and without remeasurements. As can be observed there is hardly any difference between them, indicating that the remeasurements have almost the same efficiency as the normal measurement runs. Table 22 underpins this by showing that the differences are not significant.

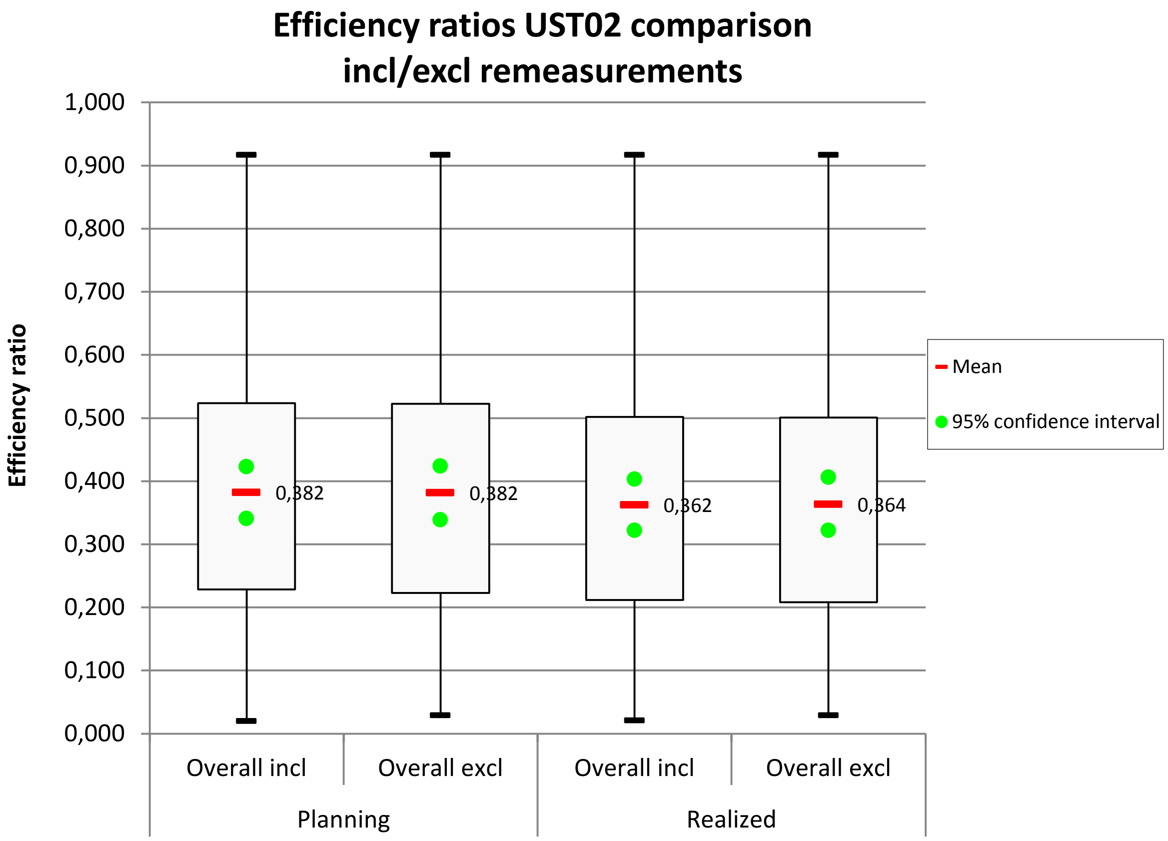


	Planning			Realized		
	Overall	2011	2012	Overall	2011	2012
# Arg	97	58	39	90	56	34
Min.	0.020	0.020	0.029	0.021	0.021	0.029
25th percentile	0.229	0.223	0.233	0.212	0.206	0.226
Median	0.383	0.366	0.403	0.355	0.318	0.417
75th percentile	0.523	0.514	0.541	0.502	0.488	0.511
Max.	0.917	0.875	0.917	0.917	0.813	0.917
Mean	0.382	0.369	0.403	0.362	0.346	0.390
95% CI low	0.341	0.316	0.334	0.322	0.296	0.318
95% CI high	0.423	0.421	0.471	0.403	0.395	0.462
St. dev	0.203	0.197	0.209	0.192	0.184	0.203

Figure 54: Boxplot UST02 incl. remeasurements

Table 21: (Two sided) p-values datasets UST02

	Planning Overall	Planning 2011	Planning 2012	Realized Overall	Realized 2011	Realized 2012
Planning Overall		0.68	0.61	0.49		
Realized Overall	0.49				0.61	0.51



	Planning		Realized	
	Overall incl	Overall excl	Overall incl	Overall excl
# Arg	97	86	90	80
Min.	0.020	0.029	0.021	0.029
25th percentile	0.229	0.223	0.212	0.208
Median	0.383	0.385	0.355	0.366
75th percentile	0.523	0.523	0.502	0.501
Max.	0.917	0.917	0.917	0.917
Mean	0.382	0.382	0.362	0.364
95% CI low	0.341	0.339	0.322	0.322
95% CI high	0.423	0.424	0.403	0.406
St. dev	0.203	0.197	0.192	0.187

Figure 55: Boxplot UST02 comparison incl/excl remeasurements

Table 22: (Two sided) p-values datasets incl/excl remeasurements UST02

	Planning Overall excl	Realized Overall excl
Planning Overall incl	0.98	
Realized Overall incl		0.96

A7. Details inspection train measurement disturbances

UFM120

Figure 56, Figure 57 and Table 23 present details about the disturbances occurred in the execution of measurements by the UFM120.

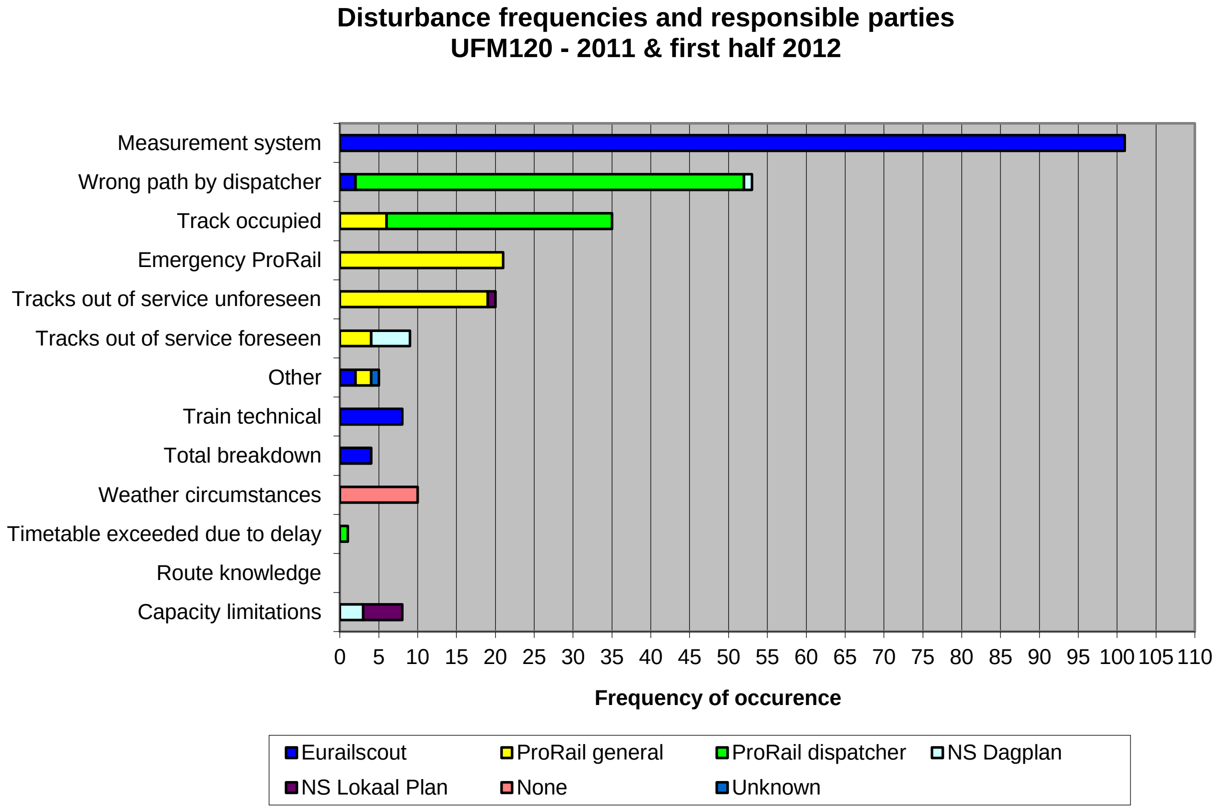


Figure 56: Disturbances occurred in realization measurements UFM120 (Occurrence is measured in train movements)

