Optimal locations for rescheduling infrastructure in public transport networks:

Enhancing the robustness value against disruptions for Amsterdam tram network

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Thesis Information

Title

Optimal locations for rescheduling infrastructure in public transport networks: Enhancing the robustness value against disruptions for Amsterdam tram network

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Preface

This thesis report is the final product of my graduation project, on which I have been working since past 8 months. With this report, I finish the Master's in Science, Transport and Planning program in Civil Engineering at Delft University of technology, The Netherlands. With this research, I could combine my interest and passion in urban public transport systems, gaining scientific knowledge and developing skills. My research topic deals with robustness of public transport system which is done with cooperation with Smart Public Transport Lab of TU Delft.

I would like to thank my thesis committee members – Niels van Oort, Menno Yap and Niek Mouter for their critical feedback and for keeping me motivated throughout the project. Niels, for his valuable approaches to deal with various issues that I faced in the intermediate levels of the project. Menno, my daily supervisor who provided constant weekly feedback on my project, was always available for the guidance and helped me to get the data from various sources. Because of the weekly feedback, I was able to complete the research project on time. Niek, for always appraising the work and providing insights from other domains. Without your support this project would not have been possible. I would also like to thank Georgios Laskaris, who explained me the model developed by him and helped me at various stages of developing and using the model to achieve the objectives of the project.

Finally, I would like to convey thanks to my parents and my sister Capt. Aishwarya, for their love and who were always there with me during this study, kept me inspired to pursue the project and always there a call away. I would like to thank Vervoort family for making me feel like home away from home. I would also like to thank my friends Giusi, Florida, Dominik, Asli and Els for their support, time and availability to meet.

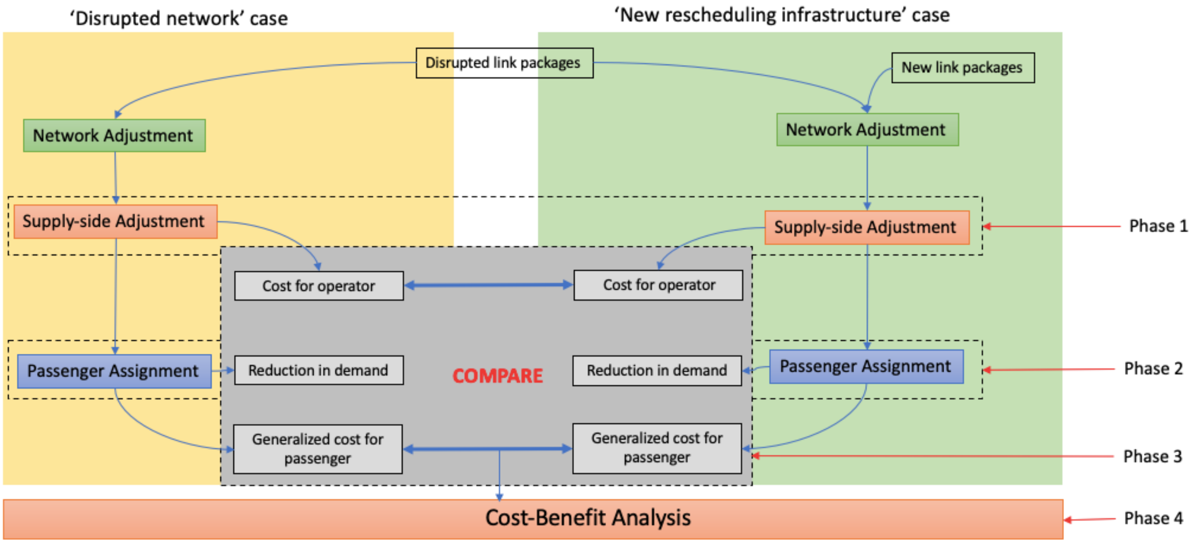
Summary

Urban public transport is often described as the lifeblood of cities (Vuchic, 2001). It is a system that transports passengers efficiently within an urban area. Disruptions in public transport systems are a common and an important issue affecting passengers, operators as well as the society. Public transport systems are vulnerable to disruptions. For example, in 2013, 3,120 unplanned disruptions and 6 planned disruptions occurred on the tram network of Den Haag and Rotterdam (Yap, 2014). The vulnerability of public transport systems to disruptions leads to heavy monetary losses. For example, the yearly monetary loss for passenger's perspective is more than €900,000 for the Rotterdam Den Haag metropolitan region (Cats et al., 2016). Thus, there is a need for making the public transport network robust against disruptions. Public transport robustness can be defined as the capacity to absorb a disruption with a minimal impact on system performance (Cats et al., 2017).

There have been several researches aiming for increasing the robustness of the public transport system against disruptions, which assess the network of public transport systems through their network performance indicators by removing the links from the network. Providing new infrastructures to the public transport network has potential to increase its robustness against disruptions (Ash et al., 2007; Cats et al., 2019; Chan et al., 2021) but no study has been executed systematically to assess the location of such new infrastructures in the public transport network where its robustness value is maximized. Due to this research gap, the following research question is formulated for the project:

What method can be developed to determine the optimal location of a new rescheduling infrastructure in a public transport network that maximizes its robustness value against disruptions?

To answer the research question, a methodology is developed where various new infrastructures at different locations are tested against disruptions and robustness of network is derived by assessing the benefits to various stakeholders. For this, two scenarios are modelled. In the first scenario, only the disruptions are modelled and in the second scenario, disruptions are modelled with the new rescheduling infrastructure. Benefits are derived by comparing the identified KPIs between both the scenarios. For the project, new infrastructure links considered are the links completing an incomplete junction connectors, plausible crossover locations and new links connecting nearby parallel lines.

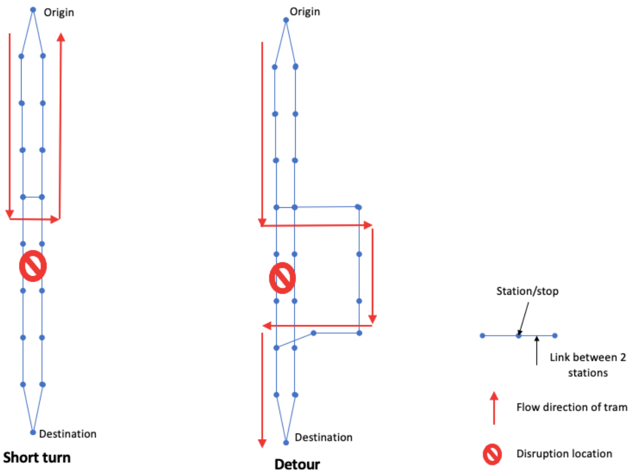


As shown in the above figure, the research project is divided into 4 phases in order to answer the research question. The disrupted link packages is a list of all possible disruptions on the PT network grouped in packages. The disrupted link packages are input to both the scenarios. The new rescheduling link package contains all the potential new rescheduling links. The new rescheduling link packages are input to the scenario 2 where disruptions are modelled with the new rescheduling infrastructure. Phase 1 of the research project develops a supply-side adjustment model which derives the plausible short turning and detouring alternatives for a given disruption and a given public transport network. In Phase 2 of the project, using a passenger assignment model, the most plausible supply side adjustment is drawn amongst the candidate supply side solutions (short-turn or detour). Both the scenarios are run through these models and the passenger and operator impacts are computed and compared, which is done in phase 3. Phase 4 of the project uses cost-benefit analysis to assess the worthiness of the investment for the new links in the network infrastructure.

The methodology developed in this project to answer the research question is a scientific contribution of the study. This study identifies, provide suggestions and insights for the locations of the potential new rescheduling infrastructure in a public transport network. This increases its robustness value against disruptions considering the benefits to the passengers, operator and society is a societal contribution of the study.

Phase 1: Deriving the plausible supply-side solutions during a disruption.

The objective of phase 1 of the project is to derive the plausible supply side solutions for a given disruption and for a given public transport network. For the same disruption, the two main types of supply side solutions for urban networks are taken into consideration: short turn and detour. In short turn adjustment, the service is provided until the possible extent of the disruption and returned to its origin. In detour, the transit service is detoured to other infrastructure to reach to its planned destination. The following figure illustrates the concept of short turn and detour.

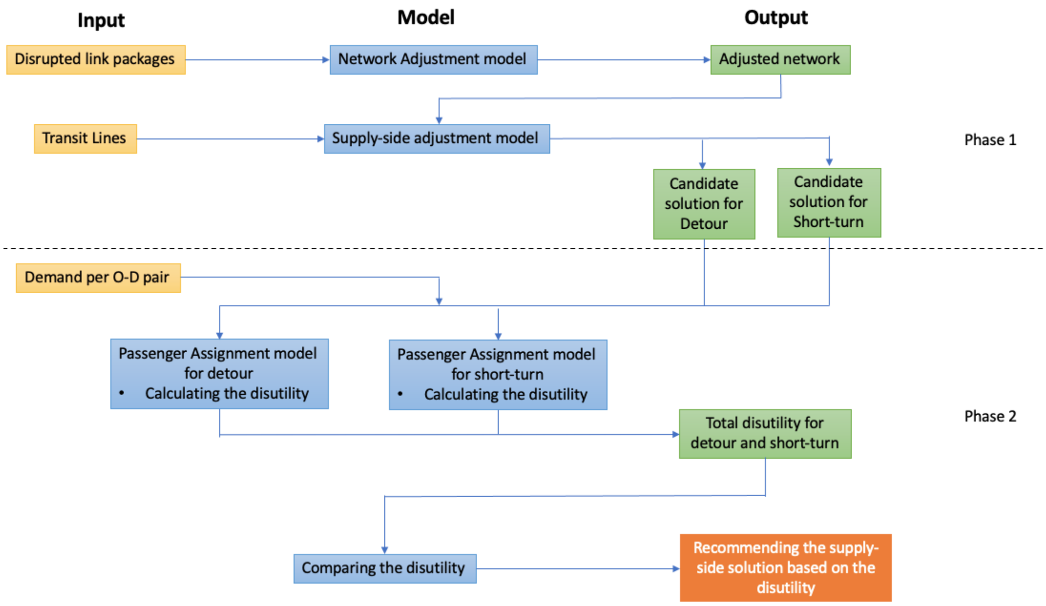


The following principles for the algorithm are considered to derive the plausible supply side solutions for a given disruption:

- The model follows an algorithm that derives the candidate solution for short turn and for detour. The modelled transit adjustments for both the types of candidate solution (short turn and detour) are done in such a way that it serves the maximum possible original route. For short turn solution, the transit line runs until the nearest point to the disrupted part where it can make a short turn back to its origin. For detour, the exit and entry point to make a detour is modelled in such a way that it is nearest to the disruption.
- Dijkstra algorithm is used for both short turn and detour solution to derive the shortest path from the exit node and entry node of a transit line.
- The bounds for extra travel time and extra travel distance for the candidate solution are constrained to not extend 40% of the original travel time and travel distance for both detour and short turn. These values are calibrated by running various combinations of extra travel time and travel distance bounds and assessing the results through it.
- If there exist no solution satisfying the threshold value bounds of extra travel time, extra travel distance and number of stops, the model returns no plausible solution for the disruption.

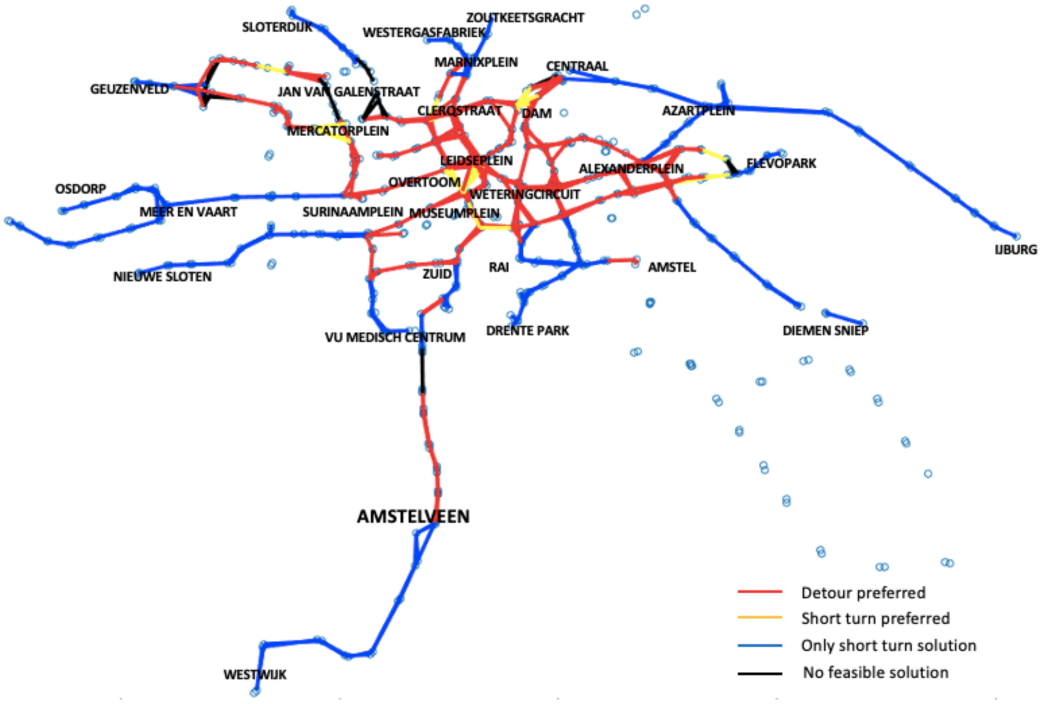
Phase 2: Deriving the most plausible supply-side solution amongst the candidate solutions during a disruption

The objective of phase two is to identify the most plausible supply side solution amongst the derived supply side solutions in phase 1 (short turn or detour). In this phase of the project, the derived short turn and detour solution for a disruption is assessed by assigning passengers to the changed transit service and by calculating the disutilities (which consists of in vehicle time, waiting time, walking time and number of transfers) to them from both the service. Comparing these disutilities, the transit solution with lower disutility is recommended amongst the two transit services. The following illustration provides the steps of phase one and two of the project.



The following principles are taken into consideration to derive the most plausible supply side solution:

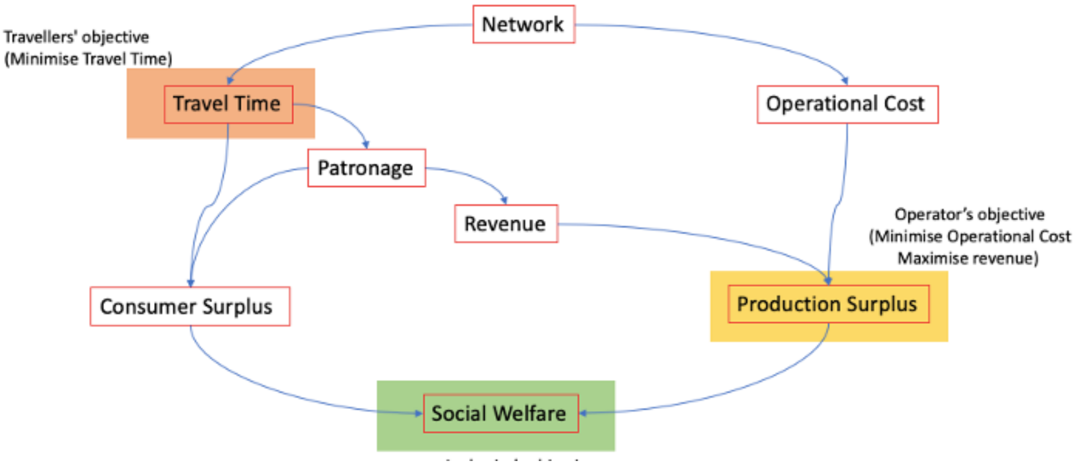
- The passenger assignment model has two main components: path generation and (dis)utility calculation. In path generation for every origin-destination pair (which is an input), the number of shortest paths is limited to three as the path generation process is computationally expensive. To derive the (dis)utility, the time components are multiplied with their respective coefficients and then summed up to derive the final (dis)utility.
- The recommendation for the transit adjustment amongst short turn and detour is based on minimizing the generalized disutility. Generalized disutility is the summed disutility for all the paths weighted by the passenger demand assigned to each path and for all the OD pairs for a disruption.
- Passengers are distributed to the routes based on the probability calculation using multinomial logit function.
- For the case study of Amsterdam tram network, the following illustration shows the most plausible supply side solution for disruptions at each locations in the network.



It is worth to note that detour, as the most plausible solution exist for the disruptions is in the central part of the network as illustrated in the figure above. It is because due to high line density, detour option is more plausible than short turn. Short turn as the most plausible solution is recommended for the disruptions lying in the branches of every line. Since there is no other tram infrastructure that exist for making a detour and due to the existence of short turn infrastructure (such as cross-over or turning loop) nearby it, short turn is preferred over detour. For few parts of network such as disruptions near Mercatorplein and Jan van Galenstraat in the northwest and disruptions near Flevopark in east, the model cannot find a feasible solution as neither detour nor short turn alternative being found satisfies the maximum travel time and travel distance constraints as specified.

Phase 3: Quantifying the passenger, operator, and societal impacts

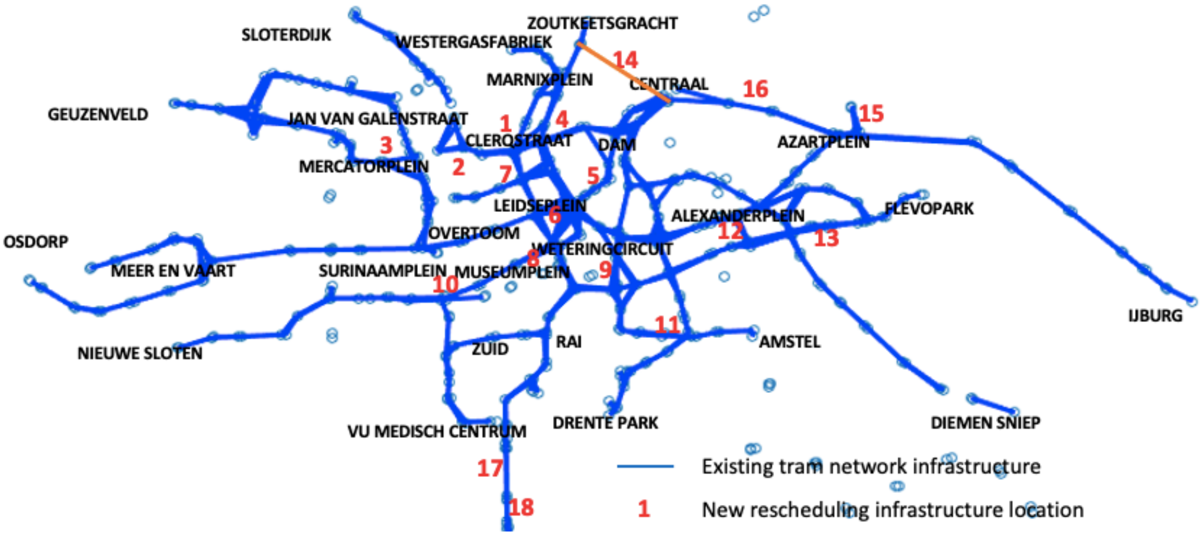
The objective of phase 3 of the project is to identify the various stakeholders getting affected by disruptions, and to quantify the key parameter indicators (KPIs) for the identified stakeholders. The following diagram as per given in van Nes (2015) is used to decide the various stakeholders' interest and the key performance indicators (KPIs) to assess the impact. The three main stakeholders identified for this project are the public transport operators, passengers and the wider society. For passengers, the travel time and travel distance are used as the KPIs. For public transport operators, the revenue generated from ticketing and the operational cost are the identified KPIs. For societal perspective, the demand loss is used as a proxy for social welfare, which identifies the passengers shifting away from public transport due to disruptions. For both the scenarios, the KPIs are calculated and compared.



The following points can be drawn from the phase 3 of the project.

- To compare the KPIs, all the KPIs are monetized. The travel time is monetized by using the value of time, travel distance is monetized by average travel cost per km (to convert it into fare) which is also revenue for operator's perspective. The operational cost is calculated by multiplying the average operational cost per hour with the operational hours and demand regain is multiplied with average fare per person to convert it into increase in revenue.
- For passengers, the generalized cost is calculated by summing costs for all the paths with their respective demands and across all the OD pairs. For operators, the operational costs are calculated by multiplying the transit line lengths with their frequency and average operational cost per km.
- 18 locations for the new rescheduling infrastructure are identified for the Amsterdam tram network but for the project, 12 new rescheduling infrastructure packages are tested. The table and the map below shows the location and name of the tested link packages.

Link package	**Location**
Link 1C	Bilderdijkstraat- De Clercqstraat
Link 3	J.Evertsenstraat - Hoofdweg
Link 4	Rozengracht -- Marnixstraat
Link 5C	Leidsestraat- Marnixstraat
Link 6	Nassaukade-Leidsestraat
Link 7C	Kinkerstraat – Bilderdijkstraat
Link 8C	P.Potterstraat -- v.Baerlestraat
Link 9F	Ceintuurbaan
Link 11	Churchill-laan – Rooseveltlaan
Link 13	Linnaeusstraat -- Insulindeweg
Link 14	Haarlemmer Houttuinen
Link 16	Ipta Lus



- For every package of proposed new rescheduling infrastructure, the benefits are calculated. It can be seen that for two-hour evening peak period for Amsterdam tram network, if the disruptions exist for the whole two hours, the total benefit of a new rescheduling infrastructure to the all the passengers is highest which ranges around 50€, followed by the benefit to the operator which is usually around 25€ followed by societal benefits which is around 5€. The following table shows the benefit share to different stakeholders for the tested new rescheduling infrastructure for 2-hours PM peak.

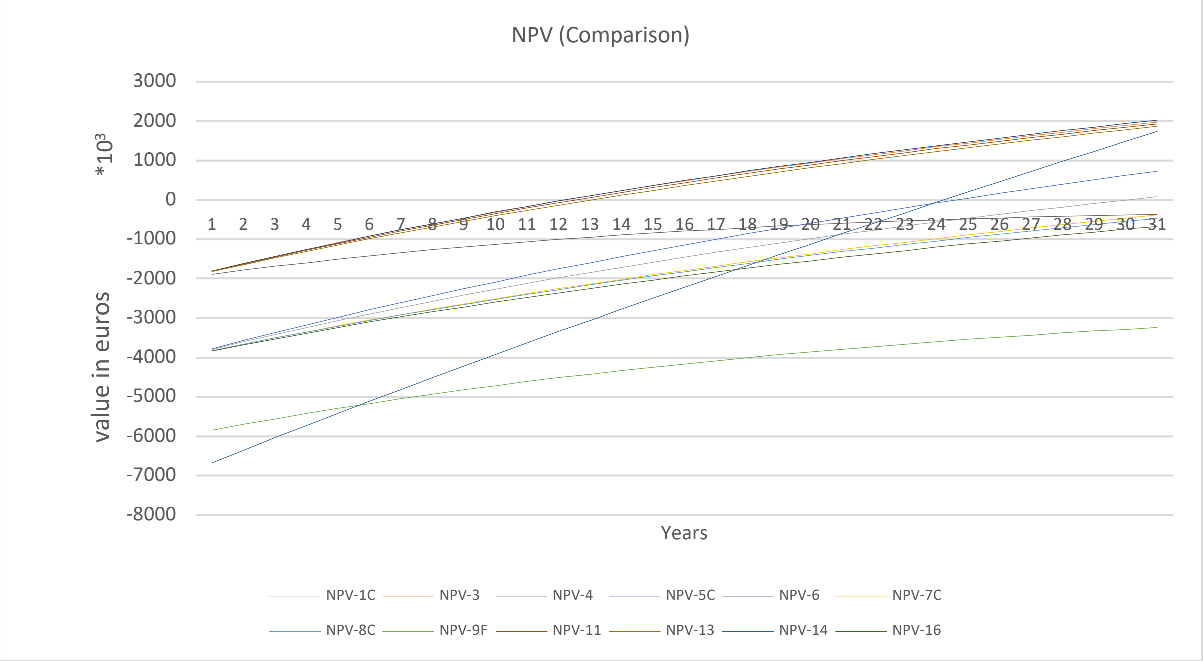
Entity	Symbol	1C	3	4	5C	6	7C	8C	9F	11	13	14	16
Monetized travel time benefit (in €)	$B_{passenger}^{TT}$	16.13	14.03	-11.96	30.25	17.12	18.72	15.0	-6.81	16.11	20.75	125.28	11.72
Monetized travel distance benefit (in €)	$B_{passenger}^{TD}$	34.00	33.81	25.37	33.94	34.02	34.10	34.02	33.50	34.00	34.01	33.99	34.16
Total benefit to passengers		50.13	47.84	13.41	64.19	51.14	52.82	49.02	25.19	50.11	54.76	159.28	45.88
Operational expenditure benefit (in €)	$B_{operator}$	64.01	57.90	49.69	61.17	55.92	52.21	54.05	65.94	55.15	49.69	50.82	53.52
Revenue loss to operator (in €)		-34.00	-33.81	-25.37	-33.94	-34.02	-34.01	-34.02	-33.5	-34.00	-34.01	-33.99	-34.16
Total benefit to operator		30.01	24.09	24.32	27.23	21.90	18.2	20.03	32.44	21.15	15.68	16.83	19.36
Revenue due to demand regain (in €)	$B_{operator}$	4.52	5.64	-4.31	5.73	5.62	5.64	5.64	5.61	5.64	5.68	6.32	5.63
Total benefit (in €)		80.15	71.94	37.74	91.41	73.04	70.93	69.06	59.12	71.26	70.44	176.11	65.244

Phase 4: Cost-benefit analysis to assess the worthiness of the investment for the new links in the network infrastructure

The objective of phase 4 is to assess the benefits of the new rescheduling infrastructure and to compare it with its cost over a time period of 30 years. A cost benefit analysis is executed to calculate the Net Present Value for current year and timeline until 2051. The following table shows the cost and total benefit for the current year of 2021.

New-Link Package		**1 C**	**3**	**4**	**5C**	**6**	**7C**	**8C**	**9F**	**11**	**13**	**14**	**16**
Cost (in *10^3 Euros)	**Purchase Cost**	4000	2000	2000	4000	2000	4000	4000	6000	2000	2000	7000	4000
	Maintenance cost	30.8	15.4	15.4	30.8	15.4	30.8	30.8	46.2	15.4	15.4	53.9	30.8
Total Cost		4030.8	2015.4	2015.4	4030.8	2015.4	4030.8	4030.8	6046.2	2015.4	2015.4	7053.9	4030.8
Benefits (Passenger) (in *10^3 Euros)	**Monetized travel time**	27.26	23.72	-20.21	51.12	28.936	31.631	25.36	-11.52	27.23	35.06	211.72	19.81
	Monetized travel distance	57.47	57.14	42.88	57.37	57.50	57.62	57.50	56.61	57.47	57.49	57.45	56.68
Benefits (Operator) (in *10^3 Euros)	**Operational expenditure**	194.73	176.14	151.18	186.06	170.12	158.84	164.44	200.60	167.77	151.17	154.61	162.82
Benefits (Society) (in *10^3 Euros)	**Revenue due to demand regain**	7.650	9.537	-7.290	9.684	9.509	9.529	9.528	9.493	9.537	9.609	10.69	9.517
Total Benefits		229.65	209.40	123.68	246.87	208.56	200.00	199.33	198.57	204.54	195.84	377.04	192.13

A discounted rate for both cost and benefit is considered to be 4%. The benefits are scaled to one year and then summed up for every year's discounted benefits. For cost, the purchase cost is taken for the first year and for the rest of the years, the discounted cost of maintenance is added. On a timeline, as soon as benefits outweighs cost, the investment in that new link is worthwhile from a societal perspective. The following diagram shows the Net Present Value of the new rescheduling infrastructure packages as identified in phase 3 of the project.