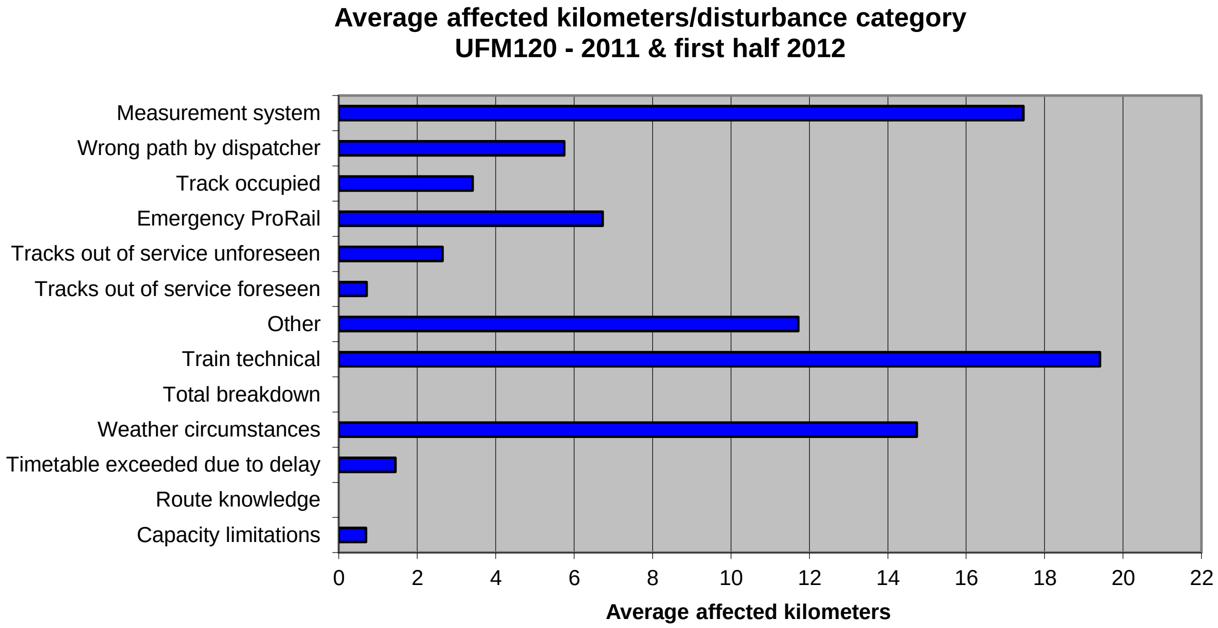


Figure 57: Average affected kilometers measurement disturbances UFM120

Table 23: Numerical overview measurement disturbances UFM120

Disturbance category	Number of occurrences	Occurrence frequency	Average affected kilometers	Total affected kilometers	Percentage of total affected kilometers
Measurement system	101	36.7%	17.5	1763.5	41.8%
Wrong path by dispatcher	53	19.3%	5.8	304.8	7.2%
Track occupied	35	12.7%	3.4	119.4	2.8%
Emergency ProRail	21	7.6%	6.7	141.3	3.3%
Tracks out of service unforeseen	20	7.3%	2.6	52.8	1.3%
Tracks out of service foreseen	9	3.3%	0.7	6.4	0.2%
Other	5	1.8%	11.7	58.6	1.4%
Train technical	8	2.9%	19.4	155.3	3.7%
Total breakdown	4	1.5%	366.4	1465.7	34.7%
Weather circumstances	10	3.6%	14.7	147.4	3.5%
Timetable exceeded due to delay	1	0.4%	1.4	1.4	0.0%
Route knowledge	0	0.0%	0.0	0.0	0.0%
Capacity limitations	8	2.9%	0.7	5.5	0.1%

Logically the total breakdown category has the highest impact on the planning and execution of the inspection runs. Days at which total breakdowns occur have to be completely planned again. For readability purposes (scales of the axes) this category is left out of the figure. From the remaining categories it can be seen that train technical and measurement systems failures have the highest impact. Although train technical disturbances do not occur often compared to other disturbances the impact is large. Other categories with high impacts regarding the average affected kilometers, are the breakdown of measurement systems and weather circumstances. Considering the total affected measurement kilometers the assigning of wrong paths by dispatchers, inspection track occupations and emergencies also have a high impact on the planning of the UFM120 due to the fact that they occur often.

UST96 and UST02

Figure 59 presents the average affected kilometers for both the UST96 and UST02. It shows that (regarding the overall values) train technical disturbances have the largest influence on the planning, followed by two days on which the train driver did not had the right route knowledge to drive a specific route, causing cancellation of this specific route. Although the occurrence frequency is low for this category (occurred only on two days in the time period under consideration causing cancellation of 14 train movements) the affected inspection kilometers are quite large. Another disturbance category that has a large influence is ‘defects on the measurement systems’.

When comparing Figure 58 and Figure 59 a striking difference between the UST96 and UST02 occurs: the UST96 had two days in which five train movements could not be performed in the original timetable due to delay, causing on average 7.5 affected inspection kilometers. Compared with the UST02: it had five days in which 17 train movements (with an average length of 4.8 kilometer) could not be performed in the original timetable.
What is causing this difference cannot be distilled from the data.

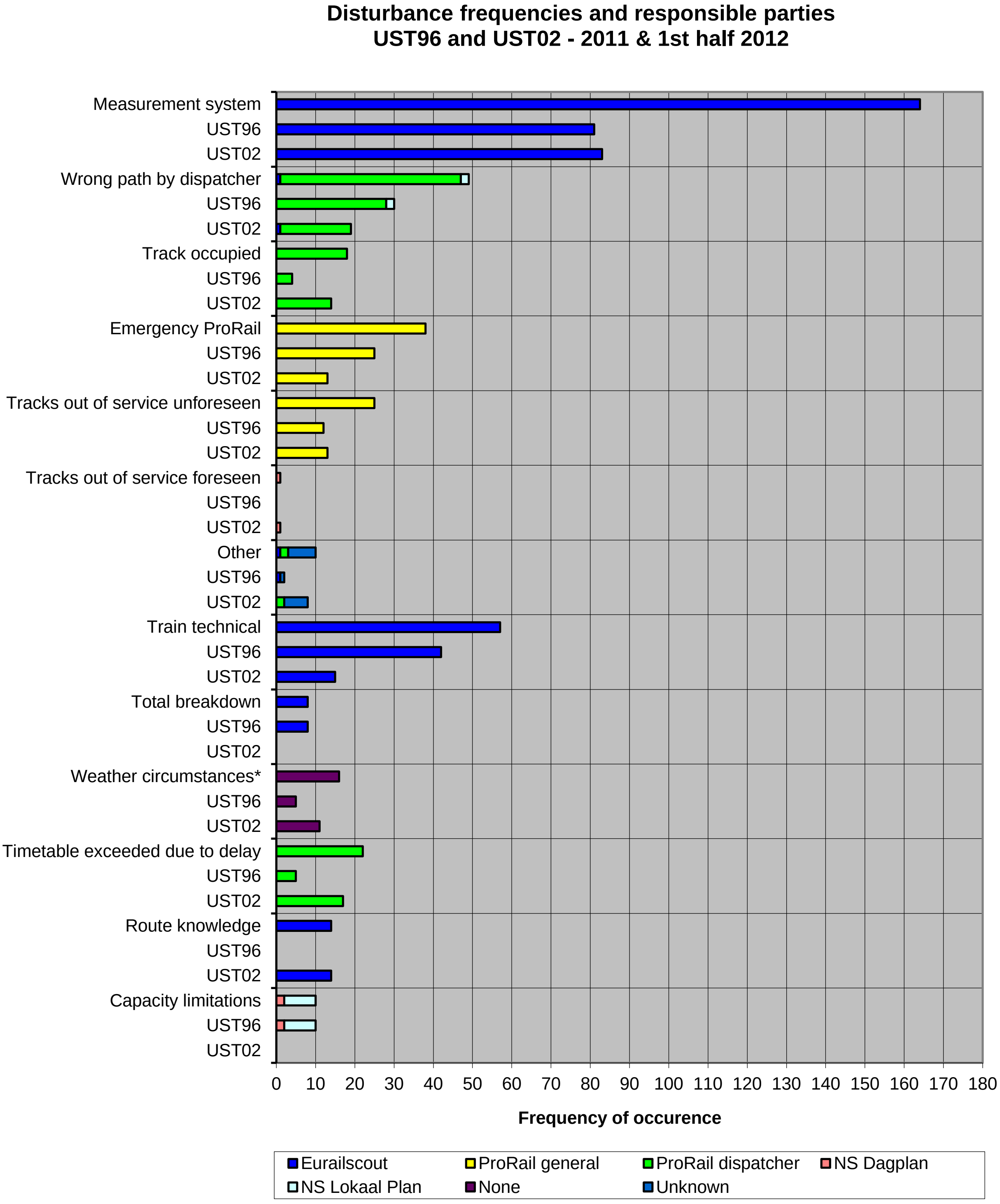


Figure 58: Disturbances occurred in realization measurements UST96 and UST02

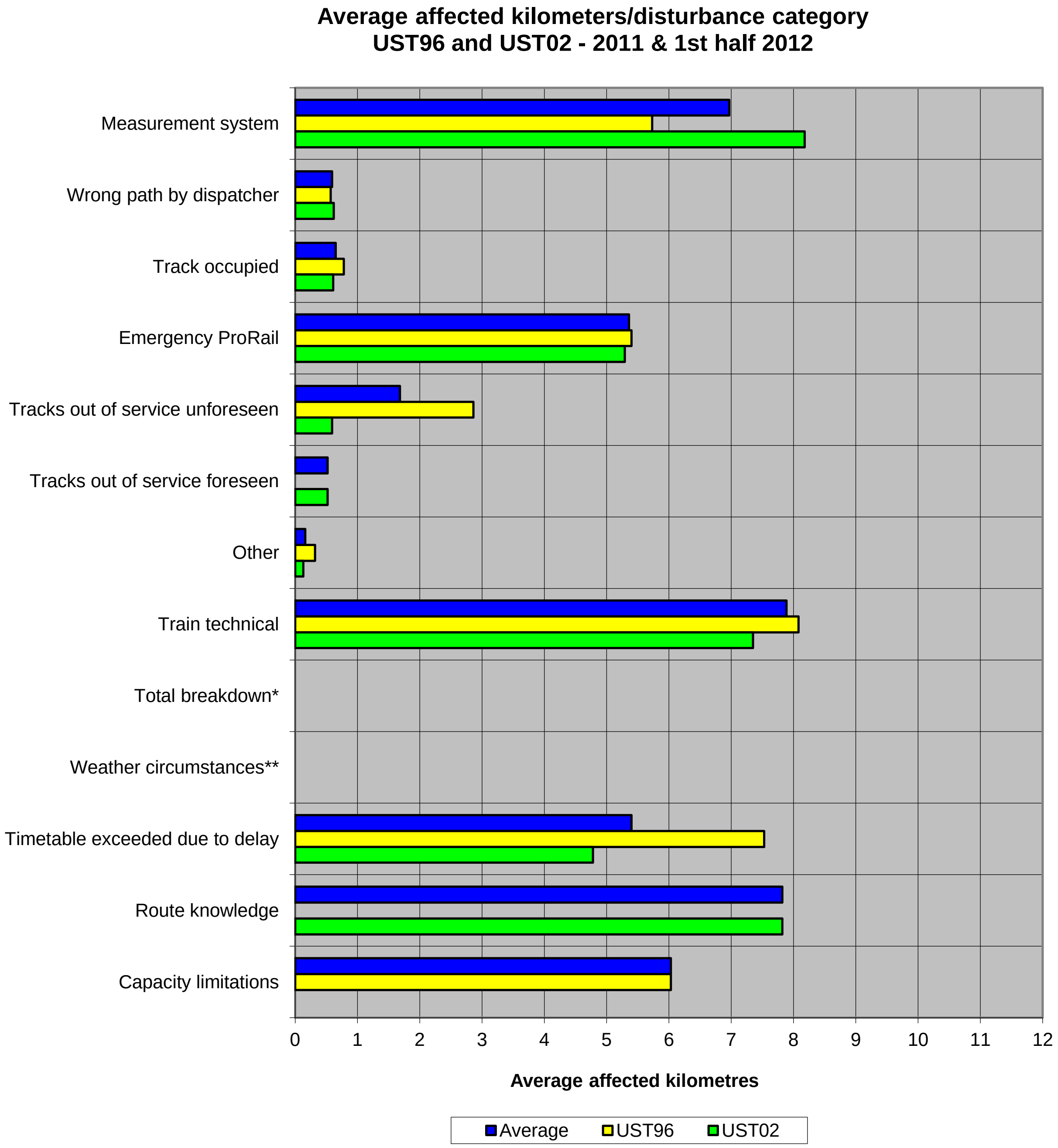


Figure 59: Average affected kilometers measurement disturbances UST96 and UST02
** For readability reasons (scale of axis) 'total breakdown' is excluded from the graph. The affected kilometers are the highest because a total day is cancelled instead of a section of a day*
*** In the first few weeks several days were cancelled due to winter weather circumstances. For the same reason as the total breakdown category this category is left out of the figure.*

Table 24 presents a numerical overview of the data presented in the analysis of the disturbances occurred by the UST96 and UST02.

Table 24: Numerical overview measurement disturbances UST96 and UST02

Disturbance category	Number of occurrences	Occurrence frequency	Average affected kilometers	Total affected kilometers	Percentage of total affected kilometers
Measurement system	164	38.0%	6.97	1143.1	23.2%
Wrong path by dispatcher	49	11.3%	0.59	28.9	0.6%
Track occupied	18	4.2%	0.65	11.7	0.2%
Emergency ProRail	38	8.8%	5.36	203.7	4.1%
Tracks out of service unforeseen	25	5.8%	1.68	42.0	0.9%
Tracks out of service foreseen	1	0.2%	0.52	0.5	0.0%
Other	10	2.3%	0.16	1.6	0.0%
Train technical	57	13.2%	7.89	449.7	9.1%
Total breakdown*	8	1.9%	126.3	1010.4	20.5%
Weather circumstances**	16	3.7%	109.07	1745.0	35.4%
Timetable exceeded due to delay	22	5.1%	5.40	118.8	2.4%
Route knowledge	14	3.2%	7.82	109.5	2.2%
Capacity limitations	10	2.3%	6.03	60.3	1.2%

** see caption Figure 59 for explanation*
*** see caption Figure 59 for explanation*

A8. Maps of line Utrecht - Alkmaar

In this appendix the nine maps of the MATLAB routing models are shown:

Map 1: Utrecht Central station

Map 2: Utrecht Central station – Amsterdam Central station

Map 3: Amsterdam Central station

Map 4: Amsterdam Central station – Zaandam

Map 5: Zaandam

Map 6: Zaandam – Uitgeest

Map 7: Uitgeest

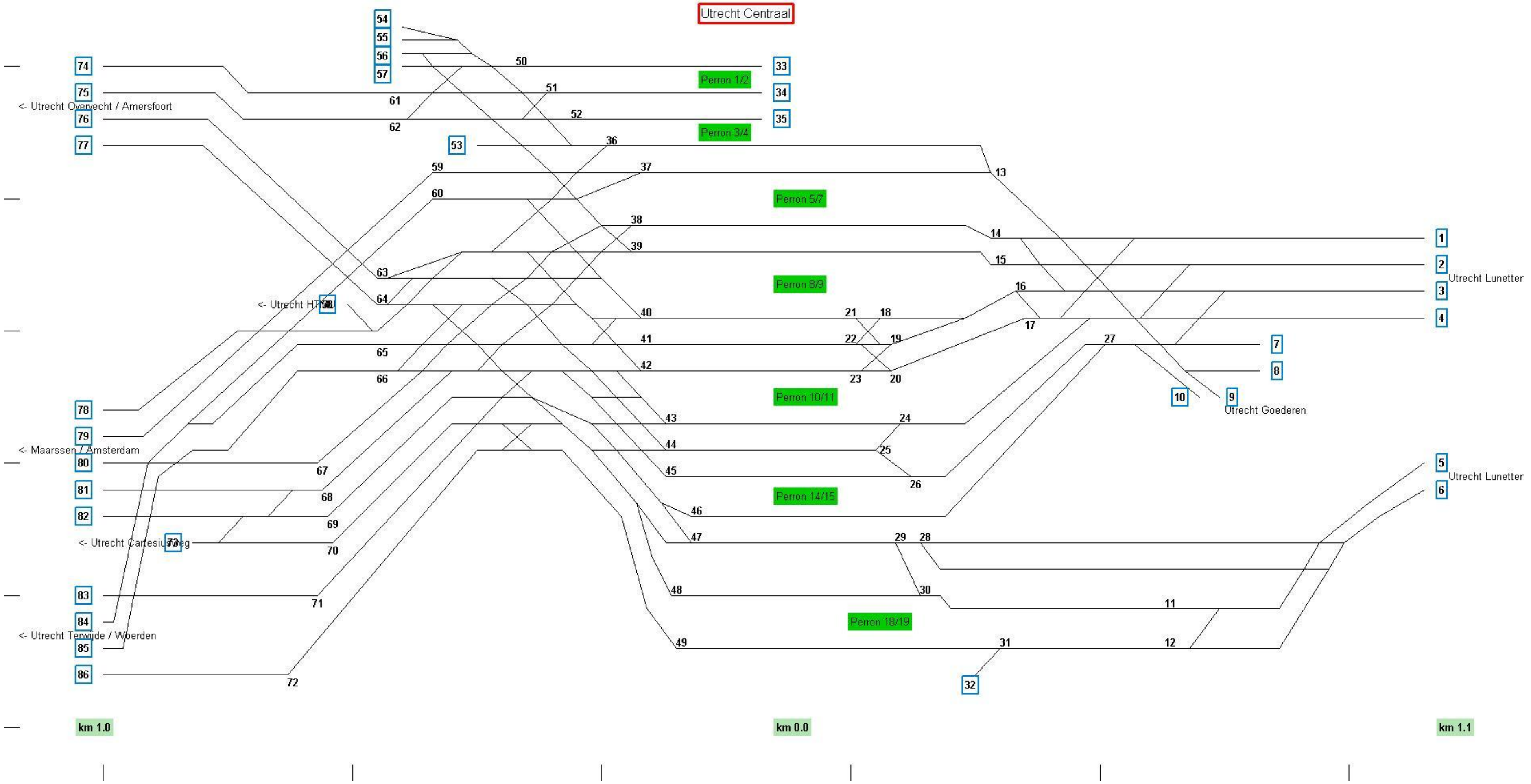
Map 8: Uitgeest – Alkmaar

Map 9: Alkmaar

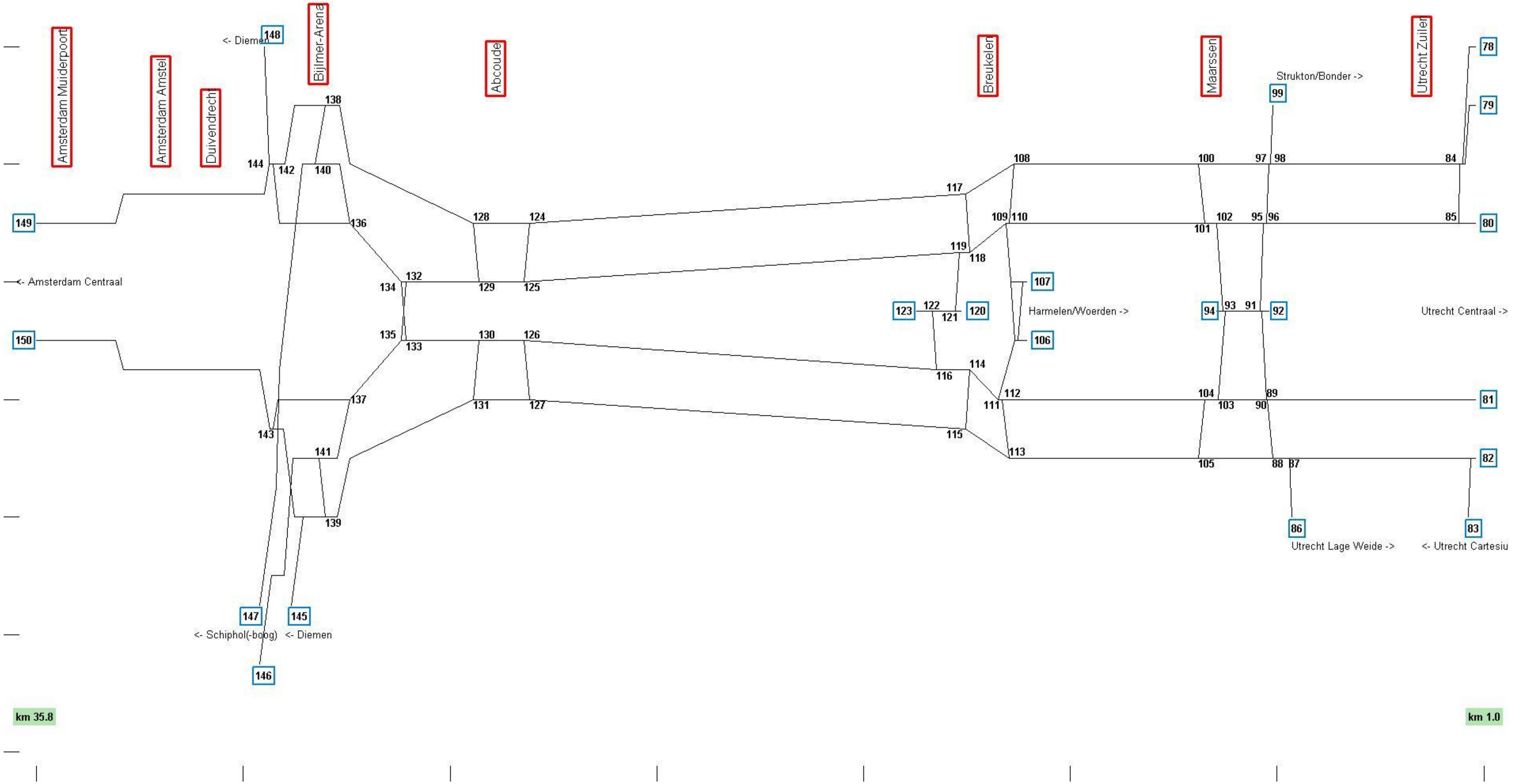
The numbers in the blue boxes represent signals at the borders of the map or buffer stops at the end of a track sections. At locations where one map transfers to the connected map, the border numbers in the blue boxes are shown on both maps. For example at the border between map 1 and map 2, the numbers 78 till 82 are displayed on both maps. The other bold numbers represent signal positions along the tracks.

Between map 2 and map 3 there is a direction change. A train running from the right to the left on map 2, enters map 3 on the left running to the right side. This direction change is included to keep the model maps the same as the ones used by Eurailscout and ProRail, to preserve the recognizability for the planners.