For the case study of the Amsterdam tram network, it can be concluded that investing for the new rescheduling infrastructure package 6 (junction of Nassaukade and Leidsestraat) and in package 3 (junction of J.Evertsenstraat and Hoofdweg) is more beneficial than the rest packages. The payback period for these packages is shorter and the Net Present Value at the end of year 2051 is higher than for the rest of the packages. It is also worth to note that the slope of link package 14 (Harleemeer Houttuinen) is steeper than the rest of the link packages, which indicates that on longer run, the NPV value for the new rescheduling infrastructure is quite high. Due to multiple sets of new rescheduling infrastructural links in 9F set (at Ceintuurbaan) and 8C set (at the junction of P.Pottersst.- v.Baerlest.), the cost of infrastructure is higher than the returns and the investment is not worthwhile on a timeline of 30 years. The table below shows the NPV and the payback period of the new rescheduling infrastructure set. For packages 3, 6, 11, 13, 14, 5C and 1C, the benefits outweigh the cost.

Link Package Set	NPV value at the end of year 2051 (in *10^3 Euros)	Payback Year	Rank
6	2,022	2033	1
3	1,971	2033	2
11	1,927	2033	3
13	1,868	2034	4
14	1,737	2045	5
5C	725	2045	6
1C	81	2050	7
4	-368	--	8
7C	-381	--	9
8C	-473	--	10
16	-676	--	11
9F	-3,238	--	12

Conclusions and Recommendations

This research project can be used for appraisal of new rescheduling infrastructure in public transport networks. It provides insights for the worthiness of an investment specifically related to its robustness value and compares various investments for new links and different locations. It allows policy makers to determine at which locations new infrastructure provide most robustness value. It also gives a tentative time period when benefit from an investment are expected to outweigh the costs. The intermediate result after phase 2 provides a tool for operators to decide the most plausible supply side adjustment based on the location of the disruption which is beneficial for both operator and the passengers. Secondly, the intermediate result also gives suggestion to transport operator to invest nearby these locations for tram infrastructure so as to provide an alternative during the disruptions in these locations. It would reduce the extra travel time and extra travel distance. With respect to the case study of the Amsterdam tram network, it is worth investing in the new rescheduling infrastructure at the junction of Nassaukade and Leidsestraat, junction of J.Evertsenstraat and Hoofdweg and Harleemeer Houttuinen.

From the cost-benefit analysis for different new infrastructural links in phase 4, it can be seen that the investments are more worthy in those new link packages having only one set of new links than those sets having multiple sets. For example, the new rescheduling infrastructure package set 3 and 6 contains only one set of link which gives higher NPV at the end of 2051 as compared to other packages having multiple sets of links.

For the project, it is recommended that the methodology could be more automated by developing a model which identifies the possible new link locations in the network infrastructure rather than manually searching. Moreover, for the project, demand regain is used as a proxy for determining benefits for the society. Advanced key performance indices such as isochrone analysis for accessibility could be used for capturing the societal impact.

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Chapter 1: Introduction

This chapter introduces the research project. In Section 1.1. it gives a brief overview to the problem related to the disruptions in public transport systems. It elaborates the terminologies relevant to it and assesses the problem because of the disruptions. Section 1.2. gives the details of the research design and discusses the research question and sub-questions that the research answers. Section 1.3. draws the research framework and section 1.4. provides the research output and the relevance of the study. Section 1.5 of this chapter identifies the scope of the research and section 1.6 gives the thesis outline.

1.1. Problem Definition

Public transport systems are exposed to disruptions due to various incidents such as equipment failures, infrastructural problem, passenger accidents, emergencies (Babany, 2015). Disruptions in public transport systems could be defined as the deviation from the normal operations of the services (Yap M. , Measuring, Predicting and Controlling Disruption Impacts for Urban Public Transport, 2020). If these disruptions are not properly handled it would have consequent impacts on passengers, public transport operators and infrastructure managers (Durand, 2017; Yap, 2020).

Impacts of disruptions

Due to the disruptions, passengers tend to have additional travel time (additional waiting time, transfer time, in-vehicle time and walking time). Disruptions also affects the accessibility to the public transport which has subsequent effects on change of modes of travel (Shelat and Cats, 2017; van Nes, 2015). Operators are responsible to handle the disruption which causes them extra cost of operation such as rescheduling costs and reimbursement costs. Furthermore, due to the less patronage during the disruption period, operators have revenue losses as well (Yap, 2020; Yap et al., 2018). For example: Transport for London refund the travel expenses to the passengers if the delay due to disruption exceeds 15 minutes as discussed in TfL (2019). The same is the case with public transport agency in Washington DC where they reimburse the travel expenses to those whose journey is delayed by 10 minutes during the rush hours (WMATA, 2019). The disruption at a single location of the public transport network not only impacts the transportation of local areas surrounding it, but also has a substantial impact of the public transport network on a global level due to spill-over effects of disruptions (Ash et al., 2007; Shelat et al., 2017; Cats et al., 2017). An example to quantify the losses into monetary terms, the yearly passenger disruption cost is **more than €900,000** for the disruption of only one link in the metropolitan region of Rotterdam and The Hague (Cats et al., 2016). The above examples show the intensity of the problem and the need to resolve it.

To tackle these disruptions, various measures can be taken, such as increasing/reducing the frequency of services, short turning of original route, detouring vehicles to go around the disruptions, diverting vehicles to other lines or cancelling the service (Durand, 2017; Durand et al., 2018; Babany, 2015; van Oort, 2011) which are elaborated in Chapter 2. To systematically study the various common disruptions, it can be classified into different types as discussed in the section below.

Categorizing disruptions

The disruptions can be categorized based on the frequency of its occurrence. These are recurrent and non-recurrent disruptions. Recurrent disruptions are those disruptions to the public transport system which occurs more frequently. Usually, the more frequent events to the public transport system such as delays of vehicle due to crowding and vehicle breakdown causes such disruptions. On the contrary, the non-recurrent disruptions to the public transport system occurs due to the non-frequent events such as accidents, closure due to construction works as discussed in Yap (2020) and Cats et al (2016). The second category of disruptions is based on the duration of disruption. It can be long term disruptions such as construction works which usually last for hours or days, and short-term disruptions such as vehicle breakdowns which usually last for few minutes. The combination of frequency and the duration of disruption events together is also known as disruption exposure (Cats et al., 2016). The third categorization of disruption is based on whether the disruption is planned or unplanned. Usually, the planned disruptions are anticipated much before the start of disruption with an alternative solution to disruptions to the public transport system. For example, the disturbances due to the construction, renovation, and maintenance work can be categorized as the planned disruptions. Unplanned disturbances to public transport system are unknown prior to the incident. Random events such as accidents, vehicle breakdown, crew unavailability leads to unplanned disruptions (Yap, 2020). Table 1 shows the types of disruptions based on the disruption property.

Table 1 Types of disruptions

Disruption Property	**Types of disruptions**	
Frequency	Recurrent	Non-recurrent
Duration	Long term	Short term
Planning	Planned	Unplanned

The public transport system is vulnerable to get impacted by these various types of disruptions. As discussed in the impacts of disruptions, it is important for the system to reduce the negative effects due to the disruption. A robust public transport system is the one which gets less affected due to any disruption. Definitions of robustness, vulnerability and resilience of the system are elaborated in the next section.

Robustness, vulnerability and resilience of public transport system

Due to the monetary losses because of the disruptions to the public transport systems as discussed in the previous section, it is important to reduce the impact of these disruptions. A robust public transport system is less vulnerable to disruptions. Public transport robustness can be defined as the capacity to absorb a disruption with a minimal impact on system performance (Cats et al., 2017). This also goes in line with public transport vulnerability, which is defined by Yap (2020) as “the degree to which a public transport is exposed to the disruptions and its impacts”. It could be stated that robustness is the inverse of vulnerability.

A more robust system is less vulnerable to disruptions and the impacts. When a disruption occurs, the system performances drop to a certain level and with time, it recovers to its original performance. The combination of both robustness and recovery of the system together is resilience of the system. In other words, resilience of the system could be defined as the system robustness against the disruptions and the recovery of the disrupted public transport system back to its normal operations and performances (Cats et al., 2016; Santos et al., 2020). The relation between vulnerability, resilience and robustness is shown in Figure 1. This figure depicting the relation between robustness, vulnerability and resilience is also called as bathtub model (Cats et al., 2016).

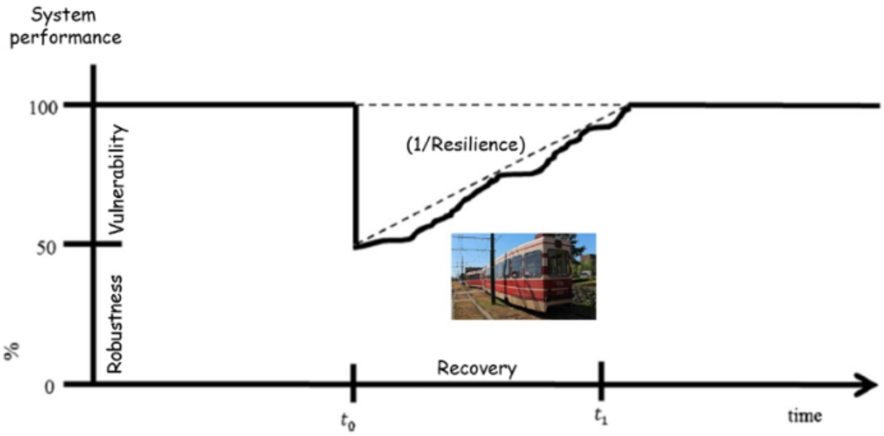

Figure 1 System performance during disruption (Cats et al., 2016)

A public transport system is resilient to certain disruptions when it is able to recover to its normal performance quickly. A resilience cycle consists of 4 phases which are “prepare”, “withstand”, “recover” and “adapt”, as shown in Figure 2. A resilient system is a one which is prepared to the disruption, can withstand it and in the post disruption phase, it can recover to its original performance and adapt to the new changes (Liu et al., 2019).

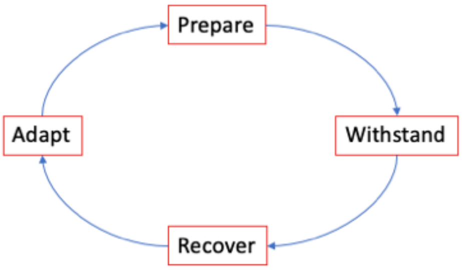

Figure 2 Resilience cycle

As discussed earlier, the disruption impacts are at both local scale due to the disruption itself and at global scale due to the spillback effect of disruption (Ash et al., 2007; Shelat et al., 2017; Cats et al., 2017). The critical locations in public transport networks which leads to disruptions must be assessed to reduce the impact of disruptions. There exist some mitigation measures that can tackle these disruptions and reduce their impacts (Jenelius et al., 2015; Cats et al., 2019). To make the public transport system more robust and to reduce the losses due to the disruptions, most of the research has been done by assessing the system performance indicators either by complete link breakdown as discussed in Ferber et al. (2012) and Oded et al. (2018) or partial reduction of capacity of the link and assessing the network indicators and analyzing the global change in network performance as discussed in Cats et al (2017) and in Sullivan et al. (2010).

The first group of research work focus the robustness of network which is assessed through the system performance indicators by complete link breakdown methods as discussed in Ferber et al. (2012) and Cats et al. (2018). In these researches, the assessment of the network is done by either removing the station (as nodes) or link between two stations from the network one by one and highlighting the changes in the network indicators such as betweenness centrality, alpha index, gamma index. Wang et al. (2015) study metro system of Athens as a topological entity and measures their robustness metrices through network science and graph theoretical concepts and investigate the performance of the system under random failures and targeted attacks. A study by Von Ferber et al. (2012) assesses the transport network of Paris and London and identifies how the accumulation of dysfunction leads to the complete network breakdown. Another study by Cats et al. (2019) exhibits the robustness properties of a metropolitan rail network during the events of random and targeted attacks and studies the network performances in terms of connectivity and additional impedance on the network which remained connected.

In the second group of research works rather than a complete breakdown of link or a node in a network, the study focuses on the robustness of network in a reduced capacity of a link(s). In the research done by Cats et al. (2017), the link criticality and degradation rapidity of network is measured by constructing network degradation curves and establishing a relation between local capacity reduction and global change in network performances. An overview of classification of the studies is shown in Table 2.

		Type of Disruption	
		Total link breakdown	**Link capacity reduction**
Type of evaluation	**Topological evaluation**	Ferber et al. (2012) Wang et al. (2015) Von Ferber et al. (2012)	Cats et al.(2017)
	Simulation	Cats et al. (2018)	Cats et al. (2019) Sullivan et al. (2010)

Table 2 Existing study on disruptions

Unsurprisingly, as discussed in Jenelius, et al.(2015) and Ash, et al. (2007), providing an additional link to the network infrastructure has the potential to reduce the loss of the robustness value. It is worth to mention that the additional link in the report refers to crossovers, turning loops as well as the PT line connecting two adjacent stops (two different nodes connected with each other) in the certain spatial radius. The types of rescheduling infrastructures are discussed in van Oort et al. (2010) aiming for the improvement of urban rail terminal design or for providing the rescheduling infrastructure facilities in the mid-way such as short turning. One can easily find out the position of an additional link that increases the robustness of a network by full scan method and assessing the values of robustness (such as total travel time etc.) but the method is limited to small scale networks. In a small-scale network, the manual process of providing link connecting two nodes and to test the robustness of the network seems to be feasible due to the limited set of nodes to be connected. If we apply the same process for a bigger scale network such as Amsterdam tram, Paris metro, London tube, the options to test through the manual process would be very big and the quantity of set of nodes would explode.

Consider a network represented as directed graph with set of nodes as every stops N= {n_1,n_2…n_n} and set of arcs as links connecting these stops E={e_1,e_2,…e_n} links. A turning loop or a cross over can potentially be added at (or nearby) any node $n \in N$ in the PT network of consideration, providing |N| possible locations. Now to simulate a disruption, the possible number of disrupted links (one disruption at a time) would be |E|. To test each potential rescheduling infrastructure for every disruption for which it can theoretically provide robustness benefits, the total number of simulations would be at least |N|*|E|. For example, consider a case of Amsterdam tram network with 543 nodes and 932 links. For a complete enumeration to determine the optimal location where new rescheduling infrastructure would provide most robustness benefits, the number of simulation runs would be 543*932 = **506,076** runs. Moreover, if we expand the assessment of infrastructure not only limited to crossovers or turning loops but additional links connecting two different stations, the total number of simulation runs required test would explode.

Amsterdam case study

Amsterdam, the capital of The Netherlands has an urban public transport system which includes trams, buses, and metros. It has various canals traversing withing the city and hence it has several bridges crossing the canals. In the coming decade, Amsterdam needs to perform several large renovations to its bridges and quays, which would lead to long lasting planned disruptions possible for several months to the public transport system of Amsterdam. These disruptions would impact the passengers and operators with great losses. These losses are well anticipated and can partially be mitigated before the disruption starts by providing alternative solutions for such disrupted part(s). To identify the location of the rescheduling infrastructures needed to mitigate the negative impacts as much as possible, the study is well relevant. Moreover, the PT closures would impact different stakeholders. In Amsterdam's case, the various stakeholders are the passengers, the municipality of Amsterdam, the tram operator GVB and the regional transport authority Vervoerregio Amsterdam (VRA). The study is not only applicable for the renovation of the bridges and quays but also for other disruptions which includes complete link breakdown. For example, this study is relevant for the recent disruption of tram line in Amsterdam as per given in GVB (2020) where the infrastructure is disrupted from Dam to Leidseplein and the closure of Bullebakbrug bridge on Marnixstraat (which lasted from January 2021-May 2021). The study is also useful for some unplanned disruptions such as the ongoing disruption of May 17th at Amstelveenseweg due to the third-party accident.

To reduce the disruption impact for passengers, transport operator and the society, this study aims at developing a method to identify such locations to construct the rescheduling infrastructure which maximizes benefits for all the 3 abovementioned stakeholders impacting due to the disruptions. To quantify these benefits, travelers tend to minimize the total travel time (access/egress time, in-vehicle time, waiting time and transfer time). The objective of operator is to gain maximum revenue (maximum profit) from the system which is dependent on the patronage and to minimize the operational cost. For the PT authority, social welfare is utmost important which is dependent on both consumer surplus and producer surplus (van Nes, 2015). The relation between the above-mentioned indicators are shown in Figure 3.

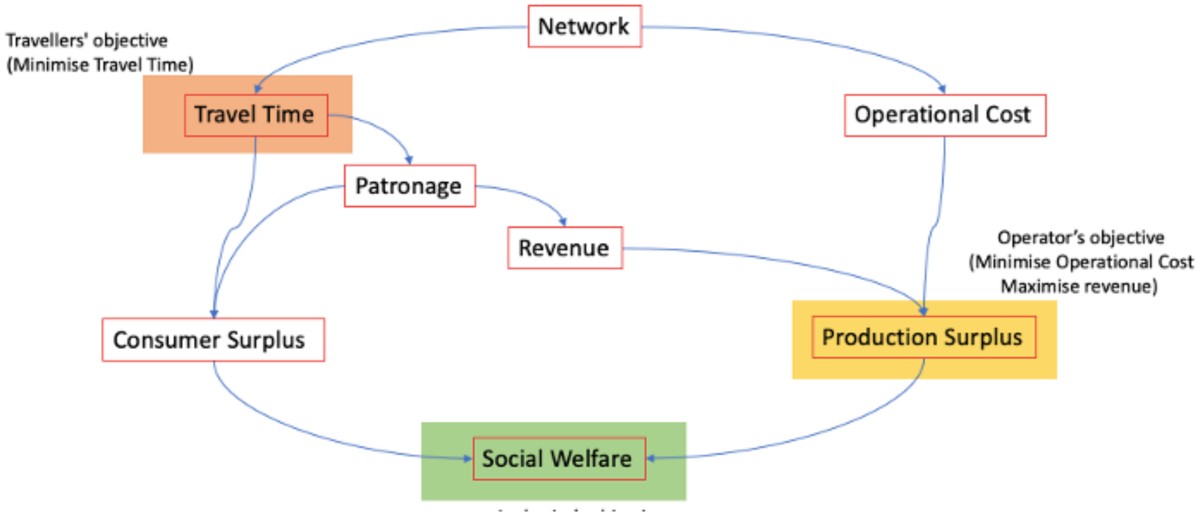

Figure 3 Network Design Objectives

1.2. Research Design and methodology

This section elaborates on the research design by identifying the research gap in the existing state-of-the-research It is then followed by framing the research question and sub questions which answer the research question. The last part of this section details the stepwise methodology to answer the sub questions with the relevant literature associated with it.

Research Gaps

In both the groups of research work by Ferber et al. (2012), Cats et al. (2017) and Cats et al. (2018) as discussed previously, the vulnerability (and so does the robustness) of the network is assessed either by removing the prominent link(s) (or nodes) or by reducing its capacity. Obviously, it will reduce the overall robustness of the network. It is obvious that additional infrastructural investments (such as an extra link to the network (rescheduling infrastructure)) to the existing public transport network will make the system more robust as discussed in Ash et al. (2007) , Cats et al.(2019), Chan et al. (2021) and Jenelius, et al. (2015). Not only it makes the system robust but also the link would have the distributive benefits to the society such as enhancing accessibility to the public transport (Chan et al., 2021). As with this additonal infrastructure to the system, the system will becone less vulnerable (more robust) to the disruptions. This additional link to the network grid will not only benefit the robustness of the system but also makes it resilient during planned and unplanned disruptions as by using the additional links, the system could recover to its original performance much earlier (Jenelius et al., 2015; Cats et al., 2019). Instead of facing the problem post disruptions, the robustness of the network could be enhanced by developing the network structure in such a way that will reduce the impact of the anticipated disruption. In this way, the public transport network can contribute to withstand the system breakdown.

However, there has been less research, or no systematic research done for identifying such links. One of the studies done by Jenelius et al. (2015) assesses the benefits of a new link in public transport network enhancing the robustness of it by the evaluating the welfare of travelers for the base network and the extended network. Ash et al.(2007) also developed an algorithm to make the system withstand in the cascading effects of disruptions. In the former study, the new link to the network is an input and the robustness is based on the welfare but only of travelers, whereas in later study, the evolutionary algorithm is used to counter the cascading effect of the disturbances or failures in a network structure. However, both the studies do not identify systematically which link one should add in the network to extract the higher benefits.

A research study by Roelofsen, et al. (2018) follows a framework which assesses alternatives in case of disruption considering passenger and operator perspectives. It also provides suggestions to select amongst the alternatives (which are short turn and detour) based on the demand ratio and length of short turn and detour. But it does not give any suggestion regarding the location of the new link in the network infrastructure and the benefit of it.

This project tries to develop a model which identifies the most plausible and cost-effective measure based on the location of the disruption. It also aims to develop a systematic methodology that will identify the location for new rescheduling infrastructure in a public transport network that maximizes the robustness of the network benefitting passengers, transport operators and the authority. Here the new link in a network indicates the local rescheduling infrastructures such as turning loops, cross overs, connecting the local junctions and tram line connecting two nearby unconnected stations.

Research Objectives

The research project aims for the following theoretical and practical objectives:

Theoretical Objective

The objective of the research project is to propose a methodology that can suggest the optimal location(s) of additional rescheduling infrastructure investments in an urban public transport network that maximizes the added robustness value for the network on a global level in a fixed budget.

Practical objective

To identify the location of infrastructural investments for any real-world public transport network to maximize the increase the robustness of the network and to reduce the impact of the anticipated (planned) disruptions. The case of Amsterdam tram network is included in this study as in the coming decade, Amsterdam tram network is going to have planned disruptions on the public transport network due to the closures of the bridges and quays for renovation purpose. The objective of the project is to support stakeholders to prioritize the infrastructure investment decisions within a fixed budget.

Research Questions

To achieve the research objectives as mentioned in the previous section, the main research question is framed as follows:

What method can be developed to determine the optimal locations of a new rescheduling infrastructure in a public transport network that maximizes its robustness value against disruptions?

The following sub-questions would help to answer the research question which are elaborated in the Research Method sub-section.

Sub questions:

1. **What method can determine the plausible supply side adjustments for a given disruption?**
2. **What would be the most plausible supply adjustment amongst short turning and detouring for a given disruption with or without the new rescheduling infrastructure?**
3. **How to quantify the passenger and operator impacts resulting from the supply adjustments with or without the new rescheduling infrastructure?**
4. **What is the method to identify the most beneficial new rescheduling infrastructure from all candidates rescheduling infrastructures that contributes to maximize the robustness for a large-scale public transport network?**

Research method

This section elaborates the method answering the sub-questions as identified in the previous section. The research is structured in a way that assesses the two scenarios which are ‘disrupted link’ case and ‘disrupted link with new link’ case. In the first case of ‘disrupted link’ the transit adjustments and passenger assignments are done to the existing base PT network having only disruption(s). In the second case of ‘disrupted with new link’, the new links to the network are tested for the disruptions and the transit adjustment and passenger assignment is done for a PT network containing both a disrupted link and new link. The first two phases of research project focuses on developing a supply-side adjustment and passenger assignment models. The third phase of research project quantifies the benefits by running both the scenarios and by comparing the identified KPIs. The last phase of the project assesses the robustness of the new link and prioritizes the investments based on cost-benefit analysis. The structure of the research project is shown in Figure 4.

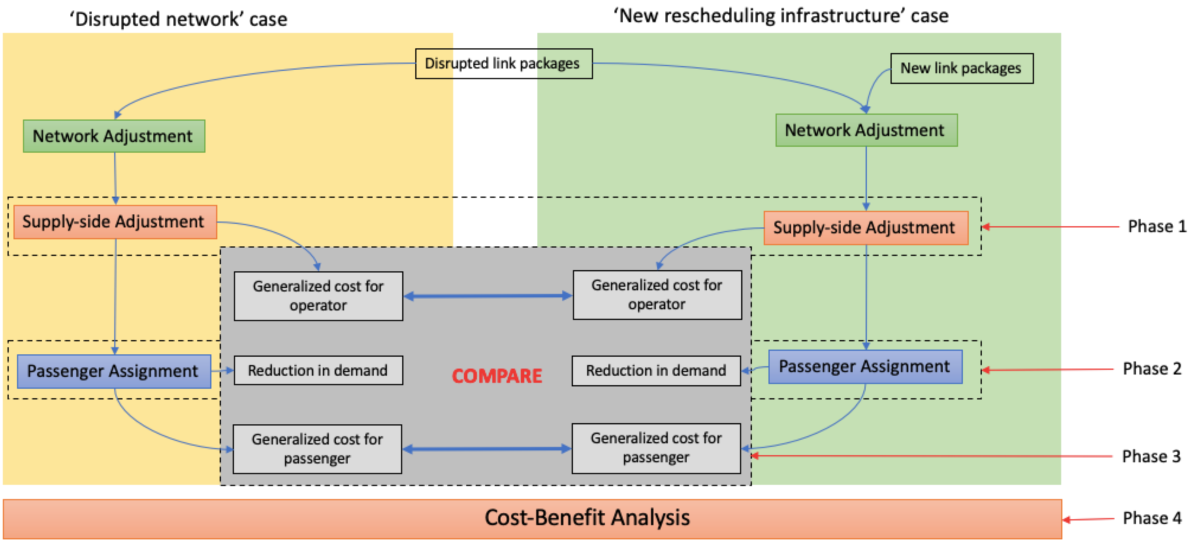

Figure 4 Research project structure

The disruption will act as an input to the public transport network as a disrupted set of links. To test the additional links in the network, it would also at this step act as an input, as these changes to the public transport network would have impacts on the services (such as detours, short turnings, rerouting, canceled services etc.). These would be quantified as the supply side adjustments due to the change in network structure. Hence the sub question:

1. **What method can determine the plausible supply side adjustments for a given disruption?**

The supply adjustments will account for the changes in the public transport services due to the changes in the network structure. These changes accounts for short turning and detouring of the services due to the additional link or disrupted link or both. These adjustments to the supply side could be done either by using an existing transport model (such as service adjustment models: CapTA (Capacitated transit assignment) model used by Christoforou et al., (2016) for transit adjustments in Paris RER disruption) or by developing a bespoke model based on the objective/requirements. As already mentioned, the input would be the changes in the network (additional link/disrupted link) and the output would be the changed services of public transport. The two types of adjustments in the services of public transport due to disruption are modelled which are short turn and detour. After the plausible candidate solution, through various filtering and selection criteria, the optimal candidate solution amongst short turn and detour is derived. Based on the selected candidate solution, the service on the network is adjusted. In this project, the supply side adjustment is modelled in MatLAB. An overview of the first step of the project is shown in Table 3.

Table 3 Process for sub-question 1

Inputs	Model	Output
Disrupted link and new link(s)	Service adjustment model developed in MatLAB as elaborated in Chapter 2.	Changed services of PT operations

Due to changes in supply side model (public transport services), there would be changes in the travel behavior which goes in line with the bi-level network design model (van Nes, 2015) as shown in Figure 5. To capture the travel behavior, passengers are assigned to the changed transit services. Since at this step, multiple plausible supply side adjustments (short turn and detour) is derived, the next step is to identify the most plausible solution. Hence the sub-question 2:

2. **What would be the most plausible supply adjustment amongst short turning and detouring for a given disruption with or without the new rescheduling infrastructure?**

The impacts on passengers due to change in services can be broadly classified into:
- Route choice impact: Passengers rerouting their routes due to the changed services
- Mode choice impact: Passengers shifting to another modes (especially during the planned disruptions).