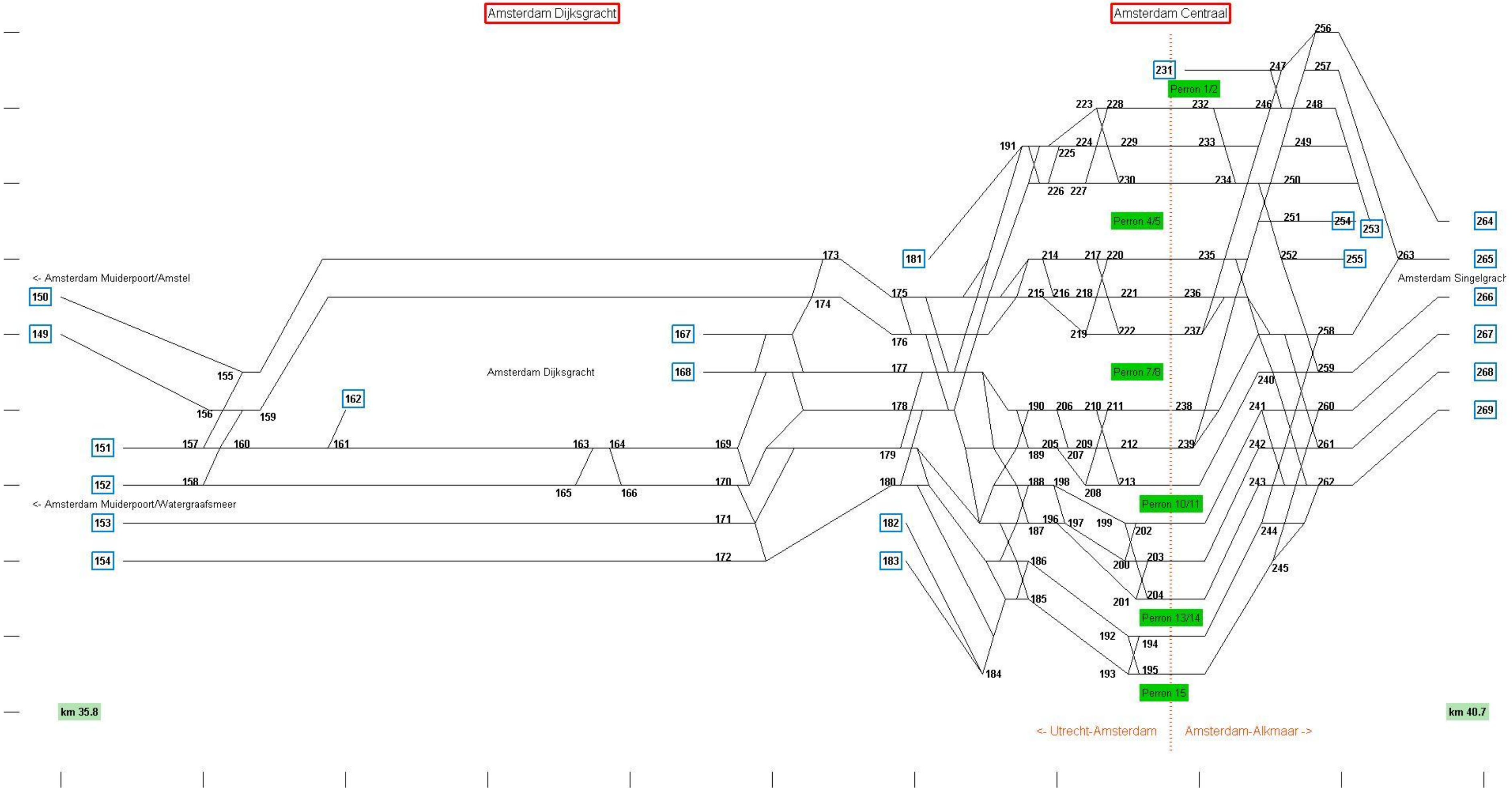
Map 1: Utrecht Central station



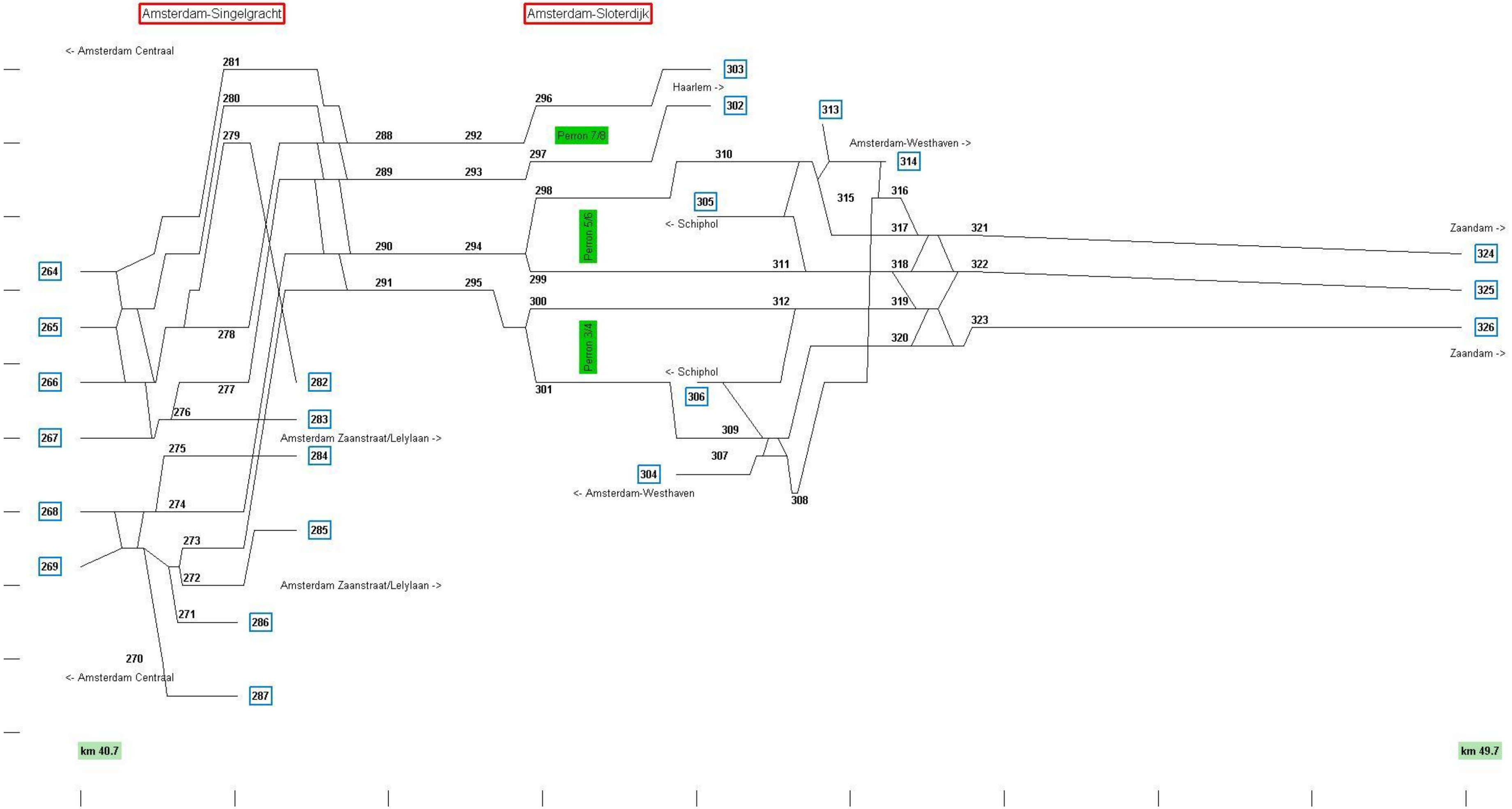
Map 2: Utrecht Central station – Amsterdam Central station