This step would quantify the demand response due to the change in the supply side. In other words, in this step, the travel behavior of the passengers (the lower level of bi-level network design model shown in Figure 5Figure 5) is captured due to the changes in the public transport services. Due to the changed transit services, there would be different paths for the passengers. This will lead to different (dis)utilities per path. Using a passenger assignment model, the new routes for every passenger are modelled. These would further account for the changes in the travel loads (travel times, travel cost, number of transfers etc.).

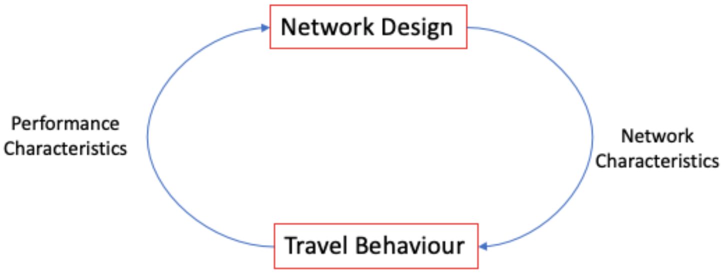

Figure 5 Bi-level network design model

There exist plethora of models dealing with passenger assignment to the transit lines such as Busmezzo, OmniTRANS, etc. Busmezzo is a dynamic transit operation and assignment model. It is a simulation model which could be applied to multi-modal transit networks (Cats, 2015). OmniTRANS is a static/semi-dynamic assignment model used for both car assignment and transit assignment. For this project the passenger assignment to the transit lines is modelled in MatLAB which is elaborated in the subsequent chapter.

The modal shift (shift from other modes to public transport) is also be taken into account due to the changes in public transport services specially for planned disruption. For unplanned disruption, the modal shift remains relatively constant due to the lack of information to the passengers. This change to demand model is assessed for both with and without the addition of new links. In this project, the demand elasticity is taken into consideration which is dependent on the travel characteristics such as travel time etc. An overview of the process to answer the sub-question 2 is given in Table 4.

Table 4 Process for sub-question 2

Inputs	Process	Output
Changed transit services	Passenger assignment modelled in MatLAB as elaborated in Chapter 3.	Changed travel time (in-vehicle time, transfer time, access/egress time), travel cost, number of transfers
Changed travel characteristics for public transport.	Demand elasticity based on travel time in Matlab as elaborated in Chapter 4.	Changed patronage.
Changed transit services	Direct changes such as vehicle km	Changed operational cost of PT

The next step is to quantify the robustness (benefit) of the network due to the new link. Hence the sub-question 3 is framed as:

3. **How to quantify the added robustness value to the public transport system due to the new rescheduling infrastructure during the disruption?**

To quantify the robustness value of the network, the benefits of the 3 stakeholders (travelers, operators and society) is considered. The value is quantified through the change in welfare of each stakeholder for the disruption scenario with and without a new link.

Let the present network structure be the base scenario and the network structure with the new link be extended scenario. The benefit of new link to the stakeholders is nothing but the difference between the welfare values in the two cases.

The next step is to identify the indicators the welfare function contains. The indicators are based on the benefits to these stakeholders. These are quantified based on their own objectives. For example: passengers try to minimize their travel time in a fixed cost, transport operators optimize the operational cost and maximizes the revenue whereas to capture the societal benefits, a proxy indicator of demand regain due to the new link to the network infrastructure is considered. Hence, the indicator for each of the stakeholder is stated below:

Indicators for travelers: Travel time and travel cost
Indicators for operators: revenue, operational cost
Indicators for society: Proxy indicator of demand regain due to the new link

These benefits would be compared to the purchased and maintenance cost of scheduling infrastructure to identify the worthiness of it.

Scenario Generation

To identify the disruption cost, the “disrupted network” and “new rescheduling infrastructure” case is generated. For both the cases, the welfare is calculated after running both, the supply side adjustment and the passenger assignment model. For every tested new link, the welfare generated in 'new rescheduling infrastructure' is compared with the welfare of 'disrupted network' case. After the welfare generation process, the welfare is annualized. To find out the worthiness of the new link infrastructure, the sub-question 4 is formulated.

4. **What is the method to identify the most plausible new rescheduling infrastructure from all candidates rescheduling infrastructures that contributes to maximize the robustness for a large-scale public transport network?**

Using cost-benefit analysis, the cost and benefit for every identified new link are extracted and the conclusions are drawn whether it is worth investing. By comparing the net present value, the most plausible new infrastructure could be found out from all other candidate new infrastructures.

1.3. Research Framework

The 'Classic 4 step model' includes trip generation, trip attraction, model split, and trip assignment as discussed in Gentile et al. (2002) and in TfL (2018). The illustration for the basic 4 step model is shown in Figure 6. In trip generation, the number of trips produced from an origin and number of trips attracted to destination is modelled. In the second step is to model the distribution of the trips from every origin to every destination. Usually, modal split is done after the distribution or parallel to the distribution. The last stage is assignment where the route for every trip is assigned.

For public transport modelling, the OD matrix is derived from modal split of individual vehicles (car, PT, etc.). Mostly, a joint mode and route choice model is used to derive the modal split and route. A basic public transport model is usually based on a static assignment. For PT modelling, the input is the network (graph) and the demand. The model performs the passenger flow assignment, and the output is the link flow, and the OD travel times as discussed in Gentile et al. (2002). Some common software packages which follow the same modelling approach are Visum, TransCAD, EMME, OmniTrans as discussed in Cats, et al. (2016) where the building blocks are choice set generation, route choice model and iterative network loading.

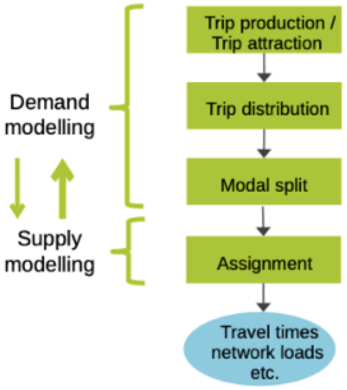

Figure 6 Classic 4 step model (Gentile, Florian, Hamdouch, Cats, & Nuzzolo)

Inspired from the classic 4 step model, the framework for this project is developed as shown in Figure 7. The input for the model is the disrupted link set and the new link set to the network. Through the changes in network, the new transit operations are generated using supply side adjustment model. In this model, the adjustments of transit lines are modelled based on the changes to the network which is elaborated in Chapter 2. There are two supply side adjustments covered under chapter 2 which are short turn and detour. By assigning passengers to both of the supply side adjustments, disutilities to all the passengers are derived and based on these disutilities, the most plausible supply side adjustment is recommended which is done in Chapter 3. On the later stage, the outputs which are changed travel time and travel cost are extracted. Demand elasticity is taken into consideration in which passenger demand is elastic to the travel time.

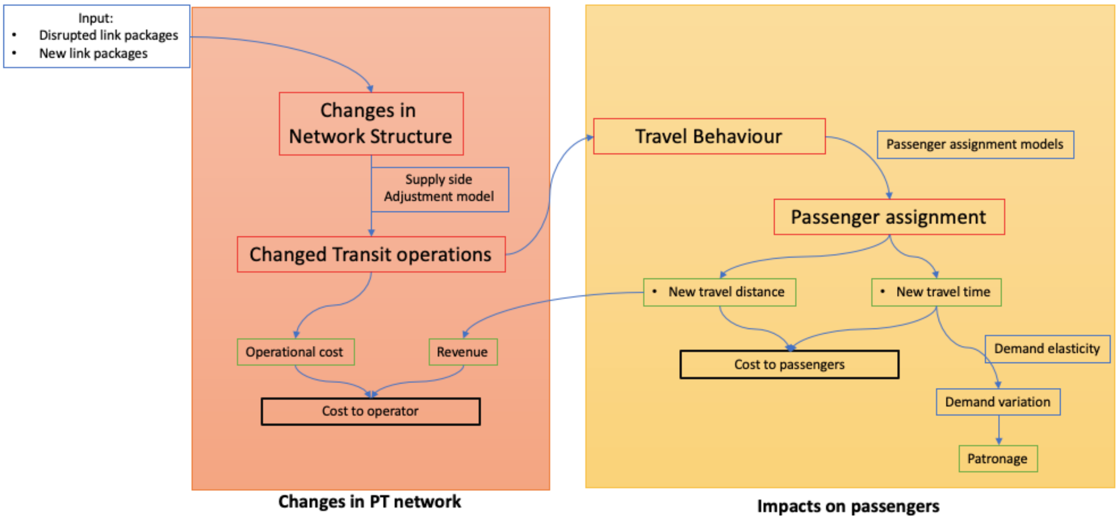

Figure 7 Model framework

1.4. Research output and relevance of study

Research output

The final output of the project would be the benefits of every new link (turning loop/cross-over, junction or line), for overall disruptions. This would help to quantify the total benefit of every link for every disruption and hence to prioritize the importance of the identified new link to increase the robustness of the anticipated disruption(s). The benefits would be quantified for operators, passengers and society for the identified new link sets and by comparing it with their cost of investment.

This project has three main deliverables. The first output is after phase 2 of the project where the most plausible supply side adjustment is recommended for different disrupted links. The second deliverable of the project is to quantify the benefits for the new link packages where the benefits are calculated for operators, passengers and society. The final deliverable of the project is to compare the benefits with their respective costs over a timeline of 30 years and to provide suggestion with the most beneficial investment decision that increases the robustness of the network.

Relevance of the study

The study has the following scientific and societal contribution.

Scientific Relevance

This study develops a method to identify the location of the new link in the public transport network that increases the robustness value. This method would identify the critical regions in a network based on the disruption impacts and frequency and gives the suggestions for the infrastructural investments on these locations. In other words, it will help to identify the location of the additional link that would enhance the robustness of the network as a whole taking into account the travelers, transport operators and the societal perspectives.

Societal relevance

From a societal point of view, the study is relevant to both passengers, transport operators as well as society. In addition to it, the study also gives a justification of the identified location for infrastructural investments by creating disruption scenarios. For passenger’s perspective, this study will develop the network in a such a way that it would have less impact on passengers during the disruptions. The study is relevant to both small scale as well as large scale public transport networks.

Moreover, the application of the study on Amsterdam’s tram system benefits those passengers suffering from the disruptions (less impedance on travel time) due to the closures of bridges and quays for renovation purpose. This would also help the areas which are prone to getting disconnected during the disruptions (for generic and Amsterdam’s case). From a transport operator’s perspective, the study gives a tool to the operators to identify the apt location as well as the type for making the infrastructural investments to upgrade the system performance. It will also provide the operators a cost-efficient way for the operations of the public transport during the disruptions. From the societal perspective, the research project benefits the overall social welfare of the public transport system by suggesting the location of infrastructural investment that will have reduced demand reduction during disruptions.

1.5. Scope

Scoping in resilience cycle

As discussed in earlier section of chapter 1 that the resilience cycle consists of 4 stages: “prepare”, “withstand”, “recover” and “adapt” (Figure 2); which also goes in line with the bathtub model. According to the bathtub model (Figure 1), the disruption causes the reduction in system performance and with time (during recovery phase) and due to certain measures, it goes back to its original system performance. The project mainly focuses on the post phase of disruption and tries to increase the robustness (decrease the vulnerability part of graph) and aiming for reducing the impact of disruption to its system performance. The influence to the recovery time is not covered under this project. Although the measures provided by this study would improve the resilience of the system (Roelofsen et al., 2018) the quantification of such measure is beyond the scope of study.

Scoping in typology of rescheduling infrastructure

The tram (or any public transport) based infrastructure varies into different typologies based on requirements and functionalities. For example: both turning loops and crossovers have the same functionality of turning the tram to the reverse direction. The difference is that the crossovers can be only used by the bi-directional trams whereas turning loops are required for the one directional tram to turn it in opposite direction. In this study, the typology of infrastructure is limited to its functionality. i.e., there is no difference made for turning loops and crossovers as they both have the same functionality. The third rescheduling infrastructure is the junction connector which is used to divert trams on another line. Another infrastructure type which is considered in this project is the link connecting two parallel lines running nearby. For example, two tram stations lying on a parallel street but are not directly connected with any link. The types of rescheduling infrastructures used for this project are shown in Figure 8.

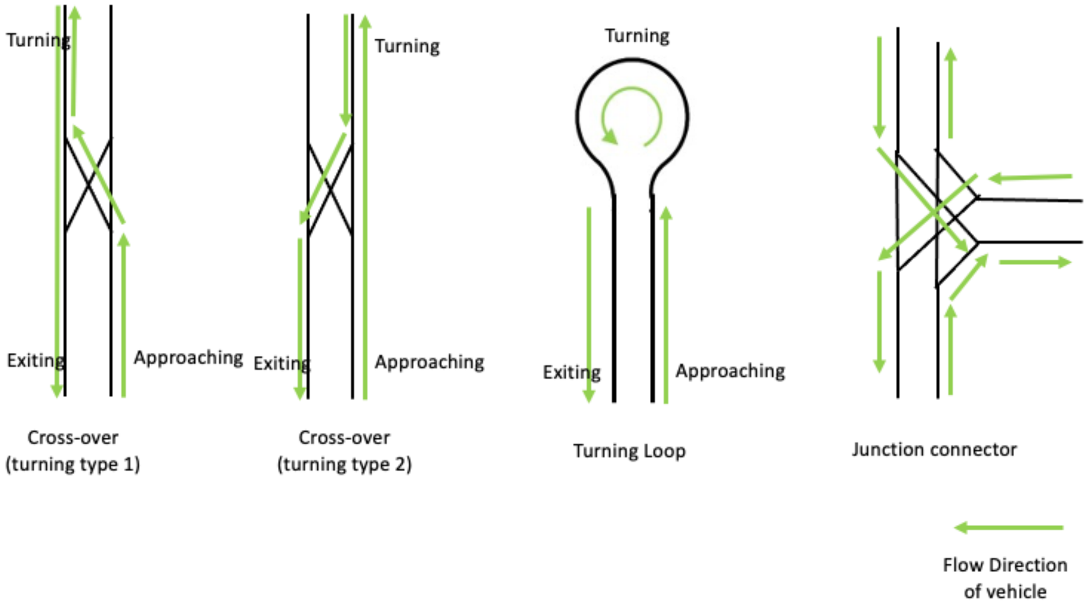

Figure 8 Rescheduling infrastructures

There exist various types of crossovers such as single cross-over, double cross over (as shown in Figure 8 (a and b), but this study considers all the types of cross-overs and turning loops into one single rescheduling infrastructure type because of its same functionality.

Scoping in applicability of the study for different modes

The research study deals with the urban rail system focusing on tram network. This goes in line with the typology of infrastructure considered for this project which are cross overs, turning loops, junction connectors and line connectors. These types of rescheduling infrastructure are applicable for all types of urban rail system as they network throughout the urban area is dense. The study deals with one of the urban rail systems which is Tram network of Amsterdam.

Scoping in 4-step modelling framework

In this study, the assignment part of 4-step model is the majorly dealt with. It is considered that there would be no impact on trip frequency and trip distribution due to the changes in PT network (new link and disrupted link). Demand elasticity is used to capture the demand variation due to the disruption.

Scoping for the indicators of the stakeholders

These exists many indicators which quantifies the welfare of the stakeholders (passengers, operators and authority). Out of these indicators, few selected indicators are chosen for this study considering the time limitation of the project. From passengers' perspective, travel time (in-vehicle time, waiting time, walking time and number of transfers) and travel distance are the indicators considered to quantify the benefit. For operator's perspective, cost to operator is the main indicator which has the operational cost (based on the transit length) and the revenue generated due to the service. To capture the societal benefits, a proxy indicator of demand regain is used in this study.

Temporal Scoping for CBA

In this study, the time period to execute cost benefit analysis is considered to be 30 years, i.e. till 2051. The timeline of 30 years is based on the average span of the tram rescheduling infrastructure as per GVB (2021). Hence to capture total cost of infrastructure and the benefits gained per year till the infrastructure can be used, an average life span of 30 years is taken into consideration.

Geographic scope

The research project deals with the case study of tram network of Amsterdam operated by GVB in city of Amsterdam and nearby cities of Noord Holland which are Amstelveen and Diemen. For the infrastructural investment, the tram infrastructure is only taken into consideration. During the passenger assignment, tram and metro both are considered as the metro network offers potential redundancy to the system. Figure 9 shows the geographic scope of the project.

Figure 9 Geographic scope of the project

1.6. Thesis outline

The structure of the report is as follows: In chapter 2, a model is developed which identifies the different candidate solutions for transit adjustments during a disruption. In this chapter, short turn and detour transit adjustments are modelled. For a disruption, the plausible solutions for both the adjustments are derived. In chapter 3 of the report, amongst the derived plausible transit adjustments (short turn and detour), the most plausible transit adjustment is modelled. This is done by assigning passengers to both the modelled transit adjustments and deriving the (dis)utilities in both the cases. These (dis)utilities entail in-vehicle time, waiting time, walking time and number of transfers per path per OD pair. Comparing these disutilities, the transit solution with lower disutility is recommended amongst the two-transit service adjustments. The chapter 4 of the report deals with extracting the passenger, operator and societal benefits. This is done by comparing the KPIs from the scenario 1: with only disruptions and scenario 2: disruptions with new rescheduling infrastructure. In chapter 5, the cost-benefit analysis is executed for the various tested new rescheduling infrastructure links. Net Present Value for every tested new rescheduling infrastructure is derived for 2051 and their worthiness is assessed. In thesis is concluded in chapter 6 with conclusions, recommendations, and suggestions.

Chapter 2: Identification of candidate solutions for transit adjustments during a disruption

The aim of this chapter is to develop a method that generates the optimal PT supply side adjustments during disruption. The common supply side adjustments as discussed in Roelofsen et al. (2018) are short-turning and detouring of the vehicles over the network, which are considered as the supply adjustments during disruption. In section 2.1, the common practices for PT adjustments used by the public transport operator and the infrastructure manager worldwide are discussed. Section 2.2 gives the data requirement and model framework for the proposed supply adjustment model (short turn and detour) which is detailed out in section 2.3. The last part of the chapter, section 2.4 gives insights on the results of the developed model with the drawbacks and critical points.

2.1 Strategies for supply adjustments during disruptions

There is a variety of practices used by the public transport operators and infrastructure manager during disruptions. The strategies used for public transport disruptions are based on the structure of the network and availability of resources such as an extra vehicle, availability of crew, etc. The operational strategies can be broadly classified into measures which changes the original route of PT line and the measures which do not change the original route as described in Durand et al. (2018). The first group of strategies include measures such as detour, short turn and diversion. In these strategies, the adjusted PT service is in such a way that results in one or more stops not being served. This group of strategies are used for both reduced capacity of link and during the link breakdown. The skipping of stop is done due to the vehicle unable to serve the stop/station because of the infrastructural constraint such as stop within the disrupted segment. The other group of strategies as discussed in Cham (2006) and in Oort (2011) includes control measures within a route. These are holding or delaying the vehicles so as to adjust the headways between the two consecutive vehicles. It is worth to note that the speed control measures can be applied within a certain route setting. These strategies can also be applied in combination with the first group of strategies. Some of the strategies need special conditions at planning level to execute. For example: the short turning infrastructure for short turns, crew and vehicle availability for adding extra vehicles for the service etc.

The strategies can also be categorized based on the applicability of such strategies either for a disruption with reduced link capacity or disruption with total link break down. For example, strategies such as speeding up, slowing down or adding vehicle. These strategies can be used during the disruption with reduced link capacity or total link breakdown. For total link breakdowns, the most common strategies used are detours and short turns. The division of the control strategies is shown in Table 5.

Table 5 Control measures for different typologies of disruptions.

		Type of disruption	
		Link breakdown	**Link capacity reduction**
Requirements	**Require special condition at planning stages**	Short turning Detouring Adding vehicle*	Adding vehicle Detouring
	Does not require special condition at planning stages		Slowing down Deadheading Vehicle holding

* Adding vehicle is an operational strategy used as a supplement strategy. For example: adding vehicles to the short turn routes to reduce the longer waiting time.

Another category of the control measures could be based on the objective of the measures which are schedule adherence and route adherence. Schedule adherence is sticking to the original/planned schedule of the route. Route adherence is maintaining the service over original planned route. These objectives can be achieved either by speed control measures or by stop-skipping measures. Speed control measures include the holding and delaying the departure of vehicles in order to reduce/ increase the headway. Station/stop skipping strategy includes the short turning, diverting, rerouting the vehicles due to the existence of disruption. These strategies discussed mainly in Durand (2017) and in Babany (2015). Table 6 differentiate the various control measures based on their objectives.

Table 6 Control measures for different objectives

		Objective	
		Schedule adherence	**Route adherence**
Type of measure	**Speed control measure**	Speeding up Slowing down Adding vehicle	
	Stop skipping measure	Detouring Deadheading	Short turning Detouring

Short turning: Short-turn can be defined as the operational strategy where the vehicles are allowed to turn and return to the origin, serving the opposite direction. The vehicle turns in opposite direction somewhere along the route to because of the existence of disruption downstream as illustrated in Figure 10.

Rerouting/Detouring: Rerouting (or referred to as detouring of vehicles) allows the vehicle to follow a different path than the original path to reach its destination. It can be defined as an alternative route for a part of original route (Oort, Service Reliability and Urban Public Transport Design, 2011). It is mostly used for a blocked section (complete link breakdown) but sometimes this measure is also applicable for reduced link capacity to maintain schedule adherence. This measure as mentioned in Oort (2011) is used during the non-recurrent disruptions. In practice, rerouting is done taking into consideration the deviation of the new route from the original route. Bounds to the deviations such as travel time and travel distance are used to avoid large deviations. For example: setting a threshold value for the new travel time and travel distance as compared to the original one. An illustration in Figure 10 shows the basic concept of detouring due to the disruption.

Adding vehicle: This measure is mainly used to restore schedule adherence (Oort, Service Reliability and Urban Public Transport Design, 2011), where the vehicle is added to line if there is a delay and there is a decrease in a frequency of service. Additional vehicle and so the additional crew is required at the planning stage for this measure.

Speeding up/ Expressing: Speeding up is a control measure where the average driving speed of the vehicle is increased if there exist a delay or higher headway gap between two consecutive vehicles. Expressing is a type of speeding measure where the vehicle skips one or more stops in its way in order to reduce the headway. An extra slack time in a schedule determines where speeding or expressing is possible over a line.

Slowing down: This measure is used when the vehicle drives at higher speed and is running ahead of its schedule time or if predecessor vehicle is delayed. By decreasing the speed or by increasing the stopping time of the vehicle, it can get back to its schedule and in second case, it can maintain the required headway.

Vehicle holding: It is a speed control measure used for schedule and headway adherence. It is similar to slowing down but by holding vehicles at a certain holding location. It includes delaying a departure of a vehicle to improve the regularity and punctuality of the vehicle. It is also used to avoid vehicle bunching (Oort, Service Reliability and Urban Public Transport Design, 2011).

Deadheading: Deadheading is similar to expressing of vehicle but with empty coaches. This is used to put on a late vehicle back to its schedule skipping few stops in its way where it was supposed to serve. The details of both expressing and deadheading are well discussed in Durand et al. (2018) , Durand (2017) and Oort (2011).

The most common measures used by the operators during disruptions are detour and short turn which are also mentioned in Roelofsen, et al. (2018). In modelling the transit service adjustments due to the disruptions, for this project these two common measures are considered. A basic representation of detour and short turn is shown in Figure 10 10.

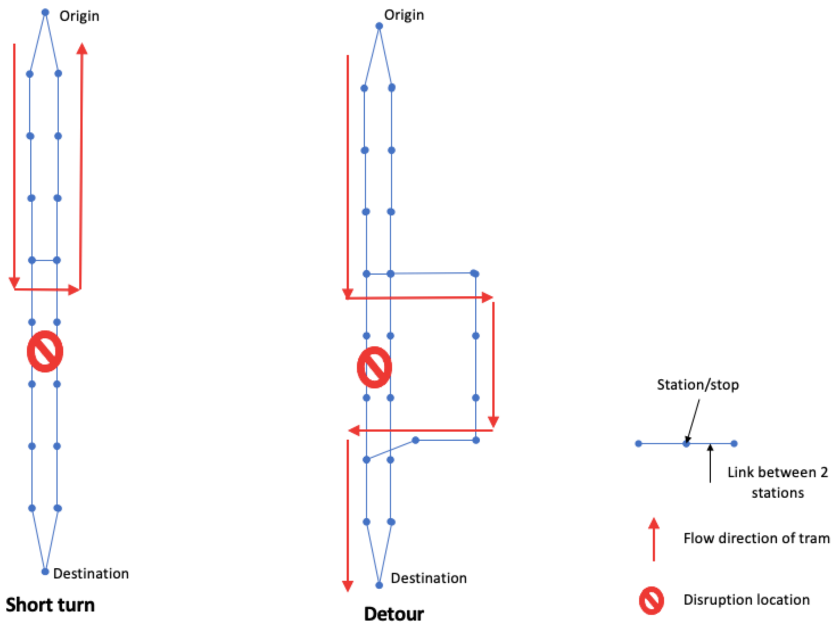

Figure 10 Short turning and detouring

Other measures

Other common measured used by different public transport operators as mentioned in Durand et al. (2018) is adding the shuttle service between the disrupted part, diverting a route, withdrawing a service and cancelling a service.

Adding shuttle service (Bus-bridging): It is a measure which retains the service within the disrupted part by providing a different vehicle to the disrupted areas. This measure is also called as bus-bridging. For example, if a tram infrastructure is disrupted, the service within that disrupted segment could be retained by providing a bus service.

Diversion: It consists of rerouting of the vehicle to reach to the destination on another branch of line (Babany, 2015). It is similar to detouring but the destination in diversion is different that its original destination and hence not aiming for route adherence.

Withdrawing: Withdrawing is a strategy used during disruption where the already scheduled vehicle is withdrawn before completing its trips. This measure is usually used during the unplanned disruptions (sudden incidents such as accidents, infrastructure failure etc.). In most of the cases as discussed in Babany (2015) and Durand (2017), withdrawing of service is often followed by cancelling of next services.

Cancellation: Due to shortage of resources, cancelling of trips may occur which can be also used as a disruption management strategy. It is used to relieve congestion on the line which is being caused by the disruption.

2.2 Data Requirements and Model framework

There exists plethora of control measures for disruptions as discussed in section 2.1. Out of these control measures, the project deals with the two most commonly used control measures. These are short turn and detour which are also discussed by Roelofsen, et al. (2018). The objective of this section is to develop a framework to generate plausible candidate solutions during disruption. It starts with discussing the data requirements followed by developing a framework.

Data requirements:

For the transit adjustment model, to consider both the detour and short turn strategies and the selection procedure between them, vehicle data, infrastructure and passenger data are required. For vehicle data, the vehicle path for all transit lines and frequency per transit line are needed which can be obtained from GTFS (General Transit Feed Specification) data source from the public transport operator or from other developed transport models. GTFS data will provide the route of vehicles on every transit line with the schedule, fare and geographic transit information.

Under the infrastructure data, the existing infrastructure grid of the public transport network with the stations and links between stations, network map, crossovers and turning loops are required. The additional link(s) and the disrupted link(s) are also used as an input for the model. The demand data of passengers' demand from every origin to every destination is also needed which can be obtained from Automatic Fare Collection system database.

Framework:

The objective of the model is to identify the plausible supply adjustment for both short turning and detouring in response to a given disruption and on the later stage, to support a choice between the identified solutions (detour and short turn). For generating alternative solutions for the disruption taken into consideration and filtering the generated alternatives, a framework similar to the framework developed by Roelofsen et al. (2018) is adopted. The model framework is structured in a way that it gives the output as a single candidate solution for every disruption. This candidate solution could be either detour or short turn of the disrupted transit line as shown in Figure 11.

The model developed by Roelofsen et al. (2018) focuses only on detour as the candidate solution and assesses the welfare from passenger and resource perspective for this detour. The contribution of the model developed for this research is that it models both the types of candidate solutions which are detour and short turn and finds out the plausible solution for each detour and short turn based on the extra travel time and extra travel distance of the solution. Furthermore, it also helps in decision making between the two solutions and give insights on the type of control measure suitable for the disruptions at different parts of the network.

The model for supply side adjustment per disruption is divided into 2 main parts. The first part of the model makes changes to the existing PT network. In this part, 'the disrupted network' and the 'additional infrastructure' to the network (such as turning loops, crossovers, junctions, links etc.) is given as an input. The second part of the model mainly deals with the supply side adjustments to the affected transit lines due to the disruption and derives the candidate solution. Figure 11 shows the model framework of supply side adjustment model who's each part is elaborated in the following section of the chapter.

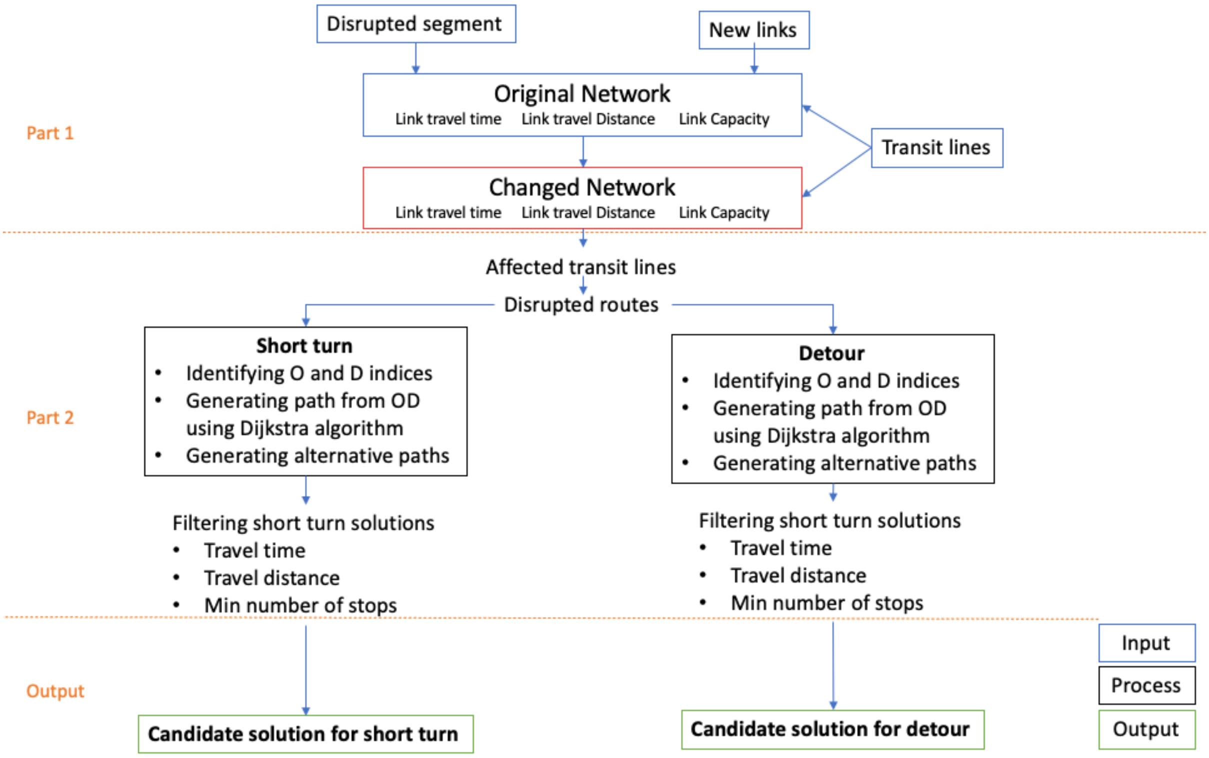

Figure 11 Framework for supply side adjustment model

2.3 Modelling supply side adjustments

The model to identify the plausible candidate solution for detour and short turn is developed in MatLAB. It is inspired by the model developed by Laskaris, et al. (2018) which generates the detour as a candidate solution as a response to the disruption. The contribution of the model developed in this project is that it identifies the plausible short turn as a candidate solution to the disruption. After the plausible two types of solution for a disruption, the model filters out the best solution amongst the two identified types of solution which is discussed in the next chapter. As discussed in the framework, the model is divided into 2 parts which is elaborated in this section.

Model Background

For the model, a network with directed graph 'G' is considered where G(S,E) is a network with set of nodes/stops as S= {s_1, s_2, ……s_n} as stops and set of links E= {e_1, e_2,….e_m} as the direct infrastructure (tracks) of the public transport connecting stops $s \in S$ Since the network is a directed graph, the links are also directed i.e., the flow is only permitted in one direction.

Part 1:

The original network (also called as the base network) 'G^B' is loaded with its edges (E) with certain attributes linked to this network. The characteristics of the links which are the public transport running times on individual links in the network 'e^B_t' in seconds, travel distances of individual links in the network 'e^B_d' in meters, and link capacities of the network 'e^B_c' in vehicles per hour. The disruptions to the network (the disrupted links) are provided as an input. As in this study, only complete link breakdowns are considered, there is no change in the capacity of the link (reduced capacity) but the link itself is removed from the network. The disruption 'd' is in form of set of links $d=\{e_1^d, e_2^d, \ldots e_n^d\}$. With the disruptions, the additional infrastructure such as turning loop, crossovers, junctions or extra links are also given at this stage as an input. This additional infrastructure 'n' is composed of set of new links where $n=\{e_1^n, e_2^n, \ldots e_n^n\}$. This new links of n are introduced in E with its characteristics such as typology of link, travel time, travel distance and capacity. The model then updates the base network and the related time, distance and capacity graphs and hence the new network 'G^D' where $G^D \subseteq G^B$, with the updated link capacities 'e^D_c', link travel times 'e^D_t' and distances 'e^D_d'. In the changed network, the transit lines 'L' ($l=\{l_1, l_2, \ldots l_n\}$) are introduced and the model identifies the disrupted transit lines L^d due to the disruptions where $L^d \subseteq L$. Every transit line $l \in L$ is a set of nodes in sequential order of their lines serving the stops.

$$l_1 = \{s_1^1, s_2^1, s \ldots .. s_n^1\}$$

where s_1^1 is the origin stop and s_n^1 is the destination stop for line l_1.

To identify the disrupted lines l^d, the model searches for every link (as a set of consecutive stops $\{s_n^l, s_{n+1}^l\}$) in every transit line $l \in L$ where these set of link matches with the introduced disrupted link $e^d=\{s_s^d, s_e^d\}$.

Part 2

This section elaborates on the method to derives the most plausible candidate solution(s) of the disrupted transit lines L^d. It could be either short turn or detour or both.

Model to find out the most plausible short turn service

To model the short turning of the vehicle serving the disrupted line, the following logic is implemented:

1. The short turning facility is considered taking into account the objective that the vehicles on the new transit line provide the services to the maximum possible stop where it can make a short turn. It is the closest node (station) to the disrupted part of transit line.

2. The new transit route should stick to the original transit route as much as possible. The upstream route to the disrupted part and the return route should be the same as of the original upstream and downstream routes.

3. If the short turning infrastructure such as cross over or turning loop does not exist on the disrupted transit line, the model tends to search such solutions for short turns with extra travel time and extra travel distance. This extra travel time and travel distance is constrained by the threshold values as an input. This concept is also discussed in (Roelofsen et al., 2018).

To achieve the objectives, the model first couples the transit lines based on upstream flows and downstream flows. In other words, the upstream transit lines are coupled with their respective downstream transit lines. Hence for every identified transit line, these are coupled with the opposite stream transit lines.

$$l^u = \{s_1^u, s_2^u, s....., s_n^u\}$$

$$/$$

$$l^d = \{s_1^d, s_2^d, s...., s_n^d\}$$

Here, the origin of one stream is the destination of their downstream. Hence $s_1^u = s_n^d$. Let us call this as 'O'. Then 'D' would be $s_n^u = s_1^d$ as shown in the Figure 12.

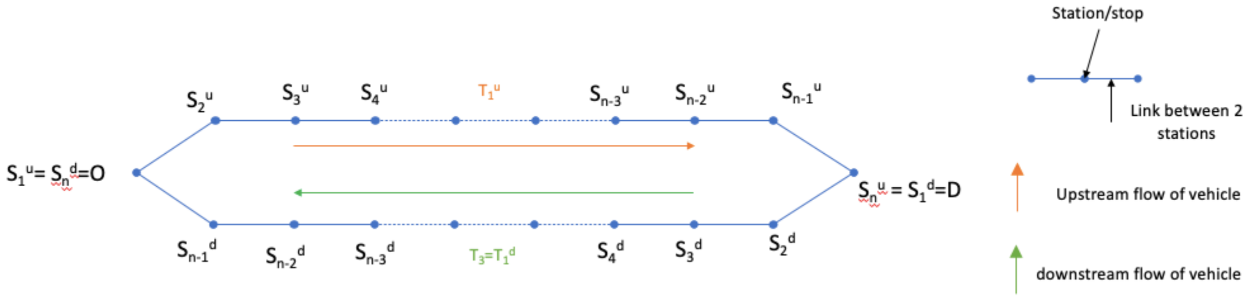

Figure 12 Coupling of upstream and downstream lines

The next part of the model searches for those nodes which gives a possibility for performing a short turning movement. Here, not only the short turn infrastructure is considered but also the junctions over the existing line providing access to the nearest short turns are considered. These nodes are searched backwards from the starting point (node) of disruption on the upstream line, and forward from the ending point (node) of disruption on the downstream. The set of such nodes on the upstream direction (named as o indices) and on downstream direction (named as d indices) is generated. These nodes are searched based on their out-degree (for nodes on upstream route) and in-degree (for nodes on the downstream route) as these nodes would be the exit points and entry points to the respective upstream and downstream. Let $O_{indices}$ be the exit points and $D_{indices}$ be the entry points sets.

$$O_{indices} = s_{i,exit}^u$$

$$D_{indices} = s_{i,\ entry}^d$$

Let the link e_s be the link starting from $s_{i,exit}^u$ to any other node. This link e is uni-directional link. i.e., flow is allowed from $s_{i,exit}^u$ to the other end node of the link but prohibited in opposite direction. Such $s_{i,exit}^u$ nodes are considered in $O_{indices}$ where $|e_s|>=2$. In other words, the out-degree is greater than or equals to 2 where the node $s_{i,\ exit}$ lies on the upstream ($s_i \in l_n^u$). In the similar way, those nodes in $D_{indices}$ are put which have $|e_s| >= 2$ (in-degree greater than or equals to 2) where $s_{j,\ entry}$ lies on the downstream ($s_j \in l_n^d$).

In the example as shown Figure 13 (left)., in the upstream flow, the model searches for the node in backward direction starting from the disruption where the out-degree is greater than or equals to 2 and finds out node number s_6^u and s_4^u as $O_{indices}$. For downstream, the model searches for the nodes in forward direction starting from the node post disruption with in-degree greater than or equals to 2 and finds out s_{n-5}^d , s_{n-4}^d and s_{n-3}^d nodes as $D_{indices}$.

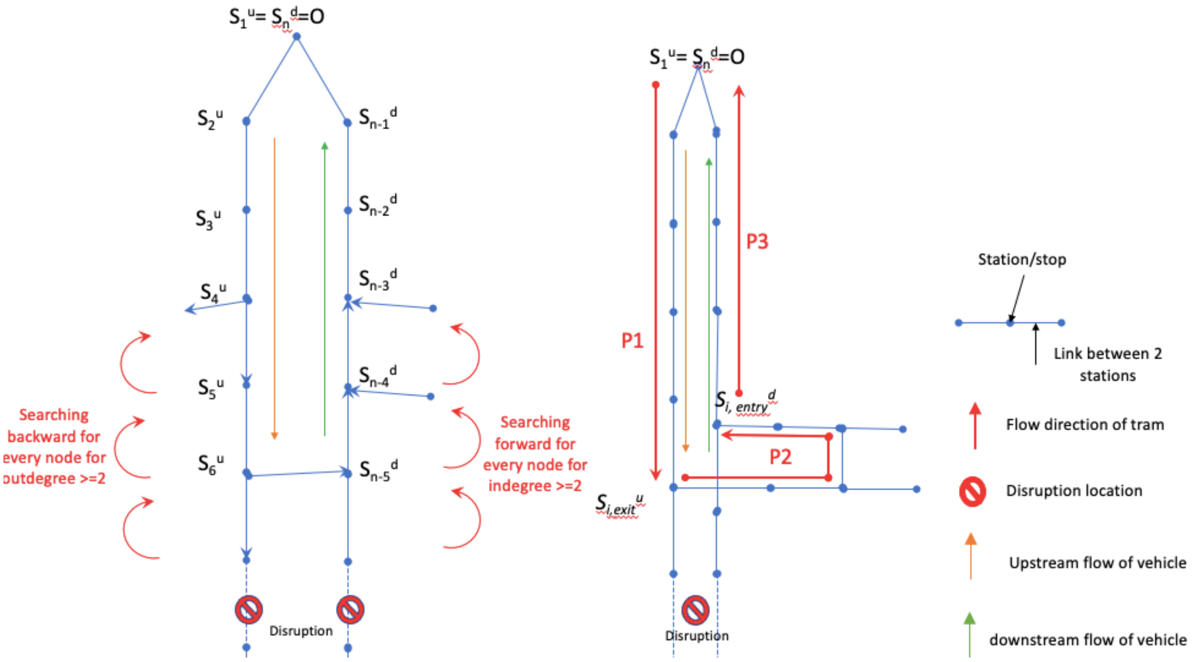

Figure 13 (Left) searching nodes with outdegree and indegree; (right) short turn with use of junction

Using the Dijkstra algorithm to find out the shortest path as used in (Roelofsen, Cats, Oort, & Hoogendoorn, 2018) and in (Yen, 1971), the one shortest paths from each $s_{i,exit}^u \in O_{indices}$ to each $s_{i,\ entry}^d \in D_{indices}$ are generated. Let these paths be $p_{Si,\ Sj}^{\ l}$ which is path from s_i^u to s_i^d of transit line l. This path is ordered set of links as identified through the shortest path. Let the sequence of stops in such path be s^c (stops in connecting line). See Figure 13 (right) where the path is indicated with path p_2 Let us call this path $p_{Si,\ Sj}^{\ l} = p_2$ for simplicity.

The new routes are generated by appending the routes from three sub-sets. Let p_1 be the path from origin ($S_1^u = S_n^d = O$) to the selected S_i^u in $O_{indices}$, p_2 be the path from s_i^u to s_i^d and p_3 be the path on the downstream line from s_i^d to origin ($s_1^u = s_n^d = O$) (Route p_3) as shown in Figure 13 (right). The new line l^s be the candidate short turn for the disruption. This line l^s is part of all transit lines L, $l^s \in L$.

Candidate Solution: $l^s = p_1 + p_2 + p_3$

where $p_1 \in l_n^u$ from ($s_1^u = s_n^d = O$) to $s_{i,exit}^u$, and $p_3 \in l_n^d$ from ($s_1^u = s_n^d = O$) to $s_{i,\ entry}^d$

There could be multiple candidate solutions l_1^s, l_2^s, …..l_n^s depending upon the number of sets S_i in $O_{indices}$ and $D_{indices}$. Let all candidate solutions be L^s where $L^s=\{l_1^s, l_2^s, ...l_n^s\}$.

As stated previously, the candidate solutions are filtered based on the threshold value (as an input) to the extra travel time and extra travel distance. Through extra travel distance ($\beta_{distance}$), the empty vehicle run km can be constrained and also this travel distance is used to adhere to original route. Travel time (β_{time}) constraint is used to make the new candidate solution reduce the empty vehicle minutes. The third filtering criteria is the minimum number of stop the candidate solution is serving.

Hence in this case, to consider the candidate solution, the travel time of the route p_2 (t_{p2}) should be within the threshold value (β_{time}) times the sum of travel time of route p_1 (t_{p1}) and route p_3 (t_{p3}). This will constraint the empty vehicle travel time (t_{p2}) based on the travel time on the original route which is t_{p1} and t_{p3}. In other words, the extra travel time for the empty vehicle should be within β_{time} times the travel times on original routes for both upstream (t_{p1}) and downstream (t_{p3}). The extra travel time β_{time} is passenger specific constant which usually lies between 0 and 1 depending on the passengers' willingness to accept the extra travel time.

$$t_{p2} <= (t_{p1} + t_{p3}) * \beta_{time}$$

Similarly for travel distance, to constraint the empty vehicle kilometer, threshold value ($\beta_{distance}$) is used which generates the following equation.

$$d_{p2} <= (d_{p1} + d_{p3}) * \beta_{distance}$$

To consider a candidate solution, both the constraints as given in 1 and 2 must be satisfied.

In case of multiple solutions l_1^s, l_2^s, …..l_n^s , the solution serving the maximum number of stops (nodes) sticking to its the original route is taken as the only candidate solution. Let the stops in $l_n^{short}=\{s_1^{lns}, s_2^{lns} .... s_n^{lns}\}$, then the final solution would be

$$L_{sol}^s = max(|s^{ls} \in s^u| + | s^{ls} \in s^d|) \ for \ \forall \ l^s \in L^s$$

Where L_{sol}^s is the final candidate solution for short turn, $|s^{ls} \in s^u|$ are the number of stops of the candidate solution l belonging to the stops in the upstream line, and $| s^{ls} \in s^d|$ are the number of stops of the candidate solution l belonging to the stops in the downstream line.

In case of multiple solutions l_n^s satisfying the objective, $max(|s^{ls} \in s^u| + | s^{ls} \in s^d|)$, the minimum number of stops in path p_2 (which is from s_i^u to s_i^d defined with set of stops as s^c) is considered as the final solution.

$$L_{sol}^{s} = min(|s^{l^s} \in s^{c}|)\ for\ \forall\ l^{s} \in L^{s}$$

In case of no solution after the filtering criteria, the model returns “no physical option available” for the short turning under the considered criteria.

Approach for testing threshold values for β_{time} and $\beta_{distance}$

By running various combinations of parameters (β_{time} and $\beta_{distance}$) for different disruptions in model codes developed in MatLAB, and by assessing through the result, β_{time} and $\beta_{distance}$ both are fixed to be 0.4. While assessing the result through various runs, the values for the parameters are fixed so as to avoid the larger empty vehicle run (in both time and distance dimension) and by considering that the plausible candidate solution should not be filtered out. The value of β_{time} and $\beta_{distance}$ =0.4 means that the travel time and travel distance on the extra route for the short turn cannot exceed the 40% of the travel time and travel distance of original route, which aims to strike a balance between serving as many stops as possible without running too many empty kilometers.

Model to find out the most plausible detour service

The objective considered for detouring of the vehicles to reach to its destination is that the vehicle should provide the maximum possible service on the same transit line which is disrupted. In other words, the line remains disrupted to the node (station) nearest to the disrupted part where it encounters the facility (such as a junction) to deviate from its original route, take a detour to its destination.

The model developed by Laskaris, et al. (2018) searches the detour as a candidate solution for the disrupted transit line. To find this detour, the model searches for the node to exit the original line and the node to re-enter the original route pre and post disrupted segment respectively. This is done for every disrupted line. In other words, the model starts searching for the node(s) with outdegree greater than or equals to 2 ($|e_i| >= 2$) from the start node of disruption in backward way till the origin ($S_n^u = O_n$) and node(s) with indegree greater than or equals to 2 ($|e_i| >= 2$) from the end node of the disrupted part till the destination ($S_n^n = D_n$). The $O_{indices}$ and $D_{indices}$ are the set of all such nodes respectively. Here, unlike short turn, the opposite stream of a disrupted transit line does not play any role. In the following example, S_3^u with out-degree =2 is a node in $O_{indices}$ and S_{n-2}^u with in-degree =2 is a node in $D_{indices}$

$$O_{indices} = S_{i,exit}^{u};\ D_{indices} = S_{i,\ entry}^{u}$$

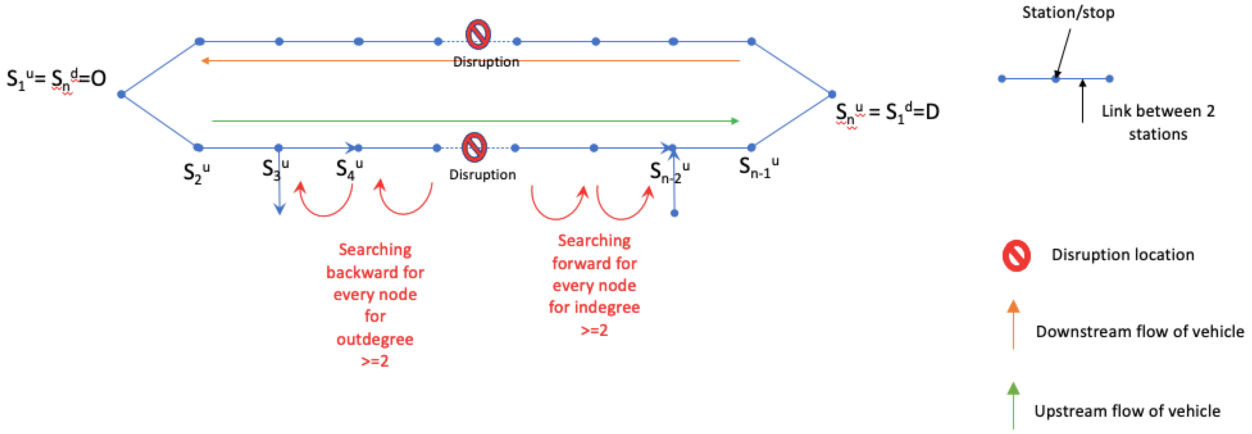

Figure 14 Modelling detour

Using the Dijkstra algorithm to find the shortest path as used in (Roelofsen et al., 2018) and in (Yen, 1971) for every pair of nodes from $O_{indices}$ and $D_{indices}$, an alternative route to the disruption is modelled as shown in Figure 14. Let p_1 be the path from origin ($s_1^u = O_n$) to $s_{i,exit}^u$, p_2 be the path from $s_{i,exit}^u$ to $s_{i,\ entry}^u$ and p_3 be the path from $s_{i,\ entry}^u$ to Destination (D_n). The new line l^d be the candidate detour for the disruption. This line l^d is part of all transit lines L, $l^{detour} \in L$.

$$\textit{Candidate Solution: } l^d = p_1 + p_2 + p_3$$

where $p_1 \in l_n^u$ from ($s_1^u = O$) to $s_{i,exit}^u$, and $p_3 \in l_n^u$ from $s_{i,\ entry}^u$ to Destination (D_n).

There could be multiple candidate solutions same as the short turning case. Let all candidate solutions be L^d where $L^d=\{l_1^d, l_2^d, \ldots . l_n^d\}$.

The candidate solutions are filtered based on the threshold value to the extra travel time (β_{time}) and extra travel distance ($\beta_{distance}$) as done for filtering the candidate solutions for short turn.

For filtering the candidate solutions, the travel time of the route p_2 (t_{p2}) should be within the threshold value (β_{time}) times the sum of travel time of route p_1 (t_{p1}) and route p_3 (t_{p3}). The extra travel time for the empty vehicle should be within β_{time} times the travel times on original routes for both upstream (t_{p1}) and downstream (t_{p3}).

$$t_{p2} <= (t_{p1} + t_{p3}) * \beta_{time}$$

Similarly for travel distance, to constraint the empty vehicle kilometer, threshold value ($\beta_{distance}$) is used which generates the following equation.

$$d_{p2} <= (d_{p1} + d_{p3}) * \beta_{distance}$$

To consider a candidate solution, both the constraints as given in 1 and 2 must be satisfied.

Similar to modeling the multiple candidate solutions for short turning cases, the multiple solutions for detour are modelled. Hence the following equations for detour are used.

$$L_{sol}^{d} = max(|s^{ls} \in s^{u}| + | s^{ls} \in s^{d}|) \text{ for } \forall\ l^{s} \in L^{s}$$

$$L_{sol}^{d} = min(|s^{ls} \in s^{c}|) \text{ for } \forall\ l^{s} \in L^{s}$$

Where L_{sol}^{d} is the final candidate solution for detour, $|s^{ls} \in s^{u}|$ are the number of stops of the candidate solution l belonging to the stops in the upstream line, and $| s^{ls} \in s^{d}|$ are the number of stops of the candidate solution l belonging to the stops in the downstream line. In case of no solution after the filtering criteria, the model returns to the “no physical option available” for the short turning under the considered criteria.

Conclusion

This part of the project gives us the output for the plausible candidate solution for short turn and for detour. The next chapter determines which amongst the two-candidate solution is beneficial based on the demand of passengers.

Chapter 3: Identification of most plausible transit adjustment amongst detour and short turn

Chapter 2 dealt with generating the supply side adjustments due to the disruptions. The aim of this chapter is to develop a sequential method that finds out the most plausible rescheduling measure amongst the short turn and detour as modelled in chapter 2. The illustration for the process in relation to chapter 2 to achieve the aim is given in Figure 15.

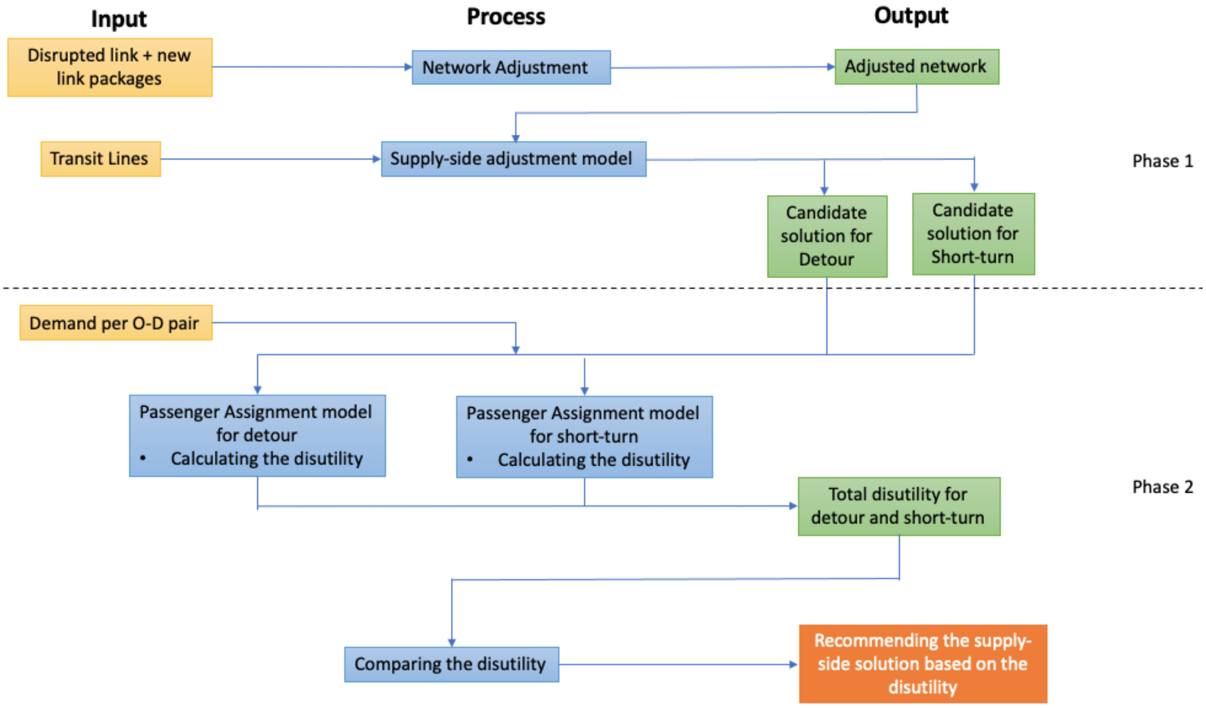

Figure 15 Outline for model recommending the supply side adjustment per disrupted link

To choose a single supply side solution amongst the candidate solution for detour and for short turn, the two solutions are assessed by assigning passengers. The recommendation for the supply side solution is based on the derived disutility in both the cases and by comparing these disutilities.