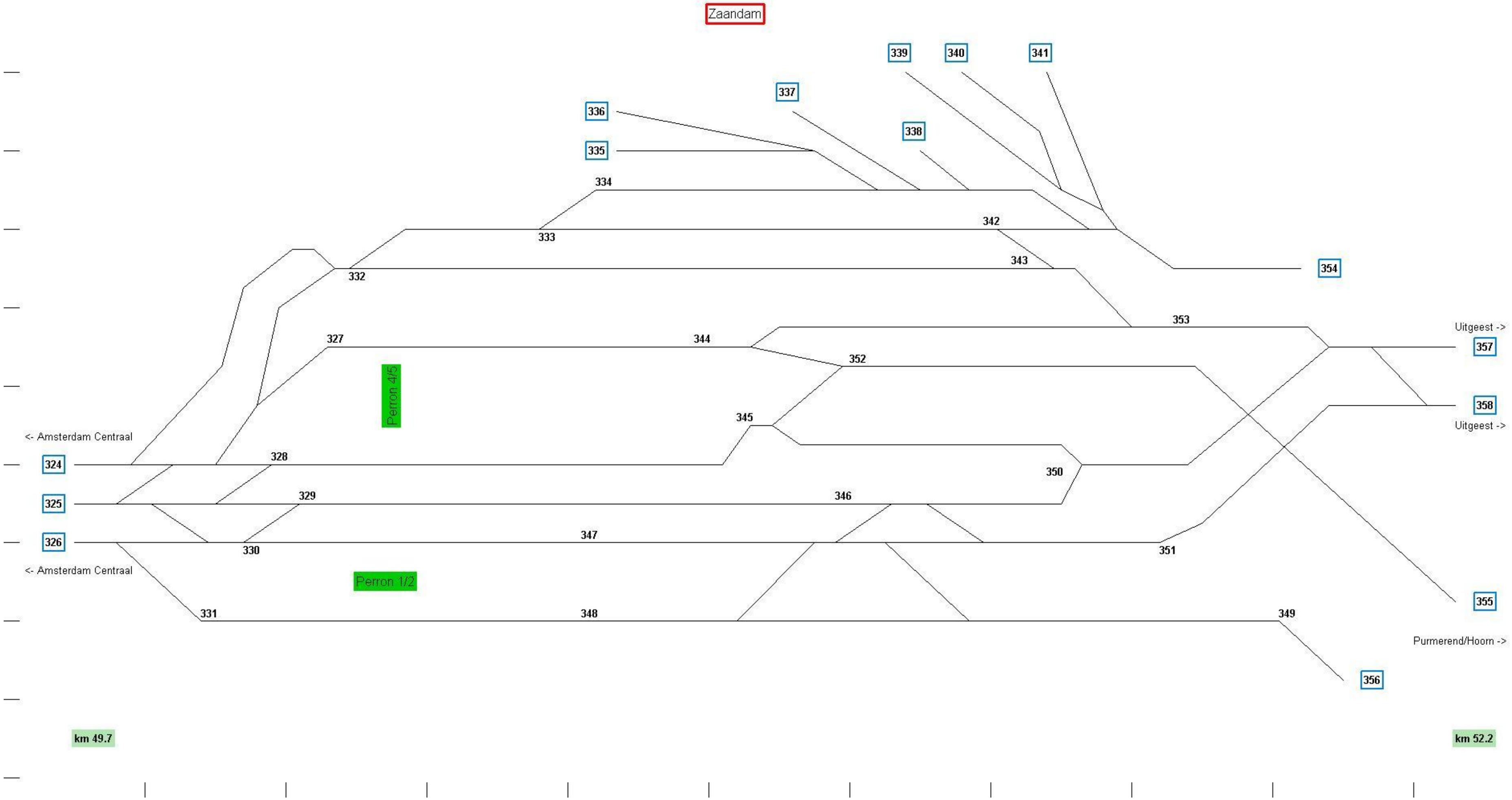
Map 3: Amsterdam Central station



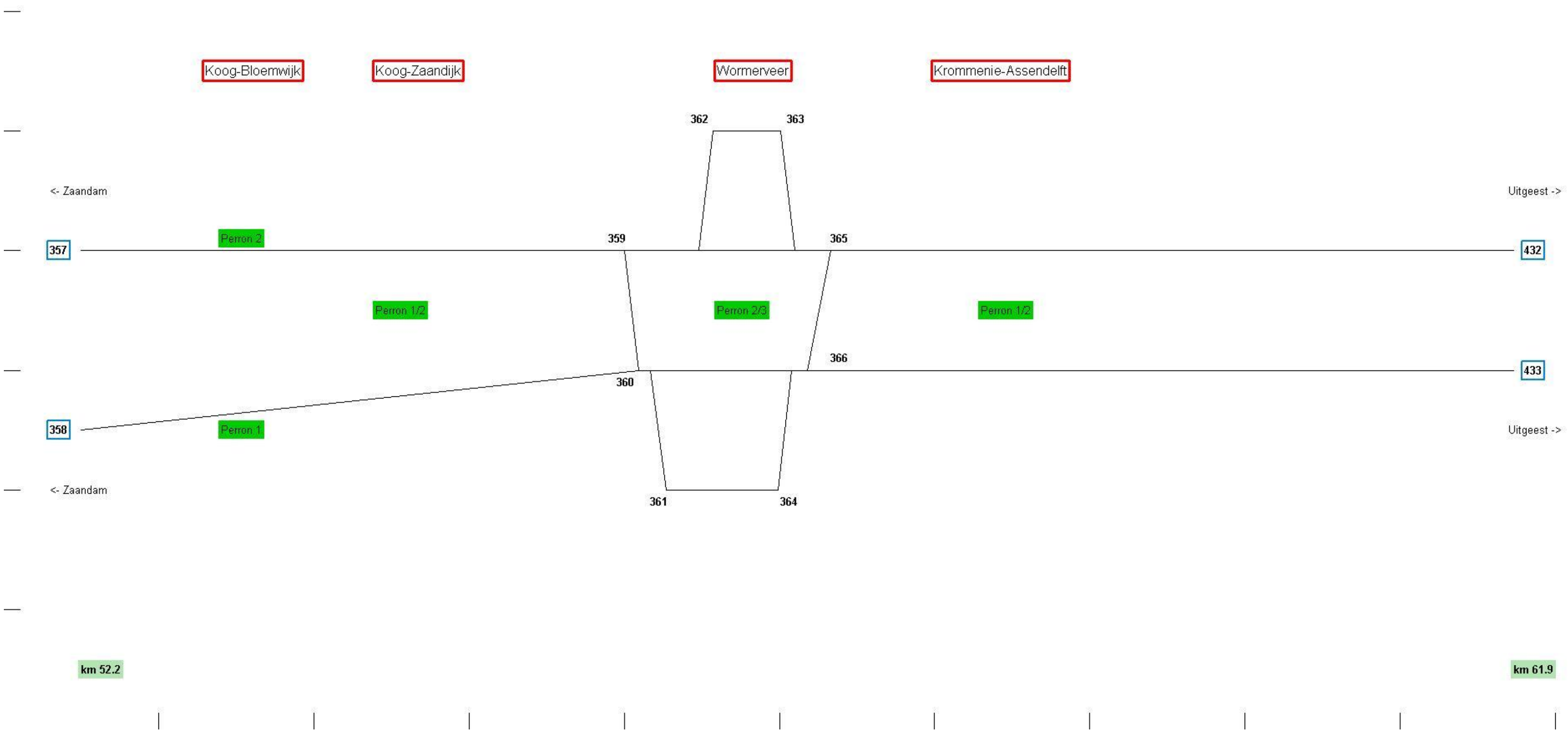
Map 4: Amsterdam Central station – Zaandam