The initial part of this chapter gives the detail of the passenger assignment model where passengers are assigned to the changed transit lines based on their origins and destinations. The travel demand from every origin to every destination is used as an input for passenger assignment. The sub-section 3.1 elaborates on the 3 main steps for the passenger assignment which are 1) path generation, 2) generating utility for every path and 3) assigning passengers based on these utilities per path. The passenger assignment model developed by Laskaris, et al. (2018) is used to assign passengers which includes all the above-mentioned parts (path generation, path utility and passenger assignment). The assignment model is used to give recommendations for different disruptions for each location in the PT network, the preferred supply-side solution (either short turn or detour) The section 3.2 gives the recommendations for Amsterdam tram network which is based on the total utility of the passengers for both the cases. Section 3.3 detailed out the input variable and its formulation. The last part of the chapter elaborates on the model run results for the case study of Amsterdam tram network.

3.1 Modelling passenger assignment

As discussed previously, the three main steps of passenger assignment are path generation, path utility derivation and passenger assignment. The three steps are discussed as follows:

Path generation

The path generation model generates the possible shortest paths for all the pairs of origin and destination using the Dijkstra algorithm as described in Yen (1971). For every pair of origin and destination, path generation process being computationally expensive, the total number of paths per OD is limited to be three. These paths for all passengers are associated with the mode of movement which includes either walking or using transit line or both to complete the journey. The mode of movement is linked with their travel characteristics.

The generated path is a sequence of nodes with their node IDs used by the passenger to reach to their destination. If the passenger is using a transit service to complete his trip, the node ID in such section of journey is the stop id of the transit line. The travel time is associated with the link connecting the two consecutive nodes in the path set which is the time taken to reach from one node to another. It could be walking time if the passenger is walking between the two nodes or in-vehicle time if the passenger is using a transit service. The other travel components are waiting time and number of transfers. Waiting time is linked to a specific node and frequency of service the line is having, the number of transfers is linked with those nodes where there is change of transit line by passenger to reach to their destination. The illustration as shown in Figure 16 draws a clear picture of the path generation and the related components for a single set of origin and destination.

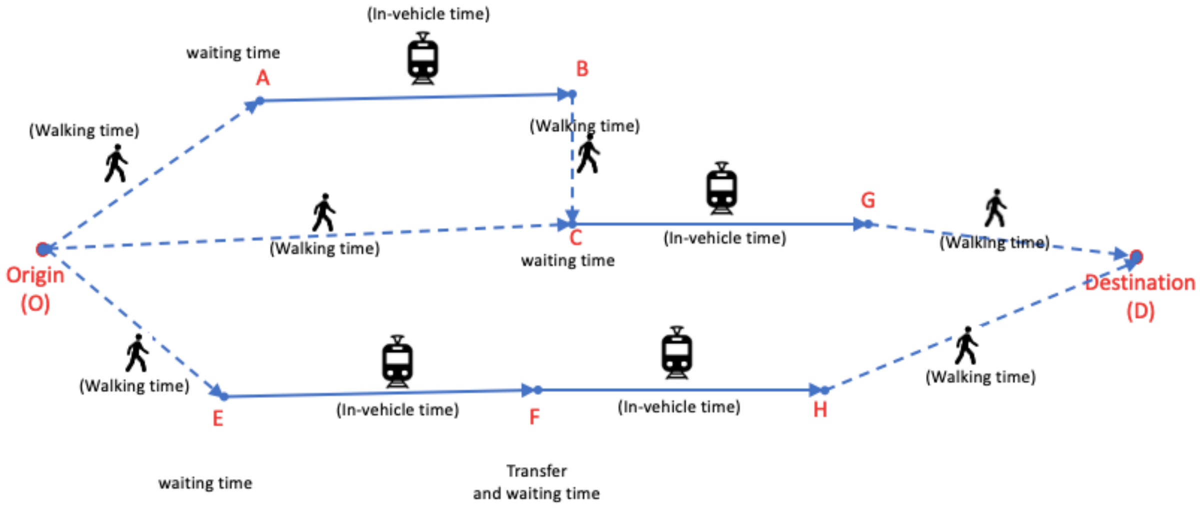

Figure 16 Path generation and its components

In the figure, three paths are generated from origin (O) to destination (D) which are combination of set of nodes. These paths are as follows:

1. O→A→B→C→G→D
2. O→C→G→D
3. O→E→F→H→D

The consecutive nodes in each path are connected with a link which contains the link attribute which is travel time between the two nodes. Every node contains the node attribute such as waiting time. For path 1, the time components are walking time from O to A (t_{walk}^{OA}), waiting time for transit vehicle at A (t_{wait}^{A}), in-vehicle time from A to B (t_{inveh}^{AB}), walking time from B to C (t_{walk}^{BC}), waiting time at C (t_{wait}^{C}), in-vehicle time from C to G ($t_{in\text{-}veh}^{CG}$) and walking time from G to D (t_{walk}^{GD}). Since in this path, there is only one change of transit line, the number of transfers linked to this path is 1. In the similar way for other paths, the travel components are derived as shown in Table 7

Table 7 Path components

Path	Walking Time	In-vehicle Time	Waiting time	Number of transfers
Path-1	$t_{walk}^{OA}+ t_{walk}^{BC}+ t_{walk}^{GD}$	$t_{inveh}^{AB}+ t_{inveh}^{CG}$	$t_{wait}^{A}+ t_{wait}^{C}$	1
Path-2	$t_{walk}^{GD}+ t_{walk}^{OC}$	t_{inveh}^{CG}	t_{wait}^{C}	0
Path-3	$t_{walk}^{OE} +t_{walk}^{HD}$	$t_{inveh}^{EF}+ t_{inveh}^{FH}$	$t_{wait}^{E} +t_{wait}^{F}$	1

The above example of path generation is for a single O-D pair. The path generation model generates such paths for all the O-D pairs in the network. As shown in the table, the travel components (travel time and number of transfers) are linked with every set of paths. The individual travel time component for a path is the sum of all such travel time components in the path as shown in the following equation.

$$t_{walk}^{p1}= t_{walk}^{OA}+ t_{walk}^{BC}+ t_{walk}^{GD}$$
$$t_{inveh}^{p1}= t_{inveh}^{AB}+ t_{in\text{-}veh}^{CG}$$
$$t_{wait}^{p1}= t_{wait}^{A}+ t_{wait}^{C}$$

Path Utility Calculation

As elaborated by Leurent et al. (2014) and Eltved et al. (2019), the route choice by passenger is assumed to follow behavioral microeconomics. It means that the route choice by passengers is based on the cognitive judgement of disutility linked with every path which differs from person to person. The higher the disutility, the lower the probability of the passenger to choose the route. Here, the disutility is the travel time component. The presumption of various time components (waiting time, walking time and in-vehicle time) by passenger differs and hence they value the various time components in different ways. For example, the statistical results as discussed in Qu et al. (2020), Eltved et al.,(2019) and by Wardman (2001) show that the perceived time for waiting is usually higher than the in-vehicle time or walking time. To capture such effect of time components perceived by the passengers, different weights (or coefficients) for different time components are assigned. Hence the final travel time component for each path is derived as

$$T_{ij}^{p1}=\beta_{walk}t_{walk}^{p1}+\beta_{wait}t_{wait}^{p1}+\beta_{inveh}t_{inveh}^{p1}+\beta_{trans}t_{trans}^{p1}$$

In the similar way, the total perceived travel time for other paths would entails the summation of the individual travel time components multiplied with their weights for the travel time components.

$$U_{ij}^{p}=T_{ij}^{p}=\sum\beta_c t_c^{p}$$

Where T_{ij}^{p} is the perceived travel time for origin i to destination j for path p. This is also the (dis)utility U_{ij}^{p} for paths p. β_c is the weight to the travel time component c and t_c^{p} is the travel time component 'c' for path p. The coefficient for different travel components varies based on various factors. Various studies and empirical research shows that parameters such as vehicle crowding, seat occupancy, travelers' frequency, etc. affects the coefficient value. From the estimation results derived in Yap et al. (2018), the coefficients are used by Laskaris, et al. (2018) for the supply side model for the project. The following are the coefficient values for different travel components are used for passenger route choice and passenger assignment.

$$\beta_{walk}=0.016$$
$$\beta_{wait}=0.016$$
$$\beta_{inveh}=0.01$$
$$\beta_{trans}=0.046$$

The weights assigned to the travel components shows that the passengers perceive higher time during waiting for a vehicle and while walking as compared to in-vehicle travel time which is 1.6 times higher. The number of transfers is converted into the time unit by giving a weight of 0.046, which means that one transfer is perceived as 4.6 minutes. These travel time components are the disutility for choosing a path. Next sub-section elaborates further on the probability of the passengers to choose a certain path based on these calculated (dis)utility.

Passenger Assignment

Passengers are distributed to different paths for every origin-destination pair. A discrete choice model with 3 alternatives is used to calculate the probability of the passengers to choose the path where the decision rule is based on the (dis)utility of every path. The basic assumption for this model is that the passengers have well defined preferences and out of the 3 options, they will only one alternative to complete their journey and they maximize their utility by choosing the alternatives with highest utility. To calculate the probability of the distribution, a path size logit (PSL) model is used which captures the correlation between the different routes which includes route utility functions. Another assumption is that the errors follow a gumbell distribution curve. Same approaches are also discussed in Duncan, et al. (2020) which gives insights on PSL model and highlights its shortcomings.

When the utility of path 'i' , (U_i) is higher than the utility of path 'j', (U_j) the probability of choosing path 'i', ($P_{(i|C)}$) is higher, the probability of choosing path i is derived using the following equation of the logit function where κ_i is the correction term for route i.

$$P_i = \frac{e^{\gamma \mathrm{Ui}+\kappa i}}{\sum_{k=i}^{k=j} e^{\gamma \mathrm{Uk}+\kappa j}}$$

For this model, since only 3 paths per od pair is considered, the denominator would consist of 3 terms. For example, the probability of choosing path 1 would be

$$P_1 = \frac{e^{\gamma \mathrm{U1}}}{e^{\gamma \mathrm{U1}} + e^{\gamma \mathrm{U2}} + e^{\gamma \mathrm{U3}}}$$

Here, e is the Euler number with value 2.71828 and γ is the scale parameter which is 1 for this model. After calculating the probability of distribution of passengers for every path per OD pair, the demand (total flow) from i to j (q_{ij}) is distributed accordingly. Let this probability be P_{ij}^{pk} where i-j denotes the origin 'i' and destination 'j' and p_k is the path used to go from i to j. Based on this probability P_{ij}^{pk}, the demand q_{ij}, where $q_{ij} \in q_{od}$ is distributed. The distributed demand or flow q_{ij}^{pk} for path p_k would be $q_{ij} * P_{ij}^{pk}$.

$$q_{ij}^{pk} = q_{ij} * P_{ij}^{pk}$$

The next step is to calculate the generalized utility GU_{ij}^{pk} for all the passengers using the path p_k for going from origin i to destination j. This is done by multiplying the utility of path p_k, (U_{ij}^{pk}) with the flow on that path q_{ij}^{pk}.

$$GU_{ij}^{pk} = q_{ij}^{pk} * U_{ij}^{pk}$$

Since this generalized (dis)utility GU_{ij}^{pk} is for a single path p_k, to calculate the generalized utility from i to j GU_{ij}, it would be the summation of generalized utility for all the paths together. Since to compare the generalized (dis)utility for all the paths going through the disruption, (dis)utilities are summed up for all the pairs of origins and destinations. Hence

$$GU = \sum_i \sum_j \sum_{pk=1}^{pk=n} GU_{ij}^{pk}$$

This generalized utility is calculated for both detour and short turn, let us represent it with GU^{st} for generalized utility for od pair i to j using the short turn as supply-side adjustment and GU^{detour} for generalized utility for od pair i to j using the detour as supply-side adjustment. If $GU^{st} < GU^{detour}$, then short turn for the disrupted link (set of links) is recommended. If $GU^{detour} < GU^{st}$, then detour for the disrupted link (set of links) is recommended.

$$\textit{If } GU^{st} < GU^{detour} \rightarrow \textit{Short turn recommended}$$
$$\textit{If } GU^{detour} < GU^{st} \rightarrow \textit{Detour recommended}$$

Threshold value decision

For Amsterdam network, the overall paths from all origin to all destination is 24,685. Since, in the model, three paths per OD pair are generated, the total paths generated is 24685*3=74,055 paths. It is computationally expensive to generate these many paths per disruption. Moreover, the computational time explodes if the same process is executed for all the identified disruption sets. In order to attain a balance between reducing the processing time and capturing the apt values without making it biased, the following approach as shown in Figure 17 is followed.

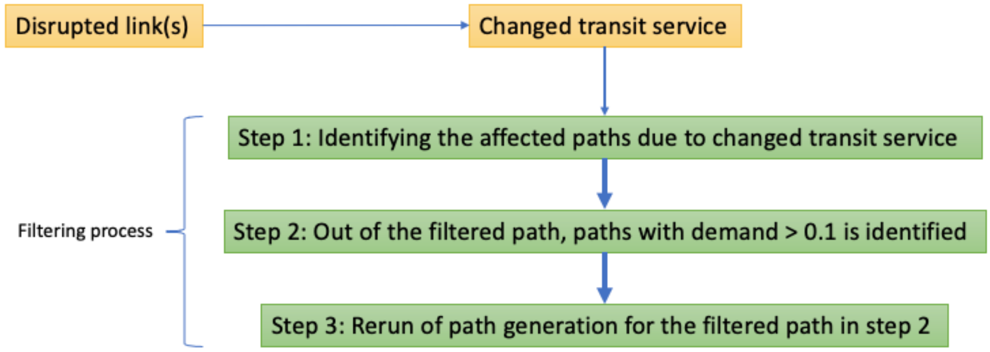

Figure 17 Filtering paths for path generation

In path generation model, the first step is to identify the affected OD pairs whose paths are affected due to changed transit lines due to the disruptions. In step 2, the paths carrying demand > 0.5 passengers per hour is captured. The decision for this threshold value is taken into consideration by assessing the total number of OD pair and the percent of total demand captured. This is done for different locations of disrupted links in the network. The lower bound threshold value is decided in such a way that it captures at least 80-85% of the total demand flowing from the disrupted link. The values of percent of demand captured by different threshold values are given in Appendix 1. In step 3, the path generation is executed for the filtered paths.

3.2 Generating disrupted link packages

This section aims to generate disrupted link packages which are set of packages containing links to be disrupted at once. The links which are to be disrupted are those links connecting two consecutive stops on a line. Disrupting such links will disconnect the identified pair of consecutive stops. These stops are on both upstream and downstream of a line. To make such disrupted link packages, the following approach is followed.

To generate this set, the model runs for all transit lines l where $l=\{l_1,l_2,\ldots.l_n\}$. In the first step, upstream and downstream lines are coupled. The stop nodes '$s^u \in l^u$' in upstream transit line is matched with the stops ‘$s^d \in l^d$’ in downstream transit line based on their stop name which is the node attribute. In other words, set of stop nodes are created which consists of one node from upstream transit line and one node from downstream transit line based on the same stop name. This step is executed to avoid the mismatch of stops ‘s’ in upstream flows and downstream flows for non-symmetric lines as shown in Figure 18. In this model, the stop(s) existing in only one direction is not grouped with any other stop and the links related to such stops are not disrupted. For example: the non-paired stop in upstream direction is not grouped with any other stop.

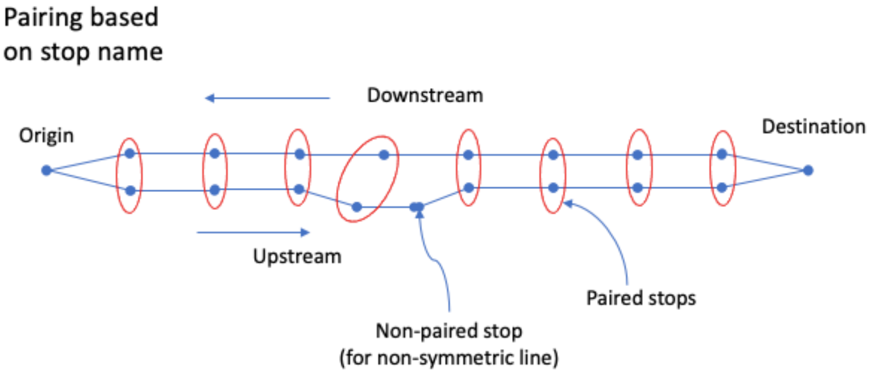

Figure 18 Pairing stops for generating set of disrupted links

For a single transit line l, the model runs for all the stops from s_1^l to s_n^l and for every stop and pairs up with their respective downstream stops. Let this set be S consisting of set of stops for every line from s_1 to s_n. Each stop set ‘s’ contains a pair of stop $\{s^u, s^d\}$ where $s^u \in l^u$ and $s^d \in l^d$.

$$S=\{s_1, s_2, \ldots . s_n\}$$
$$S_1=\{s_1^u, s_1^d\}$$

In the next step, for every stop $s \in s^u$, the model searches for all the links $e \in E$ whose origin node or start node is s. Since link e consist of set of nodes $\{s_s, s_e\}$ where s_s is the start node of the link and s_e is the end node of the link. If $s_s = s$, where $s_s \in e$ and $s \in s^u$ the link e is e_k which is considered under one of the link in the set of disrupted links E. For every stop s of the downstream line, $s \in s^d$, the model searches for all the links $e \in E$ whose destination node or end node is s. The making of different packages of the disrupted link is illustrated in Figure 19.

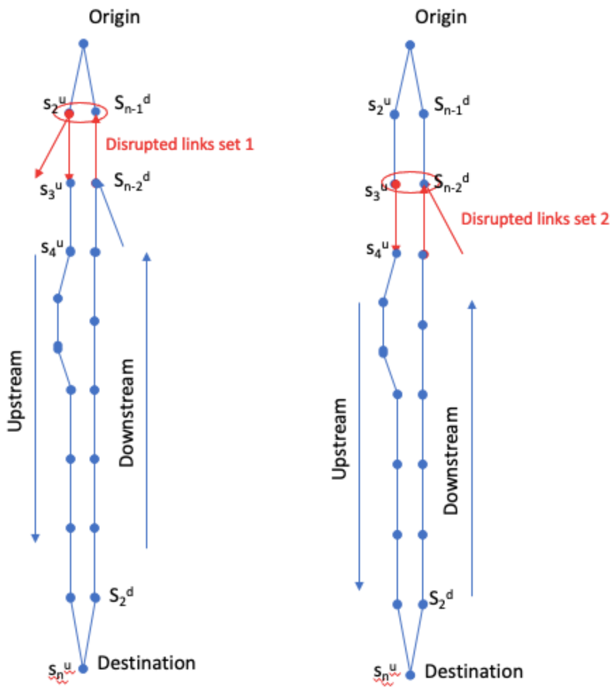

Figure 19 Disrupted link packages

The idea behind removing all the outgoing links from the stop node at upstream flow and incoming links to the stop node at downstream flow is to completely break the connection between the stop and the subsequent stop(s) on the transit line. The last step is to remove the duplicate links in a set and to remove the duplicate sets.

3.3 Supply-side adjustment for Amsterdam tram network

The model is executed for Amsterdam tram network and every link within the network is checked. The input data used for the model is for PM peak period of 2 hours. The following map in Figure 20 shows the most plausible supply-side solution for every disrupted link for the current base network. From the map, the branches of every line protruding outward mostly have only short turn as the candidate solution. It makes sense as in these regions, there exist no other parallel lines for making a detour, hence short turn is the only option. On the contrary, as one moves more towards city center, the density of lines increases, and there exist more parallel or nearby lines to make a detour if the link is disrupted. Hence the detour solution is more concentrated at the centre.

There exist few locations in the city centre (Eg: Museumplein and Dam) where the short turns are preferred than detours. Some places such as north of Jan van Galenstraat, where there is no feasible solution. This might be due to the detour solution crossing the criteria of extra distance or the infrastructure for short turning might not be available nearby the disrupted links.

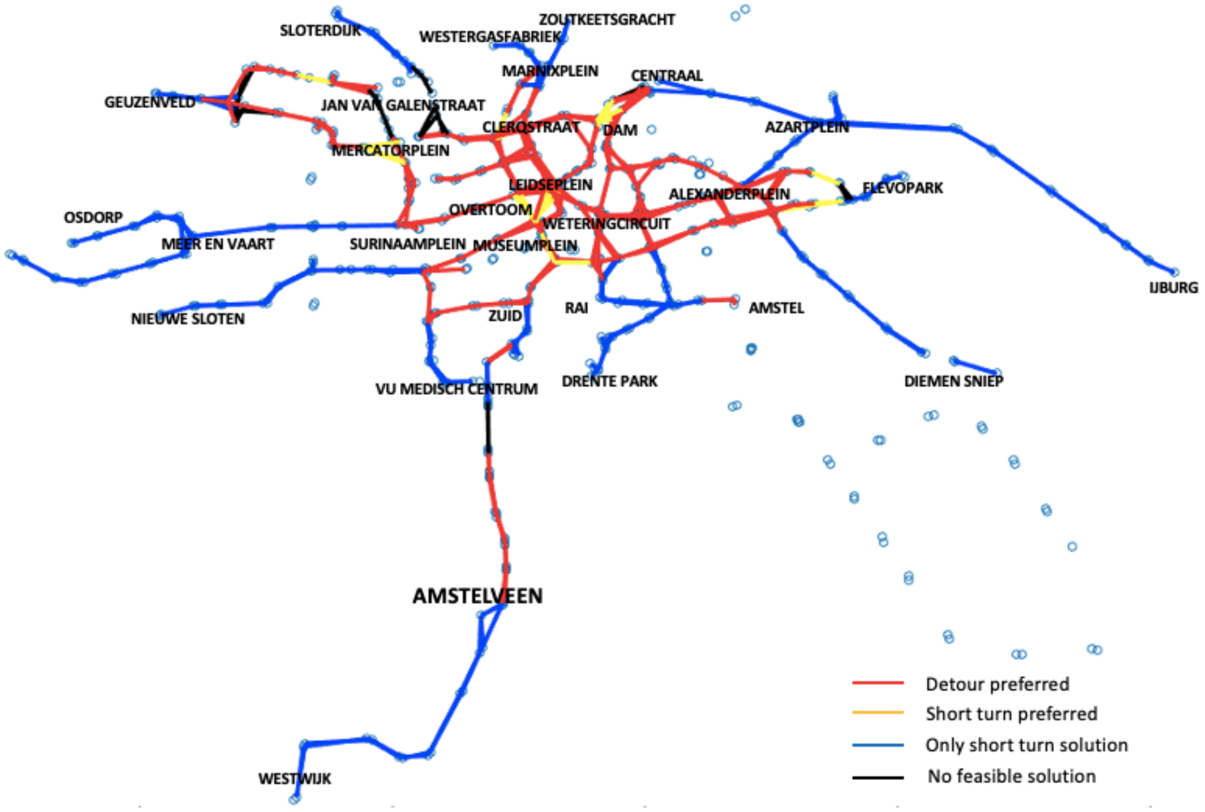

Figure 20 Rescheduling measure per disrupted link- Amsterdam tram network

Consider a disruption between 1e Con. Huygensstraat and J.P. Heijesstraat. The model identifies the disrupted line which is tram line 1 which runs from Matterhorn in west of Amsterdam to Flevopark in the east. The disrupted segment and the disrupted line are shown in Figure 21.

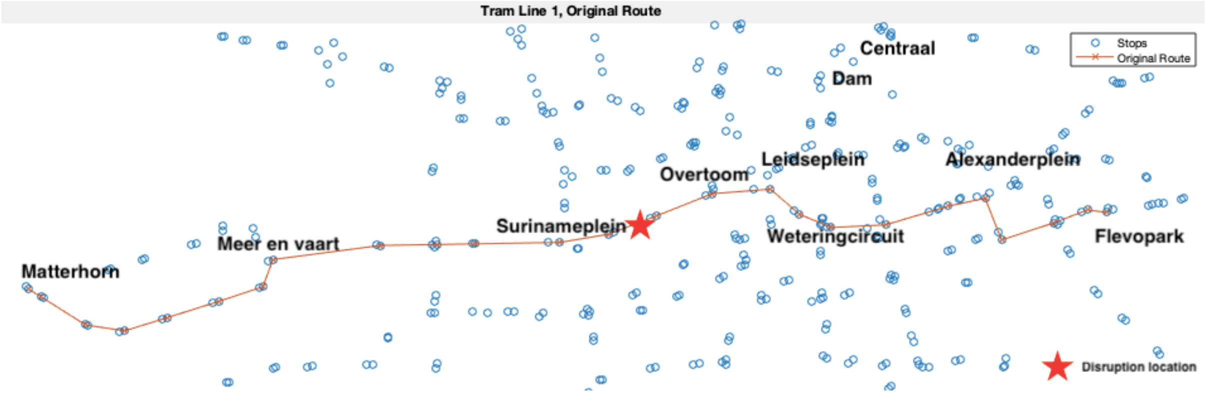

Figure 21 Disrupted line and disruption location

The transit assignment model generates the plausible supply side solution for detour and short turn for tram line 1. The plausible supply side solution for short turn as generated by the model is shown in Figure 22. The tram line 1 from Matterhorn side takes a short turn at at Surinameplein just before the disruption. From Flevopark side, the tram service follows the original path till Van Bearlestraat and at this location it turns right towards Leidseplein. At leidseplein, it turns left to Marnixstraat, again left at Clercqstraat and back to Van bearlestraat. Then it follows the original route back to Flevopark.

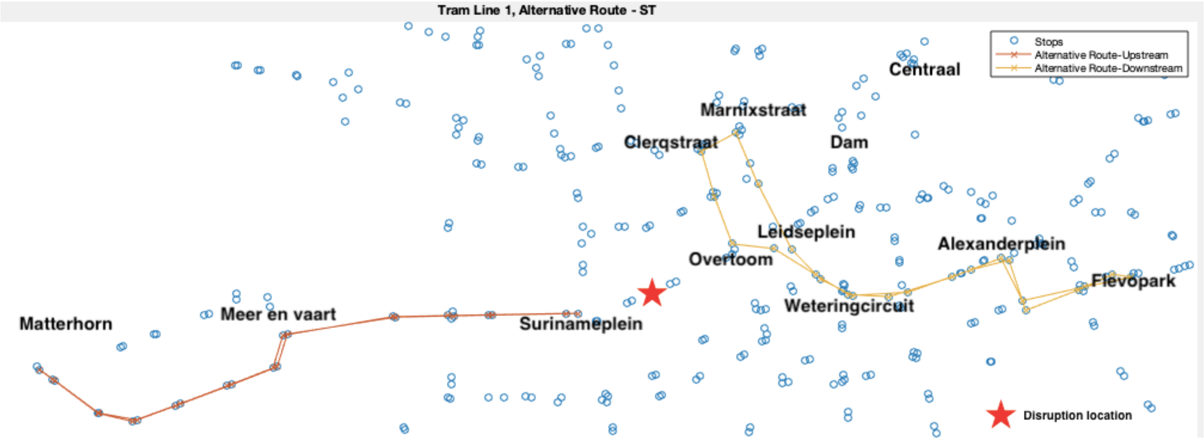

Figure 22 Plausible supply side solution for short-turn

The plausible supply side solution for detour as generated by the model is shown in Figure 23. The tram line 1 bound from Matterhorn continues on the original path till Surinameplein. At Surinameplein, it turns left and travel straight till Hoofdweg. At Hoofdweg, it turns right to Postjesweg and again turns right at Kinkerstraat to Overtoom and follows the original path. From Flevopark side, the tram turns right at Van Bearlstraat, and from Leidseplein it turns left on Marnixstraat. After Elandsgracht, it turns left on Kinkerstraat, again left at Hoofdweg and straight till Surinameplein. From there, it follows the original path to Matterhorn.

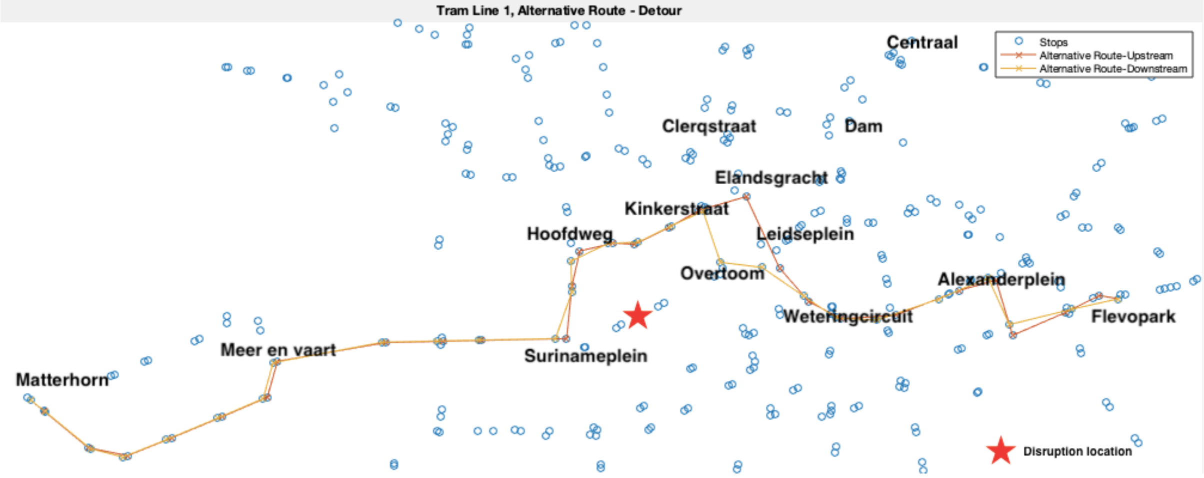

Figure 23 Plausible supply side solution for detour

Passengers are assigned to both short turn solution and detour solution of transit assignment. Disutilities for the affected OD pairs are calculated and compared. For short turn solution, the calculated disutility by the model is 320.24 sec which is the generalized cost for passengers if the transit adjustment is short turn. For detour, the generalized cost is 280.16 sec. Since, the disutility of detour is less than the disutility of short turn, detour is preferred.

Chapter 4: Quantifying the benefits of a new rescheduling infrastructure in the PT network

In this chapter, the benefits of the new links such as crossovers, links for an incomplete junction connector or a completely new link in the network is quantified. The quantification of the benefits of the new link are done by considering the benefits to the passengers, benefits to the operators and benefits to the society. The chapter starts with identification of the new link set to be tested. The second section of the chapter details out the benefit quantification from all the three-perspectives which are passengers, operators and societal perspective.

4.1 Generating new link packages

Similar to the disrupted link packages, the new link packages are also an input to the model. The new link packages (or set of links) is the potential location identified to an incomplete junction connector, plausible location for cross-overs, or a segment of line connecting two parallel lines. These links would be the candidate links for which the benefits to various stakeholders are quantified in the subsequent section. These are the links at incomplete junction connectors. For example, consider the existing infrastructure as shown in the Figure 24 (left). In this case, the trams can go from S → E, E→ S, S→N and N→S but could turn from N to E or E to N. So, a new link package with set of links is introduced where tram can turn from N to E and E to N as shown in Figure 24 (right).

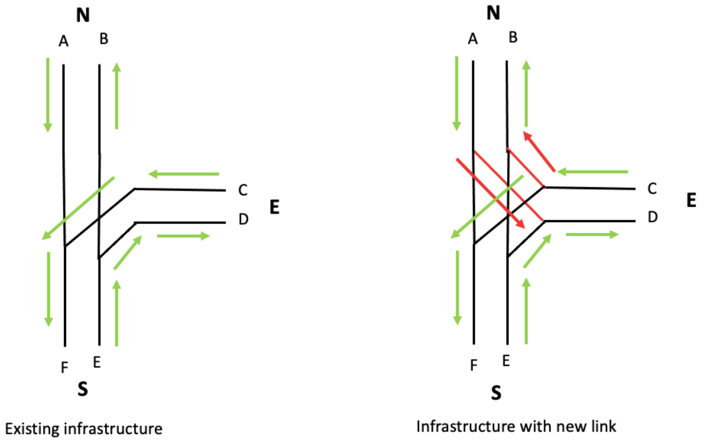

Figure 24 New link to complete the junction connector

For the second set of candidate new links, the new links are provided (tested) as crossovers at all the stops where a bi-directional tram can use to take a short turn. A new link is introduced in the network between the same stop but at opposite flow direction. In the Figure 25, a new link as a cross-over is introduced (tested) providing a link between same stops but in opposite direction. In the existing infrastructure case, the bi-directional tram does not have infrastructure to turn around but with the new link considered for testing in the infrastructure, it can turn around.

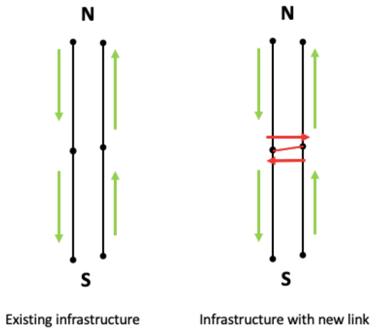

Figure 25 New link as crossover

The third set of candidate links are the new line connectors connecting the existing lines running nearby. For example, as shown in the Figure 26 (left), two infrastructural lines are running nearby but are not connected. The new link is tested at such location which connect these two lines as shown in Figure 26 (right). In such conditions, the tram can have an easy access to nearby infrastructure making the network more connected. In this third set of links, the existing links in the network which are currently not under operation are also tested for the benefit quantification.

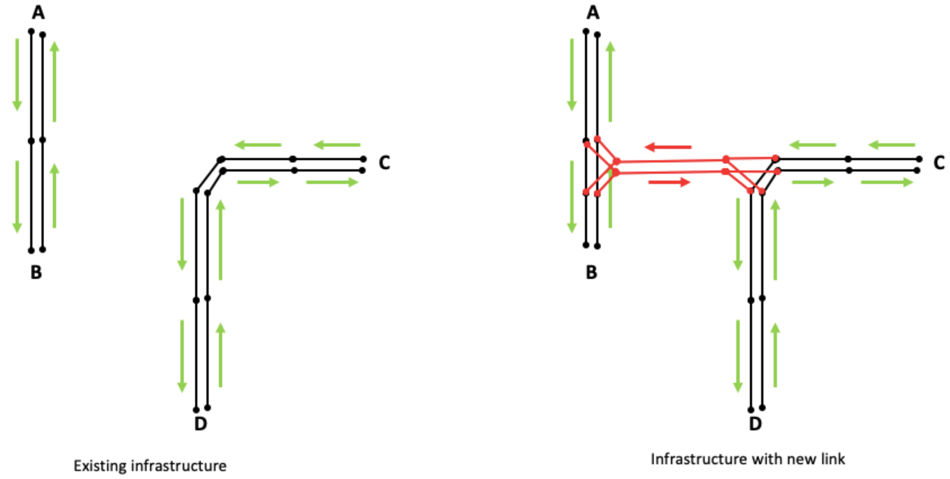

Figure 26 New links as line connectors

New link package generation for case study of Amsterdam tram network

For the case study of Amsterdam tram network, the location of the new links for all the three cases are identified manually. For the first case of completing the junction connector, in total, 13 such locations are identified and the new links to these junction connectors are proposed in such a way that allows trams to turn in all the directions where the tram tracks are leading. For the second case of proposing crossovers, since these crossovers can only be used by bi-directional trams for making a short turn, cross-over locations at every stops of line 5 and 25 are taken into consideration as these are the lines supplied with bi-directional trams between Amsterdam Zuid and Amstelveen. For new links connecting the existing lines running nearby, the Haarlemmer- Houttuinen of Amsterdam tram network is tested. The track Haarlemmer-

Houttuinen is between Amsterdam Centraal and Zoutkeetsgracht which has been placed years ago but it was never used before. This infrastructure currently exists but is not under operation. The second set of candidate links for this case is proposed at the Panama-Knoop connecting line number 26 and 7. The detailed location for the new infrastructure is given in the Table 8 and also illustrated in Figure 27.

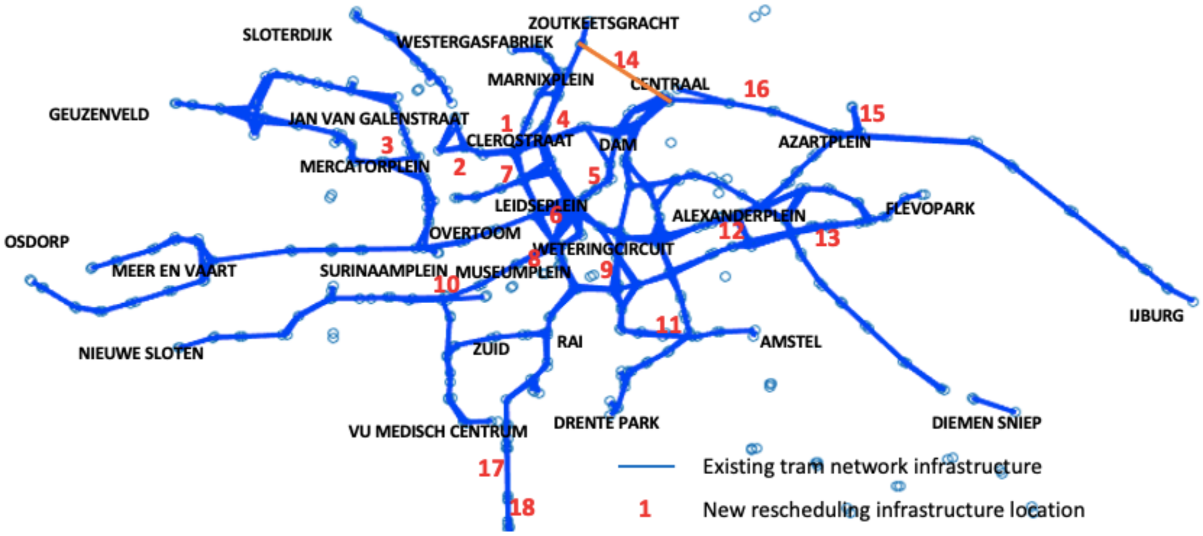

Figure 27 Locations of new rescheduling infrastructure

Table 8 New link packages (Amsterdam Tram network)

Type	S.No	Region	Direction	Combination
New links as Junction Connectors	1A	Fr. Hendrikst- de Clercqst.	SW-NW	A
	1B		NE-NW	B
	1C		SW-NW; NE-NW	A+B
	2A	W. de Withstr.- Kinkerst.- de Clercqst.	SW-NW	A
	2B		NE-NW	B
	2C		SW-NW; SE-NE	A+C
	2D		NE-NW; SE-NE	B+C
	2E		NE-NW; SE-NE; SW-NW	A+B+C
	3	Mercatorplein- Hoofdweg	SW-NW	
	4	Marnixst.- de Clercqst.	NE-NW	
	5A	Marnixst.- Leidsest.	NE-NW	A
	5B		SE-NE	B
	5C		NE-NW; SE-NE	A+B
	6	Stadhouderskade- Leidseplein	NW-SW	A
	7A	Bilderdijkst.- Kinkerst.	SW-NW	A
	7B		NE-SE	B
	7C		SW-NW; NE-SE	A+B
	8A	Paulus Potterst. – Van baerlest.	NW-NE	A
	8B		SW-SE	B
	8C		NW-NE; SW-SE	A+B
	9A	Gabriel Metsust.- Van Baerlest.	SE-NE	A
	9B		NW-NE	B
	9C	Albert Cuypst.- Ferdinand Bolst.	W-S	C
	9D	Albert Cuypst.- Ferdinand Bolst.- Van Baerlest.	SE-NE; W-S	A+C
	9E		NW-NE; W-S	B+C

	9F		SE-NE; NW-NE; W-S	A+B+C
	11	Churchill-laan- Rooseveltlaan	W-SW	A
	12A	S’Gravensandest.- Ruyschst.	W-N	A
	12B	Sarphatist.- Roeterst.-	N-E	B
	12C	S’Gravensandest.- Sarphatist	S-E	C
	12D	Sarphatist-Plantage Middenlaan	W-N	D
	12E		N-E	E
	12F		S-E	F
	12G	Ruyschst.- S’Gravensandest.- Sarphatist.-	W-N; S-E	A+C
	12H		W-N; S-E; W-N	A+C+D
	12I		N-E; W-N	B+D
	12J	Ruyschst.- S’Gravensandest.- Sarphatist.- Roeterst.- Plantage Middenlaan	W-N; N-E; S-E; W-N; N-E; S-E	A+B+C+D+E+F
	13	Linnaeusst. - Middenweg	S-E	A
New links as line connectors	14	Haarlemmer- Houtuinen	Connecting Centraalstation West with Zoutkeetsgracht	
	15	Panama Knoop	Connecting Fred Petterbaan with Piet Heinkade at Rietlandpark station	
	16	Ipta-lus	Turning loop at line 26	
Crossovers	17	Crossovers at stops of line 5		
	18	Crossovers at stops of line 25		

N- North; E- East; S- South; W- West; NE- North-East; SE- South-East; NW- North-West; SW- South-West.

The ‘direction’ column of the table shows the new links connecting the tram tracks bound to the given direction. For example: SW-NW link connects the tram tracks bound towards Southwest and Northwest direction at the junction. The ‘combination’ column of the table represents whether a single pair or multiple pair of new links are added to the network. If it is A, B or C, then single pair is added but if there is combination of A+B, two pair of links are added to the network.

These new link packages are input to the model whose benefits are quantified for every set of disruption in the network. The benefit quantification is elaborated in section 4.2.

4.2 Benefit quantification

This section of the report deals with the quantification of benefits due to the new link introduced in the network. In other words, the benefits for every identified new link (set of links) during the disruption is quantified. To quantify the benefits, the three major perspective of stakeholder is taken into consideration. These stakeholders are the passenger, the operator, and the society. The network design objectives as per discussed in (van Nes, 2015) and shown in Figure 28, travelers tend to minimize their travel cost, and travel time, operators aim is to enhance the production surplus by increasing the revenue and by optimizing the operational cost and society’s objective is to increase the social welfare.

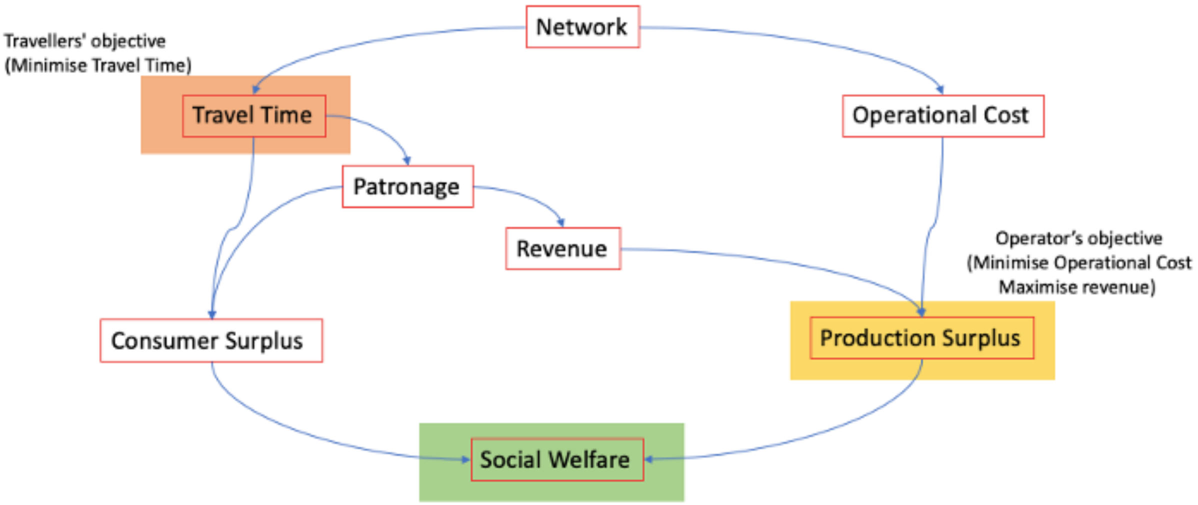

Figure 28 Network design objectives

For every new link package ‘p’ for which the benefits are to be quantified, consists of set of new links ‘e_n’ such that $e_n = \{e_1, e_2, \ldots e_k\}$ with their respective running time e_t^n, running distance e_d^n, and capacities e_c^n of the new links (which is also an input). As described in section 2.3 (part 1), the new link e consist of set of 2 node $\{s_s^n, s_e^n\}$ where s_s^n is the start node of new link and s_e^n is the end node of the new link. The network adjustment model adjusts the base network G^B and converts into new network (extended network) with the new links G^E. The new link redundancy is tested for every package of disrupted link as discussed in chapter 3. For every disruption, the model removes the links from the extended network G^E and gives the changed network G^{ED} which has the new links from the new link packages and the removed links from the disrupted link packages. To test the robustness value for every new link set, model does the supply side adjustment as elaborated in chapter 2 for all the disrupted link sets. In the next step, the passenger assignment to the changed lines are executed but to only those disruption set where there is changed supply side adjustment as compared to base case. Based on the recommended supply side adjustment, the benefits for passengers are drawn from the result of passenger assignment model and the benefits for the operators are derived from the supply side adjustment model. Generalized cost for passengers is taken as an indicator which quantifies the benefit for the passenger. For operator, production surplus is the indicator used to quantify the benefits which entails both operational cost and revenue. For societal perspective, the demand loss is used as a proxy for social welfare, which identifies the passengers shifting away from public transport due to disruptions (demand elasticity).

The robustness benefit of every set of new links in the network G^{ED} is derived by comparing the identified KPIs in the only disrupted case network G^D as shown in Figure 29. The whole process of network adjustment, supply side adjustment and passenger assignment is executed for the ‘only disrupted’ network G^D. For every ‘new link with disruption’ network G^{ED}, again the same process is executed but only for the affected disrupted link packages (with the disrupted links).

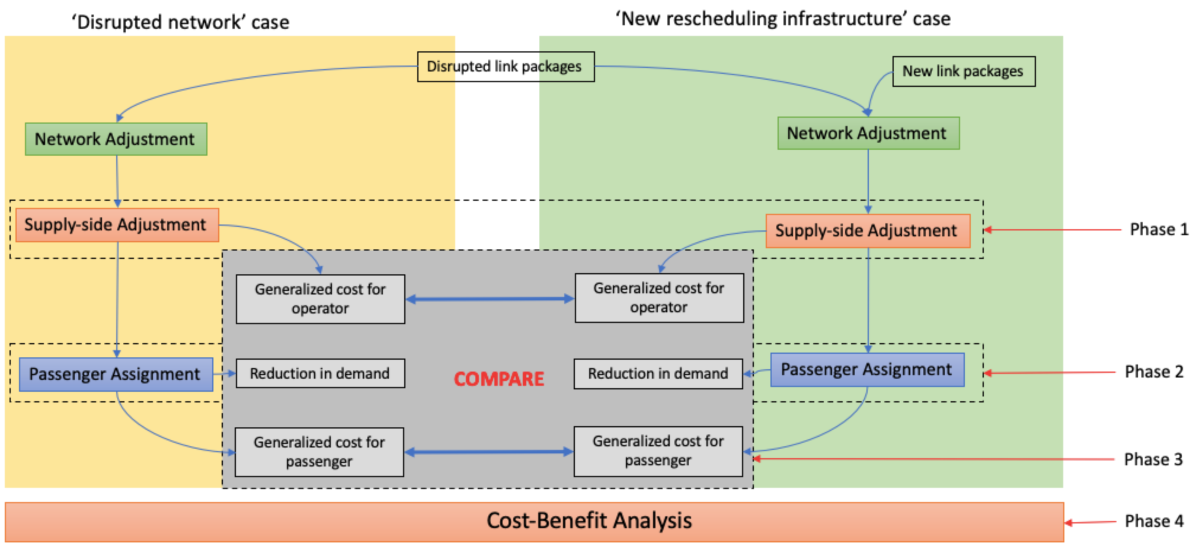

Figure 29 Flowchart to derive robustness value of a new link

Generalized cost for passengers

Generalized cost for passenger is taken as an indicator which caters generalized cost for travel time and generalized cost for travel distance. For both the 'only disrupted' network case and 'disrupted with new link' cases, for all the disrupted packages the generalized travel time and travel distance is calculated for the affected OD pairs due to disruption.

The travel time is converted into generalized travel time by multiplying the individual travel time components with their respective weights (as discussed in chapter 3). To include this generalized travel time for all the affected passengers, the demand for the affected OD pair (q_{ij}) is multiplied with the generalized travel time (GU_{ij}). This GU_{ij} entails the individual travel time components t_c with their respective weights β_c. To monetize the travel time into cost, Value of time (VoT) per hour is multiplied. Let GC_{Pass}^{TT} be the generalized cost for travel time of passengers, then

$$GC_{Pass}^{TT} = (\sum_i \sum_j \sum_{pk=1}^{pk=n} GU_{ijpk} * q_{ijpk}) * VoT$$

Where $GU_{ij} = \sum \beta_c t_c^{pk}$

To derive the benefits of new link, the generalized cost for travel time of passengers is calculated for both 'only disrupted' network N^D and for 'disrupted with new link' network N^{ED}. In the similar way as above, the net benefit for passenger for generalized cost for travel time would be $B_{passenger}^{TT}$ which is the difference between the cost calculated during the 'only disrupted' network case and 'disrupted with new link' case.

$$B_{passenger}^{TT} = GC_{Pass}^{TT,D} - GC_{Pass}^{TT,ED}$$

To convert the travel distance for every affected OD pair to generalized cost for travel distance, the demand per OD pair (q_{ij}) is multiplied with their individual travel distance s_{ij}. To monetize this value, average fare per km (ϕ) is multiplied with the term. Let GC_{P}^{TD} be the generalized cost for travel distance of passengers, then

$$GC_{Pass}^{TD} = (\sum_{i}\sum_{j}\sum_{pk=1}^{pk=n} s_{ijpk} * q_{ijpk}) * \varphi$$

In the similar way, the cost for travel distance of passengers is calculated for both 'only disrupted' network G^D and for 'disrupted with new link' network G^{ED}. Let $GC_P^{TD,D}$ be the generalized cost for travel time of passengers for the 'only disrupted' case and $GC_P^{TD,ED}$ be the generalized cost for travel time of passengers for 'disrupted with new link' case. The net benefit for passenger for generalized cost for travel time would be $B_{passenger}^{TD}$ which is the difference between the cost calculated during the 'only disrupted' network case and 'disrupted with new link' case.

$$B_{passenger}^{TD} = GC_{Pass}^{TD,D} - GC_{Pass}^{TD,ED}$$

The generalized cost due to travel distance is the redistributive value where the net benefit remains within the system as described by Pol et al., (2018). The generalized cost due to travel distance is the generalized fare that individual passenger is paying to the operator. This is the revenue part which is being generated if seen from operator's perspective. The new link introduced within the system affect the generalized cost for travel distance if seen from individual passenger's perspective, but the cost is being distributed to the operator. This is the distributive effect of benefits where holistically; the benefit remains within the system but distributed amongst different stakeholders.

Generalized cost for operator

The network design objective from an operator's perspective is to maximize the revenue through the services and to minimize the operational cost (increase the production surplus) as explained by van Nes (2015) and given in Figure 28. The revenue generated by the services is the fare collected from passengers using the service. Note that this is the distributive effect of the benefit where the net benefit remains zero.

For operational cost, the total length of all the transit service is considered. To monetize the same average operational expenditure per kilometer is multiplied with the total length of transit service. The changed transit service either due to disrupted link in the network G^D or due to the extended network with disrupted link G^{ED} is extracted from the supply side adjustment model. Amongst the two types of supply side adjustments (detour and short turn), the most beneficial transit service is considered as derived in chapter 3. Let the transit lines L^D be the set of lines when there exist 'only disruption' (where the network is G^D) and L^{ED} be the set of transit lines for the 'new link with disruption' G^{ED}. Let L^D consist of lines $\{l_1^D, l_2^D, \ldots l_n^D\}$ for the disrupted network N^D and L^{ED} consist of lines $\{l_1^{ED}, l_2^{ED}, \ldots l_n^{ED}\}$ for the disrupted with new link network N^{ED}. Let the travel distance associated with each transit line be 'd' such that d_1^D is the distance for the transit line l_1^D. Let the frequency associated with the individual transit line be 'f' such that f_1^D is frequency per hour for transit line l_1^D. let the operational cost per km be θ. The generalized operational cost for operator would be GC_O^{oc}

$$GC_{Op}^{oc} = (\sum_{i=1}^{i=n} f_i * l_i) * \theta$$

Where i=1 to i=n stands for all the transit lines in the set L and $l_i \in L^D$ for disrupted network G^D and $l_i \in L^{ED}$ for the disrupted network with new link G^{ED}. To quantify the benefit for a new link package $e_n \in P$, let $GC_O^{OC,ED}$ be the generalized operational cost for 'new link with disruption' network G^{ED}, $GC_o^{OC,D}$ be the generalized operational cost for 'only disrupted network' G^D and $GC_o^{OC,B}$ be the generalized operational cost for the base case with network G^B. If generalized cost for both 'new link with disruption' and 'only disrupted network' is higher than the base case, the benefit is the difference between them. If generalized cost of base case is higher than the 'only disrupted network' but lower than 'disrupted with new link' then the benefit is the difference between the generalized cost for 'disrupted with new link' and the base case. If GC of both 'only disrupted network' and 'new link with disruption' is lower than the GC of the base network, there is no benefit realized to the operator. The net benefit of the new link to the operator $B_{operator}$ would be

$$B_{operator} = \begin{cases} GC_{Op}^{OC,D} - GC_{Op}^{OC,ED} & \mathit{If}\ GC_{Op}^{OC,D}, GC_{Op}^{OC,ED} > GC_{Op}^{OC,B} \\ GC_{Op}^{OC,D} - GC_{Op}^{OC,B} & \mathit{If}\ GC_{Op}^{OC,D} > GC_{Op}^{OC,B} > GC_{Op}^{OC,ED} \\ 0 & \mathit{If}\ GC_{Op}^{OC,B} > GC_{Op}^{OC,B}, GC_{Op}^{OC,ED} \end{cases}$$

Societal cost

According to the network design objective, maximizing the social welfare is the ultimate objective which consists of minimizing passengers' travel time and maximizing operator revenue. To achieve this social welfare, reduction in demand loss due to the new link is taken as a proxy KPI for societal perspective. In other words, the robustness value of new link package according to the societal perspective is based on the reduction of demand loss due to the new link as compared to the 'only disrupted' case. For the case, the demand is assumed to be elastic based on the travel time. For example: if demand elasticity is -0.5, it means that for increase in journey time of 1% results in demand drop of 0.5%. More the increase in travel time, more the demand loss. To identify the reduction in demand loss due to the new link, the demand variations for both 'only disrupted network' case G^D and 'disrupted network with new link' case G^{ED} is compared with demand per OD in the original network G. Let for the case of 'only disrupted network 'the demand per OD pair be q_{ij}^D; for 'disrupted case with new link' be q_{ij}^{ED} and for base network N, the demand per OD pair be q_{ij}^N. This q_{ij} is affected by the generalized travel time between the OD pairs GU_{ij}. Let the coefficient of elasticity be γ. Then q_{ij} is proportional to $\gamma * t_{ij}$.

$$q_{ij} \propto \gamma * GU_{ij}$$

To identify the reduction in demand loss due to the new link for every disruption, the demand loss for both 'only disrupted' case and 'disrupted case with new link' is calculated which is the difference between their respective demands with the base case. Since q_{ij} is the only demand from origin i to destination j. For a network level, it needs to be summed up for all origins and destinations and for all the paths per OD pair. Let the demand loss due to only disruptions be q_{loss}^{D} . Then

$$q_{loss}^{D} = \sum_{i}\sum_{j}\sum_{pk=1}^{pk=n}(q_{ijpk} - q_{ijpk}^{D})$$

Let the demand loss due to the disruption with new link be q_{loss}^{ED}. Then

$$q_{loss}^{ED} = \sum_{i}\sum_{j}\sum_{pk=1}^{pk=n}(q_{ijpk} - q_{ijpk}^{ED})$$

The reduction in demand loss which gives the robustness value for the new link is the difference of their individual demand loss respectively. The redundancy of new link is tested for all the disrupted packages. Hence the reduction in demand loss is to be summed up for all the disruption cases. Let these cases be from d_1 to d_n. The reduction in demand loss for the new link is Q_{red}

$$q_{red} = \sum_{d=1}^{d=n}(q_{loss,d}^{D} - q_{loss,d}^{ED})$$

To monetize the demand regain due to the new link, an average fare per journey (σ) is multiplied to the demand regain. This is the monetized benefit to the society $B_{society}$

$$B_{operator} = q_{red} * \sigma$$

Deriving frequency of disruption

The robustness of new link is tested for every package of disruption. Since all the packages of disruption cannot be disrupted at a same time and disruptions cannot occur all the time, the frequency of disruption per disrupted package needs to be calculated. For this project, planned and unplanned disruptions are taken into consideration. The frequency of unplanned disruption as per given in Yap (2014) for the year 2013 for Rotterdam-Den Haag tram and metro network is 3120 disruptions per year and for planned disruption, the frequency is 6.24 disruptions per year. Considering Amsterdam's tram network length to be 60% of that of the tram and metro network length of Rotterdam-Den Haag together, a basic reduction of 40%

of the disruption frequency is considered for Amsterdam's tram network than Rotterdam-Den Haag's tram- metro network. Hence, for the case study, the unplanned disruption frequency is 2028 disruptions per year and for planned disruption, the frequency is 4.056 disruptions per year.