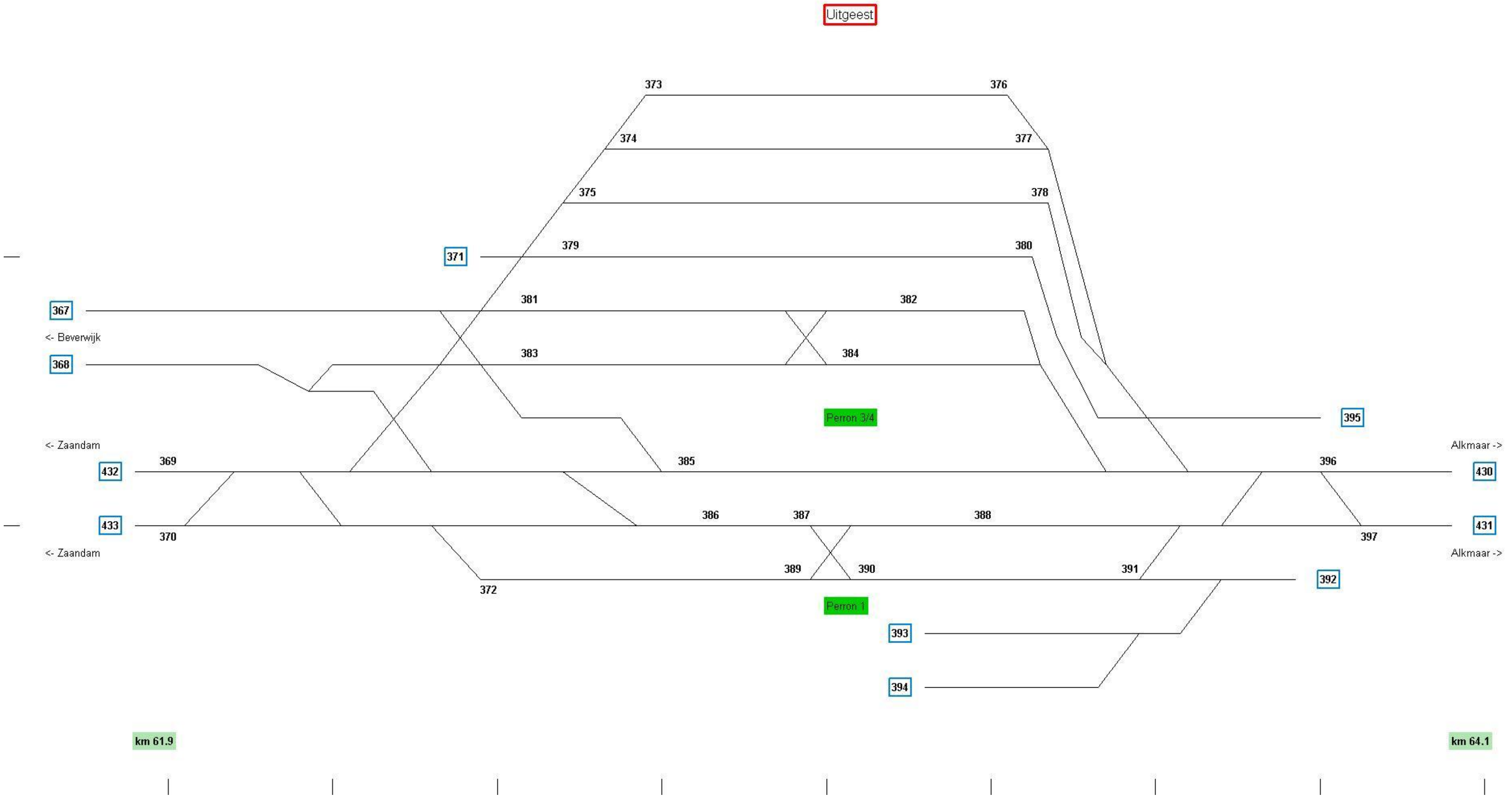
Map 5: Zaandam



Map 6: Zaandam – Uitgeest

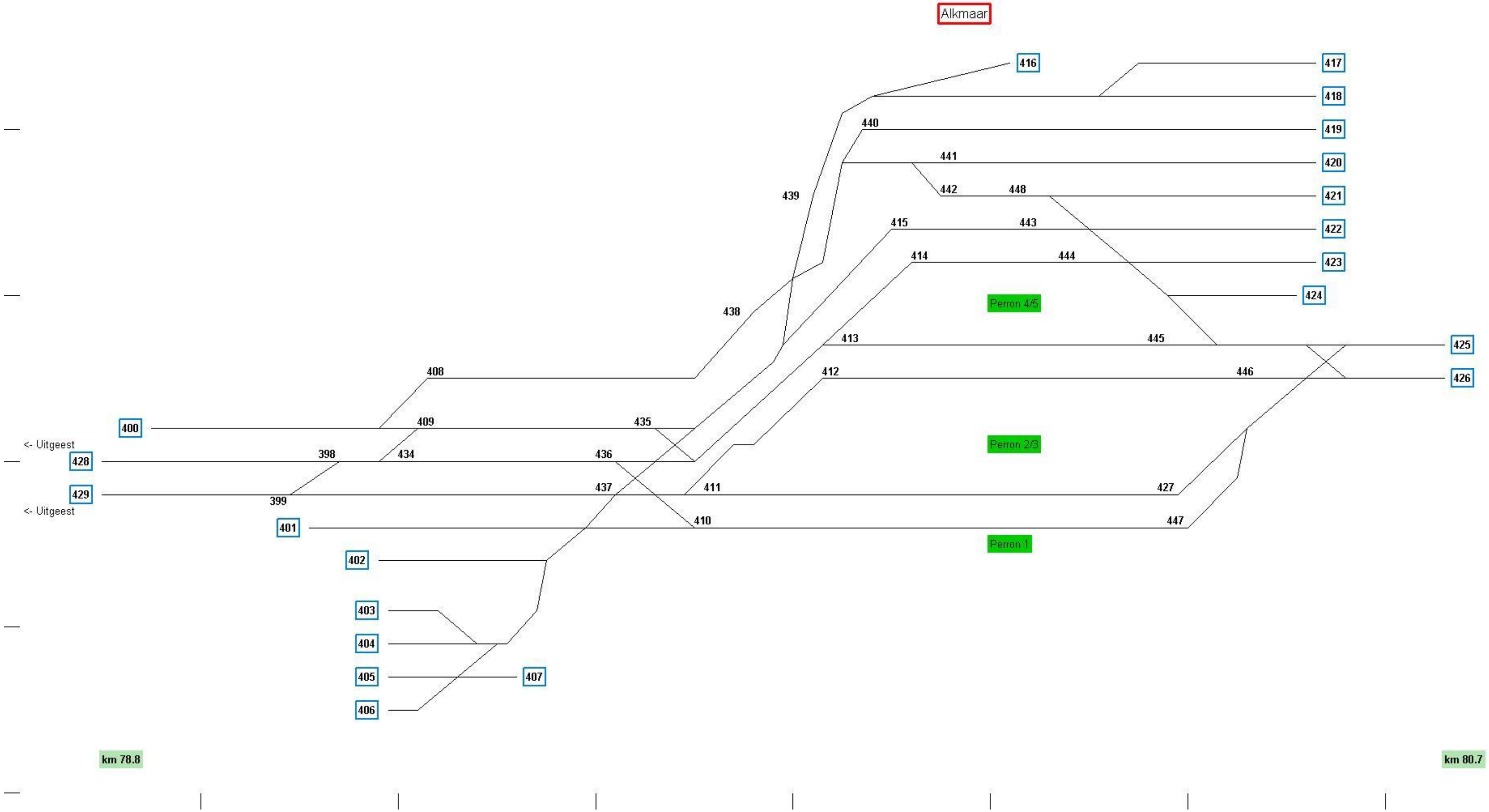


Map 7: Uitgeest



Map 8: Uitgeest – Alkmaar

Map 9: Alkmaar



A9. Example of path creation process

In this appendix the process of path creation is explained using the example situation shown in Figure 60 and Table 25. It is assumed that all links need to be inspected and the path needs to start at node 20 and end at node 22.

Assignment map creation and filtering

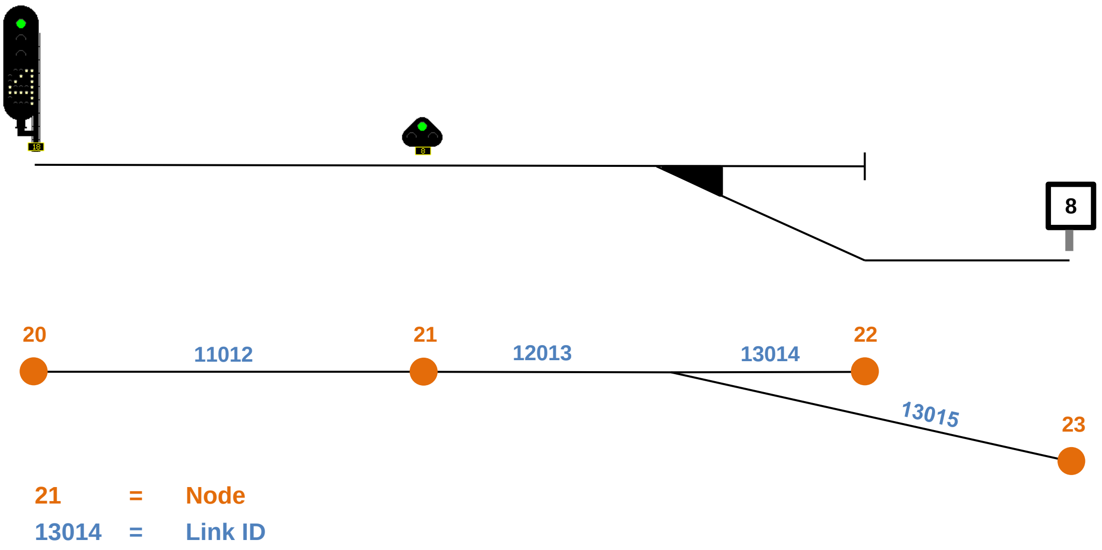


Figure 60: Example situation
(Same situation as shown in Figure 24)

Table 25: Assignment map belonging to example situation in Figure 60

			Links to be measured			
		Link-ID	11012	12013	13014	13015
		Link length	150	50	50	100
		Occures in … routes	1	2	1	1
Start node	**End node**	**Route length [m]**				
20	21	150	1	0	0	0
21	22	100	0	1	1	0
21	23	150	0	1	0	1

The rows in Table 25 show the routes between directly coupled nodes present in the example network. On top of the columns the link-id's of the links to be measured in the network are shown including their length. The assignment map is filled with '0's' and '1's': a '1' if a link is in a route, a '0' otherwise. Take for example the route from node 21 towards node 22. In Figure 60 it can be seen that links '12013' and '13014' are in this route. The assignment map in Table 25 shows the same: in the row of route 21-22 the columns of both links contain a '1' where the other columns contain a '0'.

This process is executed for all direct routes possible. When finished the column totals are placed in the column header, representing the number of routes a link occurs in.

Next step is to determine which routes need to be driven. To filter these routes the column totals are used. First the links that occur in one route only are filtered (the ‘1’s’ in the column total row). In Table 25 the first link that occurs in one route only is link 11012. It occurs in route 20-21. This route needs to be driven and is therefore added to the list of required routes to cover the links to be measured. At the same time it is checked whether there are more links that have to be measured in this route. All links present in the route are removed from the assignment map, see the adapted assignment map in Table 26.

Table 26: Step 1 in filtering assignment map

			Links to be measured		
		Link-ID	12013	13014	13015
		Link length	50	50	100
		Occures in … routes	2	1	1
Start node	End node	Route length [m]			
21	22	100	1	1	0
21	23	150	1	0	1

Routes to be driven:

- 20-21

Link 13014 occurs in one route only: route 21-22. When checking the route 21-22 for other links to be measured, it can be seen that also link 12013 is in the route. Link 12013 however occurs in two routes (21-22 and 21-23). Because link 13014 occurs solely in route 21-22, this route is added to the list of routes to be driven. Both columns of link 12013 and 13014 are removed from the assignment map because they are included in route 21-22. Link 12013 will also be driven in route 21-23, no matter whether it is removed from the assignment map. However in route 21-22 it is already inspected so it does not need inspection in route 21-23 anymore. The result of the filtering in this step is shown in Table 27.

Table 27: Step 2 in filtering assignment map

			Links to be measured
		Link-ID	13015
		Link length	100
		Occures in … routes	1
Start node	End node	Route length [m]	
21	23	150	1

Routes to be driven:

- 20-21
- 21-22

If all links occurring in one route are removed, the next minimal value is searched in the link occurrence row. In case this value occurs multiple times in this row, efficiency ratios of the routes in which this link is present are calculated (total length links to be measured in route over total route length). The one with the highest efficiency ratio is chosen. In case multiple routes have the highest efficiency ratio, the route with the longest measuring distance is chosen. If even then multiple options are left, the first best route is selected.

In the example situation only one link to be measured is left, occurring in one route. Final list of routes to be driven in the example situation now becomes:

Routes to be driven:

- 20-21
- 21-22
- 21-23

Making the nodes in the list of routes to be driven, even

Before the path creation process can start, all nodes in the path need to be even. With an even node is meant that an even number of routes must connect to the node (see Figure 61). All routes just can be driven once. In this research all routes are undirected and the provision holds. In case directed links are used the number of ingoing routes must be equal to the number of outgoing routes to call a node even. The odd node in Figure 61 causes a train, no matter in which direction a route is driven, to end in the odd node. When it arrives in the odd node for the first time (removing the route it arrived from) it has two options to leave the node. One of the two is chosen and removed from the node. The next time it arrives via the only remaining route it has no route to leave the node, leaving the train stuck at the node. Adding an extra route to this odd node making it even, solves the problem and offers the train an escape.

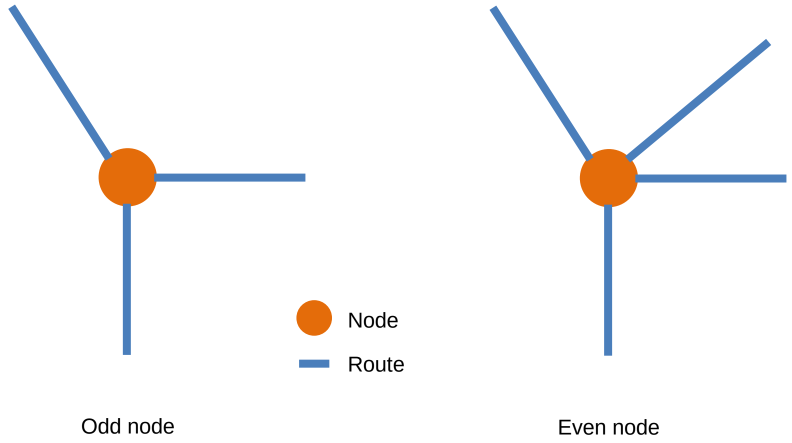
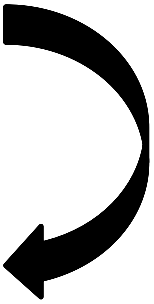


Figure 61: An odd and even node in an undirected network

In the example of Figure 60 the start (20) and end node (22) are predetermined. These two nodes must stay odd because they are (in the basis) covered once: at the beginning of the path and at the end of the path. The other nodes have to be made even, they must occur an even number of times in the list of routes to be driven:

Routes to be driven:	Odd nodes	Even nodes
• 20-21 • 21-22 • 21-23	20,21,22,23	



Routes to be driven:	Odd nodes	Even nodes
• 20-21 • 21-22 • 21-23 • *23-21*	20,22	21,23

One path must be added to make the nodes 21 and 23 even: path 23-21.

The algorithm developed to couple the odd nodes (except for the start and end node of the path) first checks which odd nodes can be directly coupled by a route. From the possible options the one with the shortest route length is added. The remaining odd nodes cannot be coupled directly. For these nodes the shortest path between every pair is determined (shortest paths calculated with the Dijkstra-algorithm [23]). Again the combination with the shortest overall length is selected. In the list of routes that need to be driven, all routes contained in the selected paths are added.

Path creation process

In the previous step the list with required routes is completed. With this list the path creation process can start. The method used for the path creation is derived from the Euler tour method as used by Edmonds and Johnson [5]. First step in this method is to create a path from the list of required routes, beginning at the start node and ending at the end node where not necessarily all routes have to be included yet. Selecting the next route is done by first checking whether routes in the same driving direction as on the current link, can be coupled. If not, the first occurring route in the list that can be coupled is selected. Selecting routes with the same driving direction, reduces the number of turnarounds decreasing the train running times required to drive the generated path.

In the subsequent step the previous found path is checked on nodes where a new sequence of routes can be inserted, until all routes in the list of required routes are used.

Applying the developed algorithm on the example situation of Figure 60 (also shown in Figure 62) is elaborated in the remainder of this paragraph.

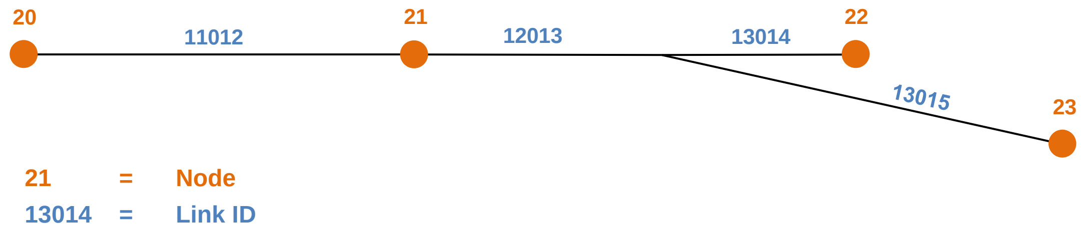


Figure 62: Example situation

From the situation as shown in Figure 62 it is determined in the previous steps, that the routes to be driven are:

20-21
21-22
21-23
23-21

Predetermined start node is 20 and end node is 22. The algorithm starts by looking for the start node in the list of routes to be driven. Outcome is that the path starts with route 20-21. This route is removed from the list:

List of routes to be driven		
21-22	*Path:*	20-21
21-23	*Driving direction:*	>
23-21		

End node of the first route now becomes the next ‘start’ node: 21. This node occurs in all three remaining routes. All three routes are possible regarding the driving direction, so the first route is chosen and removed from the list:

List of routes to be driven			
21-23	*Path:*	20-21	21-22
23-21	*Driving direction:*	>	>

Again the end node of the selected route is the ‘start’ node for the next route: 22. Because this node is the predetermined end node of the path, the first step in the path creation process is now finished. The list of required routes however, is not empty. Therefore more routes have to be added to the previous found path to inspect all tracks that need to be inspected.

In the second step of the path creation process, the already found path is searched for a point where (part of) the remaining routes can be inserted. Nodes in the remaining items in the list of required routes, are nodes 21 and 23. From both nodes only node 21 occurs in the already found path and is thus a suitable insertion point for the remaining routes:

List of routes to be driven			↓	
21-23	*Path:*	20-21		21-22
23-21	*Driving direction:*	>		>

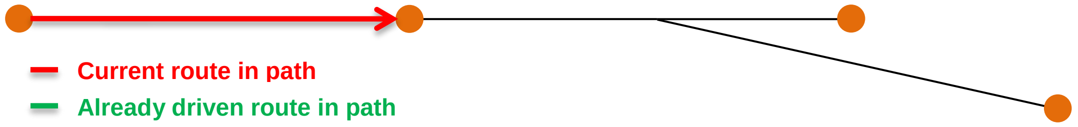
Out of the remaining routes only one sub-path can be created: 21-23 – 23-21. For the driving direction on the point where this sub-path can be inserted in the already found path, it makes no difference how this path is inserted.

List of routes to be driven					
	Path:	20-21	21-23	23-21	21-22
	Driving direction:	>	>	<	>

The path from start to end node is now determined and requires two direction changes. When drawn on the map, the generated path looks like the sequence shown in Figure 63 on page 117.

Situation:

First route in path (20-21)



Second route in path (21-23)

Third route in path (23-21)

Fourth route in path (21-22)

Final situation: all tracks to be measured are covered

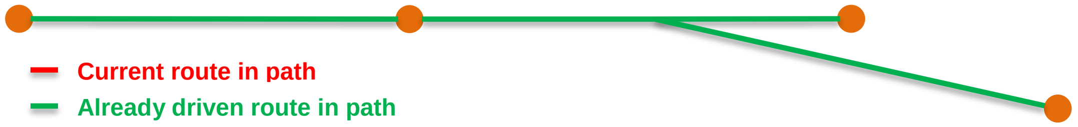


Figure 63: Determined path over example network