Since the model calculates the benefits for the PM peak period of 2 hours, the frequency of disruption should be reduced to the same time scale. Hence, the frequency for unplanned disruption is 0.67 disruptions per two hours and for planned disruption (2028 disruptions per year → 39 disruptions per week (52 weeks per yr) → 6 disruptions per day (assuming serving of 6.5 days per week) → 0.67 disruptions per 2 hrs (assuming service of 18 hours per day), the frequency is 0.0013 disruptions per hour. For the project, it is assumed that the frequency of any one of the disrupted links packages to get disrupted is same, the probability of a single package to get disrupted will be 1/229 as there are in total 229 disrupted link packages. Hence the frequency of any one of the disrupted link packages to ger disrupted for both unplanned and planned disruption get reduced to 0.002925 disruptions per 2 hours and 0.00005676 disruptions per 2 hours respectively.

Assuming that the duration of the planned disruption lasts for 2 week and durations of unplanned disruption lasts for average of 1 hour. Projecting the frequency of the disruption based on the duration for both planned and unplanned disruptions which comes out to be 0.001462 for unplanned disruption and 0.006641 for planned disruptions. Summing up them the average fraction of the PM peak being disrupted for 2 hours is 0.004782. The calculations for deriving the frequency of disruption is shown in Table 9.

Table 9 Frequency of disruptions

Disruption types	**Rotterdam Den Haag**	**Amsterdam**				
	Per year	**Per year**	**Per 2 hours**	**Frequency per disruption package**	**Frequency per disruption package (with duration)**	**Sum**
Unplanned disruption	3120	2028	$6.7*10^{-1}$	$4.31*10^{-3}$	$1.46*10^{-3}$	$4.78*10^{-4}$
Planned Disruption	6.24	4.056	$1.3*10^{-3}$	$5.67*10^{-5}$	$3.32*10^{-4}$	

Benefit quantification of new rescheduling infrastructure for Amsterdam tram network

For the case study of Amsterdam tram network, amongst the identified new rescheduling infrastructure packages, 12 of the packages are tested in this project. After executing the plausible supply side solutions and the preferred solution amongst the identified supply side adjustments (as discussed in section 3.4) for the identified packages of disruptions, the new link as identified in section 4.1 and its robustness value is tested for every disruption. As shown in Figure 29, the whole process of network adjustment, transit adjustment and passenger assignment are carried out for both 'only disrupted' network and 'disrupted with new link' network. In the further step, as elaborated in the previous sub-sections, the generalized cost for passengers, generalized cost for operators and the demand loss for both the cases are derived. The following constants as shown in Table 10 are used for the case study.

Table 10 Constant values used for Amsterdam tram network

Entity	Constant	Value	Comment
Value to Time	VoT	€ 9.5 per hour	Average value of time for public transport as per suggested in Jong et al., (2019)
Coefficient of demand elasticity	γ	-0.99~-1.00	Increase in generalized journey time of 1% results in demand drop of 0.5% Yap M (2021)
Operational cost per hour	$\Theta_{\text{per hr}}$	€200 per hour	Average operational cost per hour as per GVB (2021)
Average fare per km	ϕ	€0.14 per km	Interview with Yap M (2021)
Average fare per journey	σ	€1.24 per journey	Interview with Yap M (2021)

As per (GVB, 2021), the operational cost per hour is €200. To convert the same to operational cost per km, an average speed of Amsterdam tram is assumed to be 25kmph which gives the operational cost per hour to be €8 (θ).

Using the values as per given in Table 10, the generalized cost for travel time and travel distance for the passengers for 'only disrupted' case and for 'disrupted case with new links' are calculated. The benefit for passengers every tested new link is derived as elaborated in the previous subsection. In the similar way, the generalized cost for operator is also calculated for both the cases and by comparing them, the benefit to the operator due to the new link is extracted. For societal benefits, the revenue generated due to demand regain is calculated which is the benefits to the operators. Considering the disruption frequency to be 4.78×10^{-4} for 2 hours evening peak period as calculated in Table 9, gives the benefits to passenger, operator and society for the tested new rescheduling infrastructures. These are the values for 2 hours.

Table 11 Benefit calculation for new link sets (Period of evening peak hour (2 hrs))

Entity	Symbol	1C	3	4	5C	6	7C	8C	9F	11	13	14	16
Monetized travel time benefit (in €)	$B^{TT}_{passenger}$	16.13	14.03	-11.96	30.25	17.12	18.72	15.0	-6.81	16.11	20.75	125.28	11.72
Monetized travel distance benefit (in €)	$B^{TD}_{passenger}$	34.00	33.81	25.37	33.94	34.02	34.10	34.02	33.50	34.00	34.01	33.99	34.16
Total benefit to passengers		50.13	47.84	13.41	64.19	51.14	52.82	49.02	25.19	50.11	54.76	159.28	45.88
Operational expenditure benefit (in €)	$B_{operator}$	64.01	57.90	49.69	61.17	55.92	52.21	54.05	65.94	55.15	49.69	50.82	53.52
Revenue loss to operator (in €)		-34.00	-33.81	-25.37	-33.94	-34.02	-34.01	-34.02	-33.5	-34.00	-34.01	-33.99	-34.16
Total benefit to operator		30.01	24.09	24.32	27.23	21.90	18.2	20.03	32.44	21.15	15.68	16.83	19.36
Revenue due to demand regain (in €)	$B_{operator}$	4.52	5.64	-4.31	5.73	5.62	5.64	5.64	5.61	5.64	5.68	6.32	5.63
Total benefit (in €)		80.15	71.94	37.74	91.41	73.04	70.93	69.06	59.12	71.26	70.44	176.11	65.244

Note that the calculated figures for monetized travel time benefit, monetized travel distance benefit, operational expenditure benefit and the reduction in demand is only for the evening peak hour data which is of 2 hours. For further comparing the benefits to the cost of infrastructure, the figures must be pulled up to one day and further to a year which is done in the subsequent chapter. Note that the revenue loss to the operators is nothing but the distributive benefit which cancels out with the monetized travel distance benefit.

Benefit of new rescheduling link package 6 (junction of Stadshouderskade and Leidseplein) for a disrupted link between Overtoom and Van Baerlestraat

This section elaborates on the benefit of new rescheduling link package 6 for a disrupted link between Overtoom and Van Baerlestraat as an example for the case study. For the case study, the link between Overtoom and Baerlestraat of the Amsterdam tram network is disrupted. The benefits of the new link package 6 which connects the Overtoom with Rijskmuseum at the Stadshouderskade and Leidseplein junction as illustrated in Figure 30.

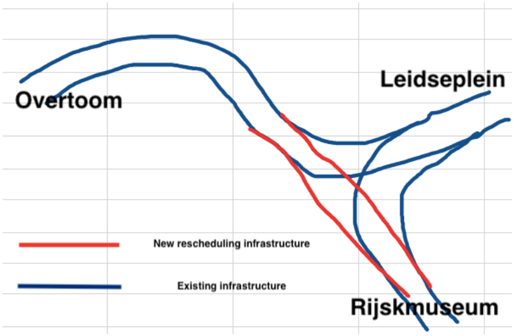

Figure 30 New rescheduling link package 6

For the base case (without the new rescheduling infrastructure), the model first searches and finds out that the tram line 3 which runs from Westergasfabriek to Flevopark is disrupted due to the disrupted segment. The Figure 31 shows the route of tram line 3 and the location of the disruption. As elaborated in Chapter 2, for this disrupted tram line 3, the plausible candidate solution for short turn and detour is derived which is shown in Figure 32 and Figure 33.

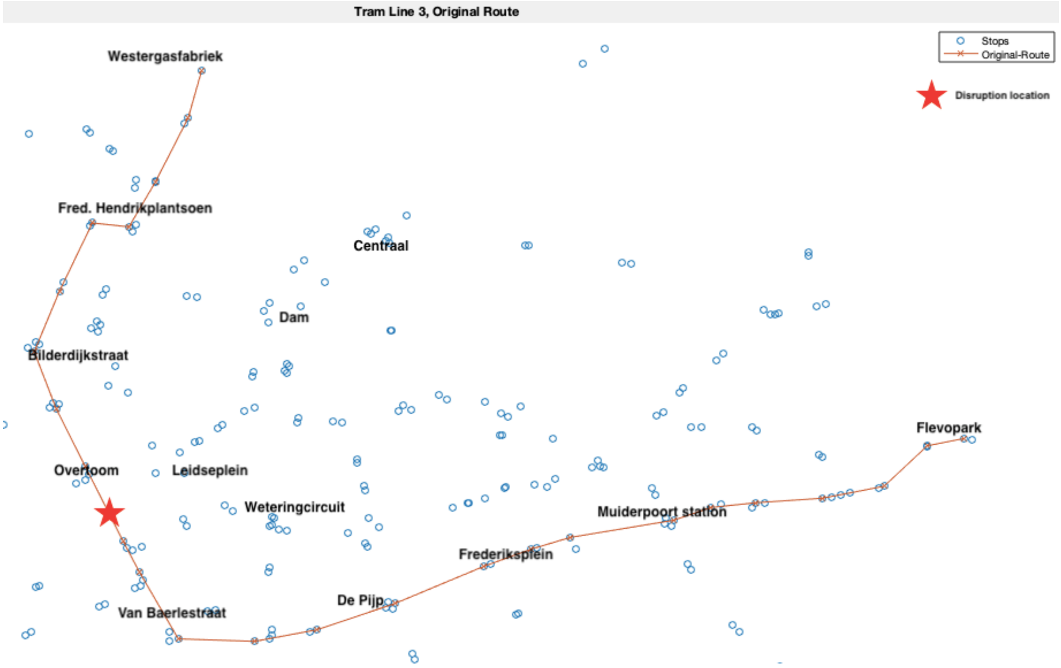

Figure 31 Disrupted tram line 3

For short-turn, from Westergasfabriek end, the tram line runs till Overtoom and turns left on Leidseplein and from Elandsgracht, it again turns left to Bilderdijkstraat back to its downstream route (Wetergasfabriek→ Overtoom→ Leidseplein→ Elandsgracht→ Bilderdijkstraat→Westergasfabriek). From Flevopark end, the tram line runs till Van Bearlestraat and turns right towards Leidseplein. At Leidseplein, it again turns right to Weteringcircuit and towards Pijp. (Flevopark→ Van Bearlestraat→ Leidseplein→ Weteringcircuit→ Pijp→ Flevopark).

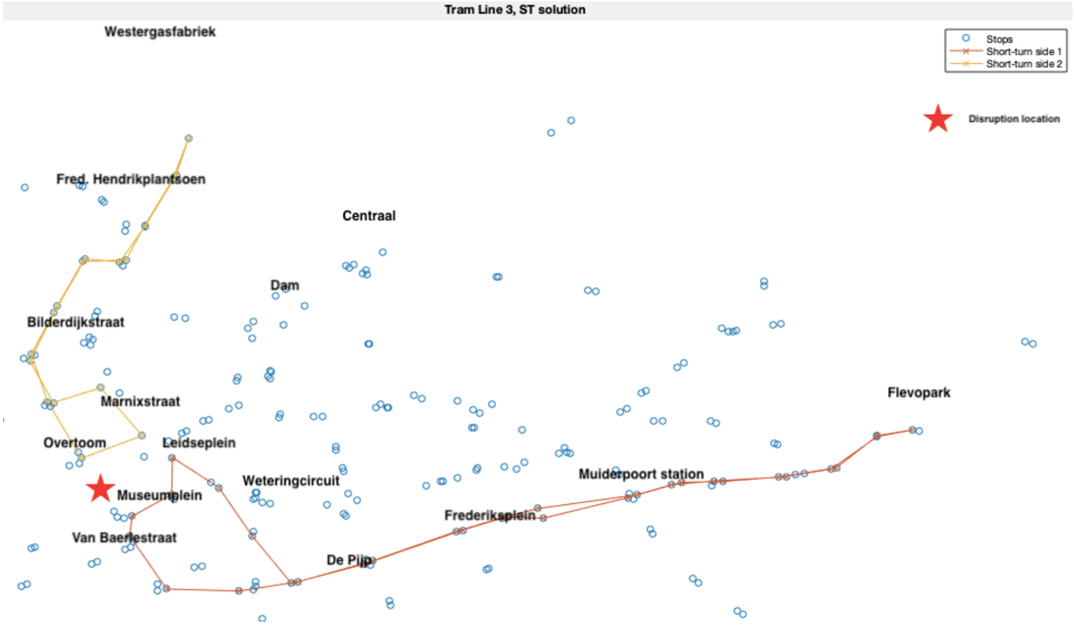

Figure 32 ST solution for disrupted tram line 3

For detour candidate solution, from Flevopark side, the transit line exits the original route at Van Baerlestraat, takes the route via Leidseplein, Elandsgracht and joins the original route at Bilderdijkstraat. (Flevopark→ Van Baerlestraat→ Leidseplein→ Elandsgracht→ Bilderdijkstraat→ Westergasfabriek).

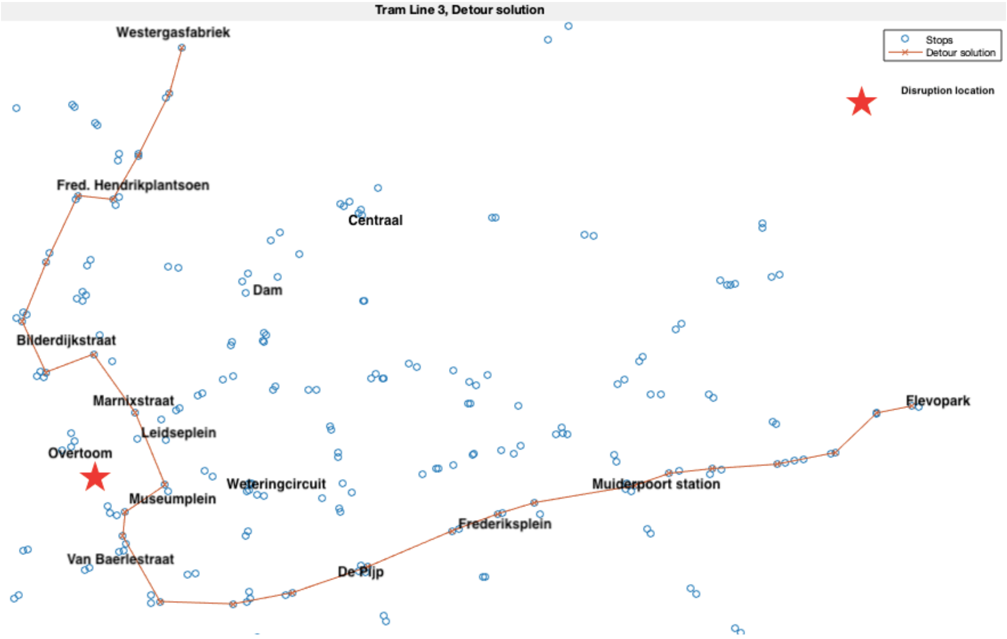

Figure 33 Detour solution for disrupted tram line 3

After the passenger assignment to these two-candidate solution, the disutility for both short turn and detour is derived for the affected OD pairs. The disutilities are shown in Table 12. Since, the disutility due to detour is lower than that of short turn, the detour solution is preferred.

Table 12 Disutility due to short turn and detour

Disutility (for affected OD pairs)	
Disutility due to short turn	$1.2968*10^4$
Disutility due to detour	$8.8470*10^3$

For the scenario 2, the new rescheduling infrastructure (at the junction of Stadshoudskade and Leisdeplein) is introduced in the network. The model regenerates the candidate solution for detour as shown in Figure 34. Due to the new rescheduling link, instead of turning right at the junction of Stadshoudskade and Leisdeplein towards Leidseplein, the tram continues straight directly to Overtoom to its original route. It escapes the higher detour (which was from Eladsgracht to Bilderdijkstraat) and joins the original route directly at Overtoom because of the new rescheduling infrastructure. The new detour solution is Flevopark→ Van Baerlestraat→ Rijskmuseum→ Overtoom→ Westergasfabriek.

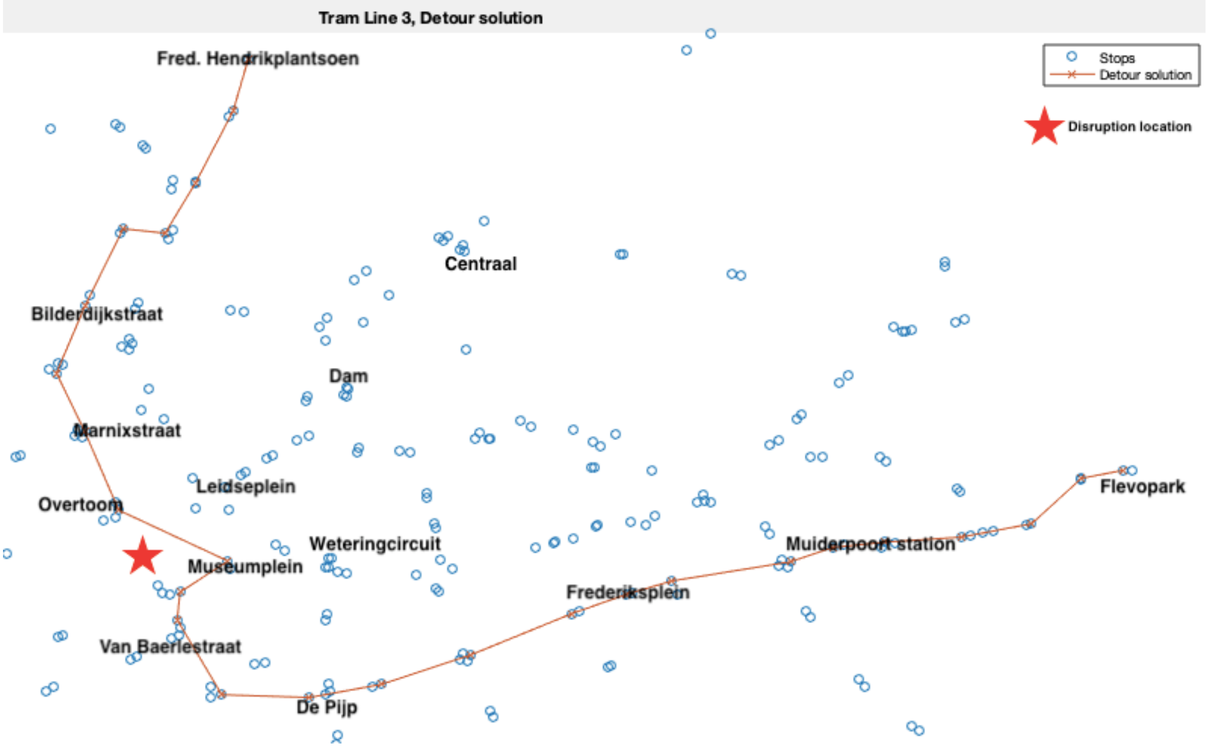

Figure 34 Detour solution for disrupted tram line 3 with new rescheduling link

The Table 13 shows the KPI values for scenario 1 (only disrupted link) and scenario 2 (disrupted link with new rescheduling infrastructure package 6). These values are for a time period of 2 hours PM peak. In scenario 2, there has been reduction in the values of the KPIs. For passengers' perspective, both generalized travel time and generalized travel cost is reduced. For operator's perspective, there is reduction in operational cost of 26 euros. Also, the demand loss in scenario 2 is less than that of scenario 1.

Table 13 KPI comparison for scenario 1 and scenario 2

KPIs (for affected ODs)	**Scenario 1 (only disrupted link)**	**Scenario 2 (disrupted with new rescheduling link)**
Generalized Travel time	152.66	148.85
Generalized Travel distance	1.258	1.015
Operational cost	1058	1032
Demand loss	1.467	0.982

Chapter 5: Evaluation of robustness value

In the previous chapter, the benefits of the new link packages to the passengers, operator and the society are calculated. In this chapter, the worthiness of the new link is derived. In other words, the benefits due to the new link is analyzed with their respective costs by assessing through the societal Cost Benefit Analysis (CBA). The chapter starts with providing an overview of the of CBA in section 5.1. Section 5.2 deals with the cost benefit analysis for the identified new link packages.

5.1 Cost-Benefit Analysis

The purpose of cost-benefit analysis (CBA) is to make an informed decision to estimate the benefits and cost and to determine the worthiness of a decision as discussed by Pol et al. (2018) and Wilbrink (2018). CBA is done to estimate the viability of an investment in a project or to compare two similar projects and determine the most feasible investment. CBA is the most common used instrument for transport infrastructure investments (Mouter, 2018). Certain input parameters are required to execute a CBA. These include the temporal extent of the cost benefit analysis, the costing of the project/ infrastructure, the discount rate and type of CBA required to assess the project.

Different methods of CBA

As per (Mutairi, 2017) the different methods to assess CBA could be categorized into the following:

Benefit Cost Ratio (BCR)

It is the ratio of benefits of the project/investment to its cost. The total discounted benefit is summed for the whole time series and it is divided by the total discounted cost of the project. Let BCR be the benefit cost ratio, then

$$BCR = \frac{\sum_{i=1}^{i=n} B_i / (1+d)^i}{\sum_{i=1}^{i=n} C_i / (1+d)^i}$$

Where B_i is the benefit gained due to the investment during year 'i' and C_i is the cost incurred for the investment for year 'i'. 'd' is the discounted rate which is explained in the subsequent section. If BCR<1, it means that the cost exceeds the benefits, and the project is less viable. If BCR=1, then the investment could be worth but with less viability and if BCR>1, then benefits exceed the cost and the investment in the project is viable.

Incremental Benefit Cost Ratio

This method gives the insight to compare investments in multiple different projects. It determines the marginal value by which a project is beneficial or costly than the other project. The difference of the benefits is compared with the difference of their costs.

$$Incremental\ BCR = \frac{\sum_{i=1}^{i=n} B_i^1 - \sum_{i=1}^{i=n} B_i^2}{\sum_{i=1}^{i=n} C_i^1 - \sum_{i=1}^{i=n} C_i^2}$$

B^1 and B^2 are the benefits of the project 1 and project 2 respectively and C^1, and C^2 are their respective costs.

Net Present Value

The Net Present Value calculates the difference between the discounted benefits of an investment to it discounted cost. It gives an absolute value where if the NPV is positive the project is worth investing. Higher the value, more it is viable.

$$NPV = \sum_{i=1}^{i=n} {B_i}/{(1+d)^i} - \sum_{i=1}^{i=n} {C_i}/{(1+d)^i}$$

Here, B_i is the benefit gained due to the investment during year ‘i’ and C_i is the cost incurred for the investment for year ‘i’.

Payback Period

It is a time period required for the total discounted benefits to surpass the total discounted cost. It could be achieved by calculating the cumulative discounted benefits per year and cumulative discounted cost per year. The year at which the discounted benefits surpass the cost, it is the payback period.

Discounted rate for cost and benefits

The present value of money or goods is not the same for how much it is valued in the future years. According to Mutairi (2017) and Pol et al. (2018), the future benefit and cost of a project is less valued. To incorporate the same in the cost benefit analysis, a discounted rate is assumed which reduced the current value to suit the future years. The discounted rate anticipate the cost and benefit of a project for future years. If the discount rate is low, the value for benefits and cost in future years remain high (more or less near to the present value). If the discount rate is high, the decrease of value per year is high and the benefits and costs in the future years would be valued less.

5.2 Methodology to evaluate robustness of new link through CBA

The very first step of CBA is to decide the temporal scale/time horizon of CBA to be performed. After deciding the temporal scale, the next step is to annualize the values. For example: if the assessed benefits are for 1 hour, it needs to be pull up to 1 day→ 1 week→ 1year and so does the cost of the investment should also have the same time scale. The next step is to decide the method to assess the CBA as described in the previous sub-section. After opting for the appropriate method, the discounted rate needs to be decided which helps in projecting the proper value of benefits and costs in the future year. The variables which are subject to change with respect to time needs to be projected to the timescale of the CBA. For example: if population is used to quantify the benefits for a project, then the population should be projected meeting the timescale of the CBA. The overview of the checkpoints to evaluate an investment through CBA is given in Figure 35.

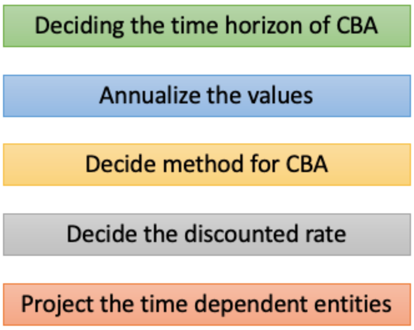

Figure 35 Methodology for CBA

Time horizon of CBA

The new links in the network infrastructure for this project is either a crossover, a junction connector or a total new link connecting two different transit lines nearby as discussed in section 4.1. Since the lifespan of these infrastructure as recommended by GVB- Amsterdam is between 30-40 years (GVB, 2021), the time horizon for the new links to assess the Cost benefit analysis is decided to be of 30 years. Deciding the time horizon to be of 30 years also help to decide the discounted rate.

Discounted rate for CBA

The discounted rate assesses the depreciation of value with respect to time. As per the study done by Mouter (2018) which analyzes the discounting policies by various countries (Northern European countries) by interviewing the experts from academia, consultant and policy maker background, the result highlights the following discounting policy outcomes:

- Higher the discount rate, high the risk adjustment to the depreciating value would be. Hence the Dutch Discount Rate Working Group suggests the discount rate of 4.5% for physical infrastructural projects to incorporate higher risks. Incorporating higher discount rate in a project also considers the fluctuations which is riskier in economic terms.

- The UK practice green book suggests and establishes a declining discount rate with respect to time which is based on consumption behavior approach. The green book of UK suggests the discount rate of 3.5 % for a 0-30 years of time horizon of CBA; 3% for 31-75 years and 2.5% for 76-125 years.
- The Norway's discounting rate policy also works on the declining rate with respect to time, but their time span is bigger than that of UK's green book suggestion. They suggest a risk-free discount rate of 2.5% for first 40 years followed by 2% for the next years.
- The Swedish ASEK guidelines suggest that a constant discount rate of 4% without the declining rate with respect to the time horizon.
- The discount rate as determined by the Ministry of Finance in Denmark suggests the declining discount rate with respect to the time horizon of the CBA. It suggests a discount rate of 4 % for the first 35 years, 3 % for 35-70 years and 2 % for CBA time horizon of more than 70 years.

The following Table 14 gives the overview of discount rate suggested by various countries as per discussed in Mouter (2018).

Table 14 Discount rate for CBA by different countries

Country	Discount rate	Time-horizon	Comments
Netherlands	4.5%	Constant time	Incorporating higher risk. More pragmatic than theoretical. Determined by Dutch discount rate working group
United Kingdom	3.5%	0-30 years	Declining discount rate with time. Consumption behavior approach. Determined by Green Book
	3%	31-75 years	
	2.5%	76-125 years	
Norway	2.5%	0-40 years	Risk free discount rate,
	2%	40 years +	
Sweden	4%	Constant time	Based on Ramsay model
Denmark	4%	0-35 years	Determined by Ministry of Finance
	3%	35-70 years	
	2%	70 years+	

In this study, by assessing through the discounting rate figures for various countries as given in Table 14, the discounting rate of 4% is used which is the average discount rate as suggested by various organizations of North-Western European countries. It means that the value of cost and benefit every year would have a decline of 4% as compared to the previous year's value.

Method to assess CBA

Since the project aims to identify such new links which increases the robustness of the tram network of Amsterdam and it also gives the priority of the investment based on CBA, the absolute value of the analysis is required which can be achieved by calculating the Net Present Value (NPV). As described earlier, it calculates the difference between the discounted benefits and discounted costs, the absolute values could be used to suggest the priority of the investment. Higher the NPV, higher the benefits.

Annualization

Since the data regarding the demand from every origin to every destination is for the evening peak hour from 1600 hours to 1800 hours (PM peak), it needed to be scaled up to one day. Assuming a thumb rule that the evening peak hour demand caters for 20% of daily ridership (TfL, London's Strategic transport models, 2018), the parameters having demand within it ought to be scaled up by 5 (20% scaled up by 5 to reach 100%) to get the values for a day. Thus, the values $B^{TT}_{passenger}$, and $B^{TD}_{passenger}$ derived in section 4.2 is multiplied with 5 to get the values for one day. Also, the demand loss (Q_{red}) must also be scaled up by 5.

For scaling up the transit lines, the benefits quantified for operator's perspective is for 2 hours. Since the tram service tentatively start around 0600 hours and runs until mid-night, the total hour of run is 18. Hence the benefits quantified for operators must be scaled up by 9. Thus, the value $B_{operator}$ is multiplied with 9 to get the values for one day. It is assumed here that the frequency of tram lines remains constant for the whole 18 hours period. This might over-estimate the values.

For scaling up to a week, to incorporate the weekly variations on demand pattern and for the supply side (For example: less demand during Sundays as compared to other days and less frequent transit service) a 6.5 multiplier is used. Scaling up to a year, the monthly variations and seasonal variations are not taken into consideration. A direct multiplier of 52 is considered (52 weeks in a year). The scaled-up values for the benefits are given in Table 18.

Infrastructural costing

In this project, the purchase cost for new infrastructure as suggested by GVB (2021) is taken into consideration. The suggested values are the approximate cost for the infrastructure which vary depending upon the location, turning radius of infrastructure and other parameters. More detailed cost estimation would account for more promising figures for cost benefit analysis. The costs for the infrastructure are shown in Table 15.

Table 15 Costs for new infrastructure

New Infrastructure	Cost (in euros)
Double track junction connector	2 million
Crossover	0.6 million
Turning loop	1.8 million
Single track Junction connector (left turning)	1.2 million
Single track junction connector (right turning)	0.8 million

For the project, there exist some modified cases for new infrastructure. For example: the existing tram infrastructure between the Haarlemmer- Houttuinen which is currently not under operation. Another example could be the reactivating the turning loop at Muziekgebouw Bimhuis. For such cases, based on the suggested costs for tram infrastructure by GVB, we estimated these costs as shown in Table 16.

Table 16 Cost of new infrastructure

New Infrastructure	Cost (in euros)
Infrastructure between Haarlemmer Houttuinen	12 million
Reactivating the turning loop at Muziekgebouw Bimhuis	1.5 million
New link at Panama Knoop	3 million

A general thumb rule of maintenance cost for maintaining the new infrastructure is also taken into consideration. As per mentioned by Trommelen et al. (2020), an average maintenance cost for a life span of 13 years infrastructure is 10% of the purchase cost. Considering the same ratio, the total maintenance cost per year for the project is considered as 0.77% per year of purchase cost and equally distributed across all years.

Demand Projection

The overall passengers per year as per given in GVB (2020) providing a year overview of 2019 is extrapolated to year 2051 by using the time series analysis of previous 5 years (from 2015 till 2019). In the coming decades, it is expected that the population is going to expand. This accounts for more passengers availing the public transport services provided by GVB. An average increment of percent of passengers is considered and the total passengers till 2051 is projected. **Error! Reference source not found.** shows the passengers per year travelling on t he entire GVB network which includes tram, bus, train, and boats.

Table 17 Passengers per year travelling on GVB network

Year	**2015**	**2016**	**2017**	**2018**	**2019**
Passengers (in million)	16.8	21.0	23.3	24.3	22.4

To project the given data, the data has been smoothened with single exponential smoothing and using the same logic, it is being forecasted till 2051. The projected passenger demand data is given in appendix. The Figure 36 represents the passenger forecasting through exponential smoothing. The final passenger demand data in 2051 is 27.02 million passengers which is used for the projecting the values of $B_{passenger}^{TT}$ and $B_{passenger}^{TD}$. The average annual passenger growth according to the single exponential smoothening method comes out to be 0.5%.

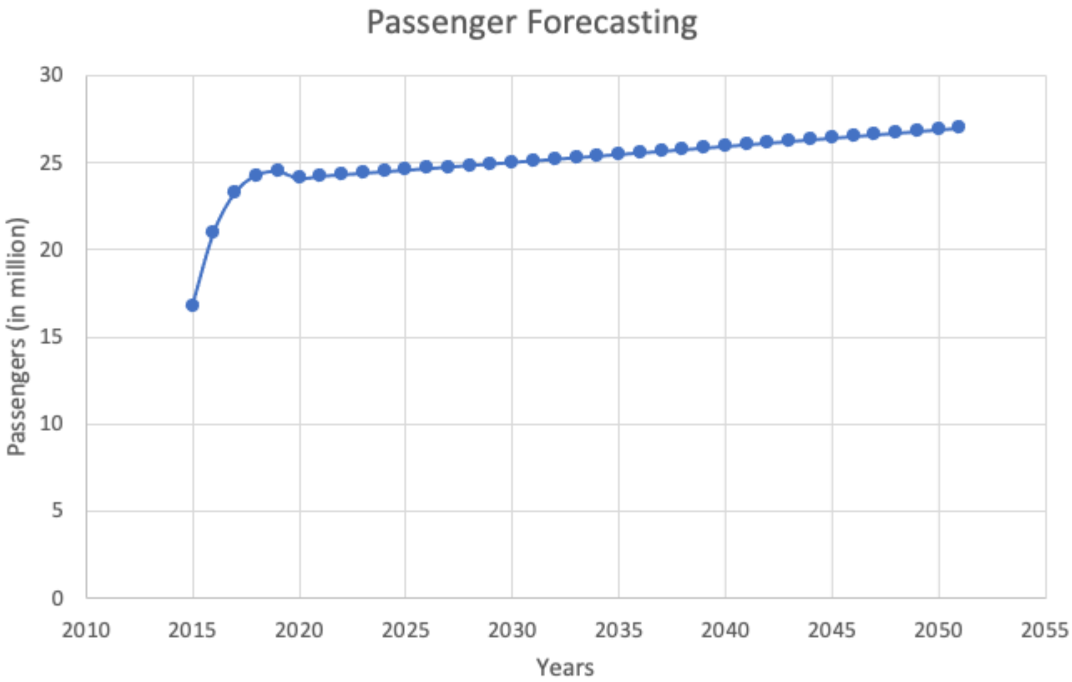

Figure 36 Passenger forecasting through exponential smoothening

5.3 Result analysis

As per the methodology described in section 5.2, the benefits are first annualized for the current year of 2021. In the next step, for every new link package, the benefits and the costs are projected till 2051 with their discounting rate. The annualized benefits for all the stakeholders for year 2021 is shown in Table 18.

Table 18 Cost and Benefits for year 2021

New-Link Package		**1 C**	**3**	**4**	**5C**	**6**	**7C**	**8C**	**9F**	**11**	**13**	**14**	**16**
Cost (in *10^3 Euros)	**Purchase Cost**	4000	2000	2000	4000	2000	4000	4000	6000	2000	2000	7000	4000
	Maintenance cost	30.8	15.4	15.4	30.8	15.4	30.8	30.8	46.2	15.4	15.4	53.9	30.8
Total Cost		4030.8	2015.4	2015.4	4030.8	2015.4	4030.8	4030.8	6046.2	2015.4	2015.4	7053.9	4030.8
Benefits (Passenger) (in *10^3 Euros)	**Monetized travel time**	27.26	23.72	-20.21	51.12	28.936	31.631	25.36	-11.52	27.23	35.06	211.72	19.81
	Monetized travel distance	57.47	57.14	42.88	57.37	57.50	57.62	57.50	56.61	57.47	57.49	57.45	56.68
Benefits (Operator) (in *10^3 Euros)	**Operational expenditure**	194.73	176.14	151.18	186.06	170.12	158.84	164.44	200.60	167.77	151.17	154.61	162.82
Benefits (Society) (in *10^3 Euros)	**Revenue due to demand regain**	7.650	9.537	-7.290	9.684	9.509	9.529	9.528	9.493	9.537	9.609	10.69	9.517
Total Benefits		229.65	209.40	123.68	246.87	208.56	200.00	199.33	198.57	204.54	195.84	377.04	192.13

The net present value for the current year 2021 for every new link package is unsurprisingly negative as the purchase cost at the starting of the timeline contributes to the maximum portion of expenditure. In the remaining years, the maintenance cost is only the expenditure whereas, the benefits every year is accumulated to the previous one. The slope of benefit for a new infrastructure is higher than the slope of its costs. The cost-benefits graph for different link packages over the time of 30 years is give in Appendix 2.

Comparing the different NPVs for different new link packages

This section discusses the NPV graph for different new link packages over the time period of 30 years. The graph shows the difference between the total cost to the total benefits per year which is the net present value of the investment. It is also used to get insight when at what point of time the investment is beneficial. In other words, at which year, the benefits outweigh the cost of investment. As soon as the NPV value is positive, it is worth to invest in a project.

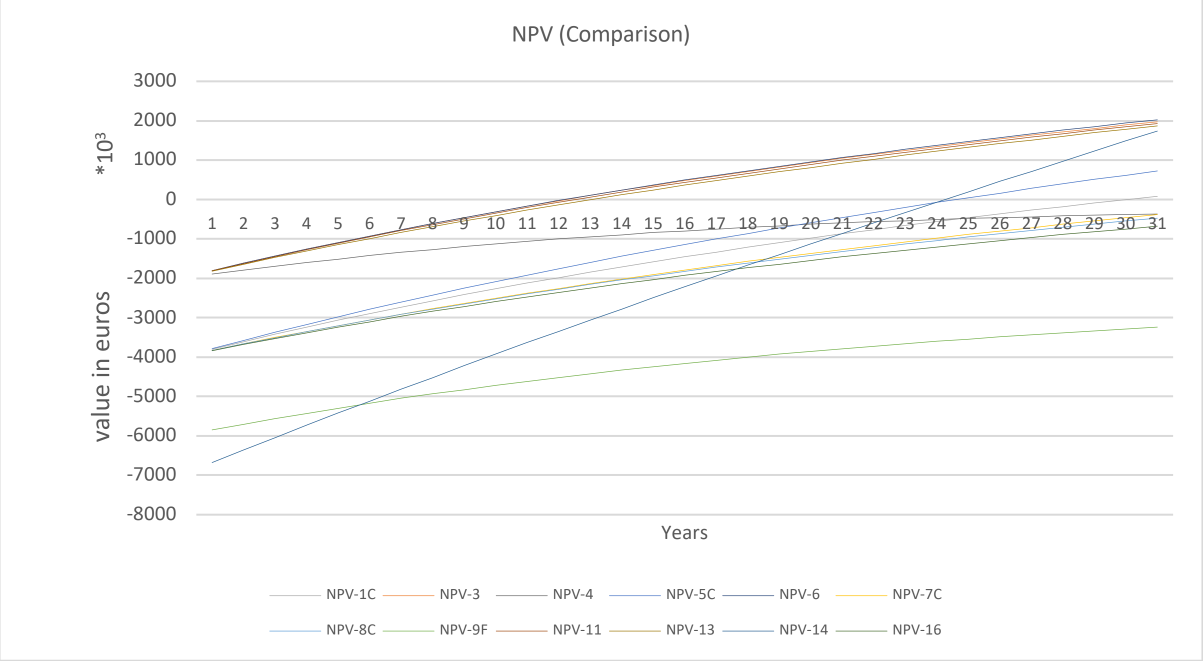

Figure 37 Net Present Value comparison

From the Figure 37, the new link packages 6, 3, 11 and 13 have the highest net present value at the end of year 2051 which is which lies between 1800*10^3 – 2000*10^3 euros. These 4 new rescheduling link packages are worth investing as they extract the highest benefit at the end of 2051. Amongst these 4 packages, package number 6, which is the set of links connecting Stadhouderskade and Leidseplein ranks 1 with NPV value of 2,022*10^3 euros. The figures for link package 6 make sense as the set of links in package 6 is located at the central part of Amsterdam tram network which gives possibility of better rescheduling infrastructure to the transit lines in the vicinity such as line 1, line 3, line 5 and line 6 during various disruptions.

The Table 19 gives an overview of NPV values for different set of link packages at the end of year 2051.

Table 19 NPV values for different link packages

Link Package Set	NPV value at the end of year 2051 (in *10^3 Euros)	Payback Year	Rank
6	2,022	2033	1
3	1,971	2033	2

11	1,927	2033	3
13	1,868	2034	4
14	1,737	2045	5
5C	725	2045	6
1C	81	2050	7
4	-368	--	8
7C	-381	--	9
8C	-473	--	10
16	-676	--	11
9F	-3,238	--	12

The payback period is the time required for the total discounted benefits surpass the total discounted cost. The earliest payback period is for new link packages 6, 3 and 11, followed by 13, 14, 5C and 1C. For packages 4, 7C, 8C, 16 and 9F, since the benefits does not outweigh the cost of investment on the timeline of 30 years, there is no payback period.

From the Figure 37, it is worth to note that the slope of NPV-14 (Haarlemmeer- Houttuinnen link) is steeper than the NPV graph of the rest of the new rescheduling link packages. This shows that on a long run, the NPV value of link package 14 would cross the rest of the new link packages.

From the graph, it can be seen that the benefits from the new link packages (Link package 6, 3, 11 and 13) with only one set of junction connector outweighs the cost earlier than the one with more than one set of junction connectors (Link package 5C, 1C, 7C, 8C and 9F). This is because the cost of investment due to multiple link connectors in link packages 1C, 5C, 7C, 8C and 9F is higher than link packages of 6, 3, 11 and 13 which only have a single set of connectors. It is worth to note that at one incomplete junction with multiple possibilities of the new link sets to be connected, it is high worth investing to only one of the set of link connector than all of them as the summed up benefits for multiple set of link connectors barely outweighs the extra cost of investment.

Chapter 6: Conclusion and Recommendations

In this chapter, the conclusion of the study is formulated which is elaborated in section 6.1. The second section of the chapter discusses the policy implications for the research project, and the last section of the chapter details out the recommendation for the improving the methodology and for further research.

6.1 Conclusions

The following research question is formulated for the project which can be answered in this section.

What method can be developed to determine the optimal locations of a new rescheduling infrastructure in a public transport network that maximizes its robustness value against disruptions?

A model structure is developed in this study as shown in Figure 38, which tests the robustness against disruptions of new links at different locations in the network infrastructure based on the benefits to various stakeholders. The methodology developed in this study first assesses the disruption scenarios at different locations. In the disrupted scenario assessment, it develops the method to change the network structure and the transit adjustments are modelled based on the changed network which are namely short-turn and detour. Out of these two transit adjustments, the most beneficial transit adjustment is identified for every location of disruption. Passengers are assigned to the changed transit lines and the parameters for the benefit calculation is extracted. The same steps are repeated for the identified candidate new rescheduling infrastructure links in the network and the parameters (KPIs) are compared to the disrupted scenarios using cost benefit analysis. The study is divided into the following phase which answers the sub-questions

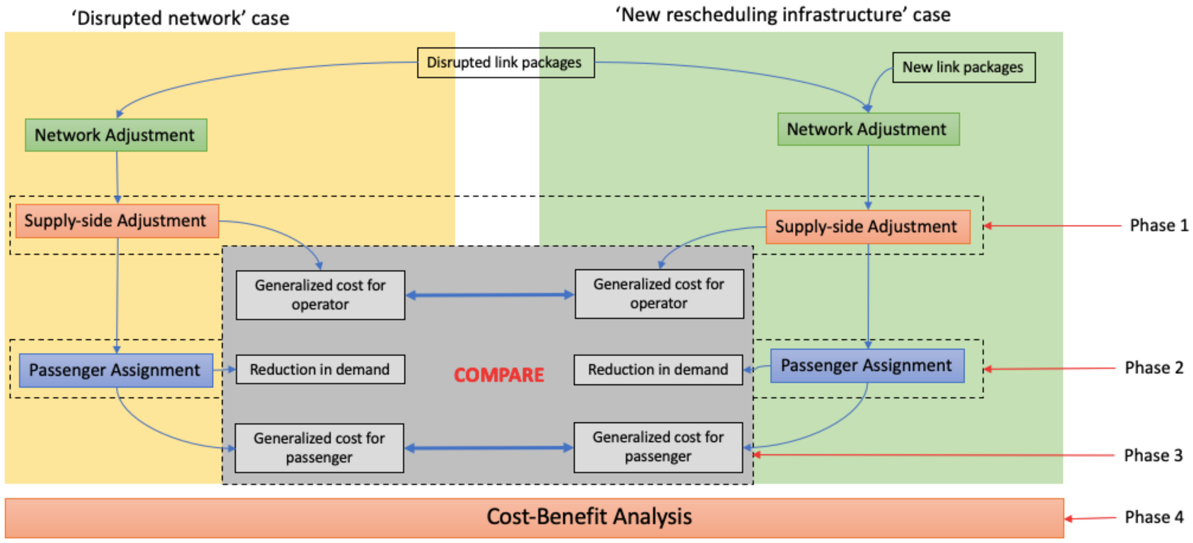

Figure 38 Research project flowchart

Phase 1: Modelling the candidate solution for transit adjustment
Phase 1 of the project answers the sub question 1, which is as follows:

1. **What method can determine the plausible supply side adjustments for a given disruption?**

The objective of phase 1 is to identify the plausible supply side adjustments during a disruption. These adjustments are plausible short-turns and detours for a disruption. A method is developed in MatLAB which updates the network and its related components (such as travel time, travel distance and link capacity) when a link is removed/ added to the network. Due to the changes in network, the transit adjustments are modelled. The short turn and detour candidate solutions are created by using Dijkstra's shortest path algorithm. The following conclusions from the first phase of model can be formulated:

- Modeling the new transit line solutions to the disruption is done by sticking to the original route to the maximum possible extent. The short turn candidate solution covers the maximum extent of the original transit service till the disrupted segment and finds a way back to its origin. The detour candidate solution for a disruption too runs to the maximum possible original route and finds out detour option to join the original route down the disruption.

- In the adjustments, candidate solution for short turn and detour are created considering various bounds to extra travel time, extra travel distance, number of stops served by the new adjustment etc.

- The candidate solution generated for every disruption not necessarily contains both short turn and detour solution. Most of the candidate solutions are filtered due to the filtering criteria of travel time, travel distance and number of stops.

- The extra travel time bound, and extra travel distance bound to the new transit line solution is decided to be 0.4 for both. This means that the new transit line is allowed to have a flexibility of 40% of extra travel time and travel distance than the original travel time and travel distance. The decision of 40% of extra travel time and travel distance is calibrated by running various combination and the judging the plausible transit solutions based on these combinations.

- The result is an algorithm which can automatically determine the most plausible short-turning and detour alternative for a given disruption and a public transport network. This algorithm is successfully applied to Amsterdam tram network and for the modelled disruptions. For example, consider a disruption between 1e Con. Huygensstraat and J.P. Heijesstraat. The model identifies the disrupted line which is tram line 1 which runs from Matterhorn in west of Amsterdam to Flevopark in the east. The algorithm determines the plausible short turn solution from both the ends as shown in Figure 39 and detour solution as shown in Figure 40

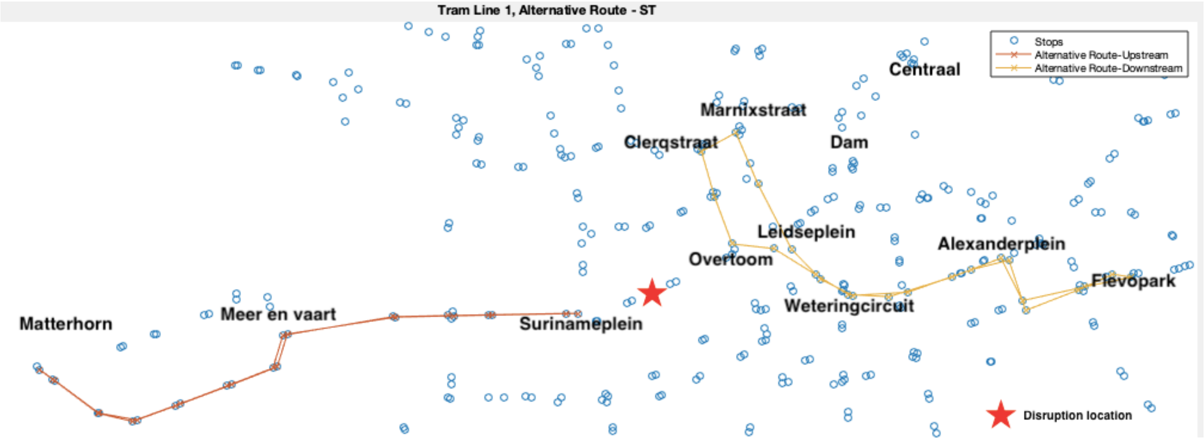

Figure 39 Plausible short-turn solution for a given disruption

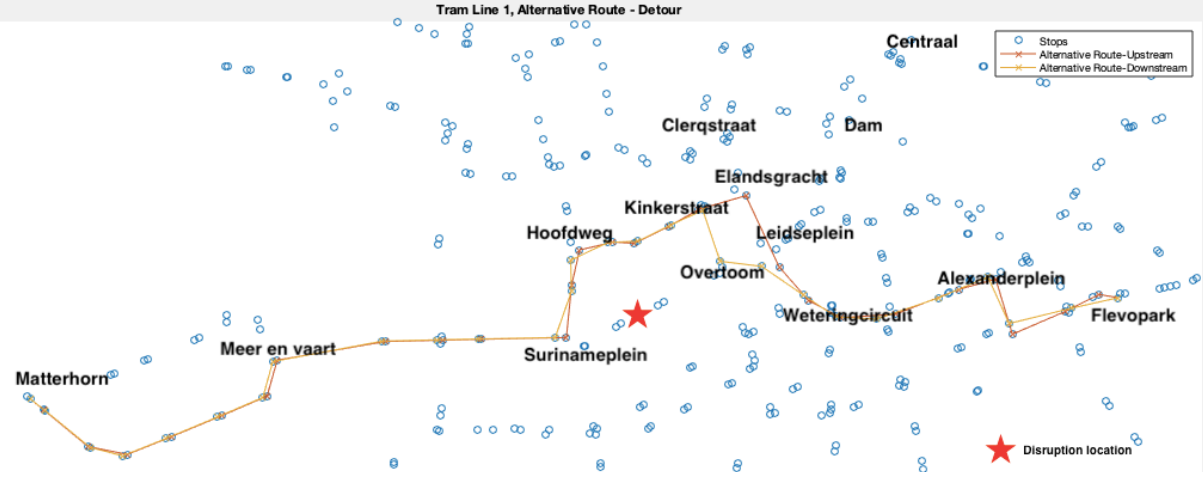

Figure 40 Plausible detour solution for a given disruption

Phase 2 Identifying the most plausible supply side adjustment

The objective of phase 2 of the project is to identify the most plausible supply side solution for a disruption amongst the modelled solutions in phase 1 which are short turn and detour. This section is elaborated in chapter 3 which answers the following sub-question

2. **What would be the most plausible supply adjustment amongst short turning and detouring for a given disruption with or without the new rescheduling infrastructure?**

In this phase of the project, the passengers are assigned to the changed transit services due to the disruption. This is done for both short turn candidate solution and for detour candidate solution. For assigning passengers to these new services, the demand per OD pair data is used. The first step in this phase is to generate paths from every origin to every destination which is followed by calculation of the utilities of each path and based on these utilities, passengers are assigned. In this phase, the disrupted link packages are also generated and for every package, the most plausible supply side adjustment (either detour or short-turn) is modelled which is based on their respective disutilities. The following conclusion from the second phase of the project could be made:

- The path generation per OD pair being computationally expensive, have been limited to generate the 3 shortest paths from O to D. The changed transit services as modelled in phase 1 have been used while generating paths.

- The most plausible supply side solution for all the packages of disruption for the case study of Amsterdam is shown in Figure 41. It is worth to note that detour as the most plausible solution exists for the disruptions in the central part of the network. Due to high line density, detour option is more plausible that short turn. Short turn as the most plausible solution exists for the disruptions lying in the branches of every line. This could be explained with the reasoning that since there is no other tram infrastructure for detour and due to the existence of short turn infrastructure (such as cross-over or turning loop) nearby it, short turn is preferred than detour. There exists few 'no feasible' solution' this is because whatever candidate solution (either detour or short turn) exist, they are out of the travel time and travel distance bounds. The locations for 'no feasible solution' indicate that the new rescheduling infrastructure at these locations could be potentially worthwhile.

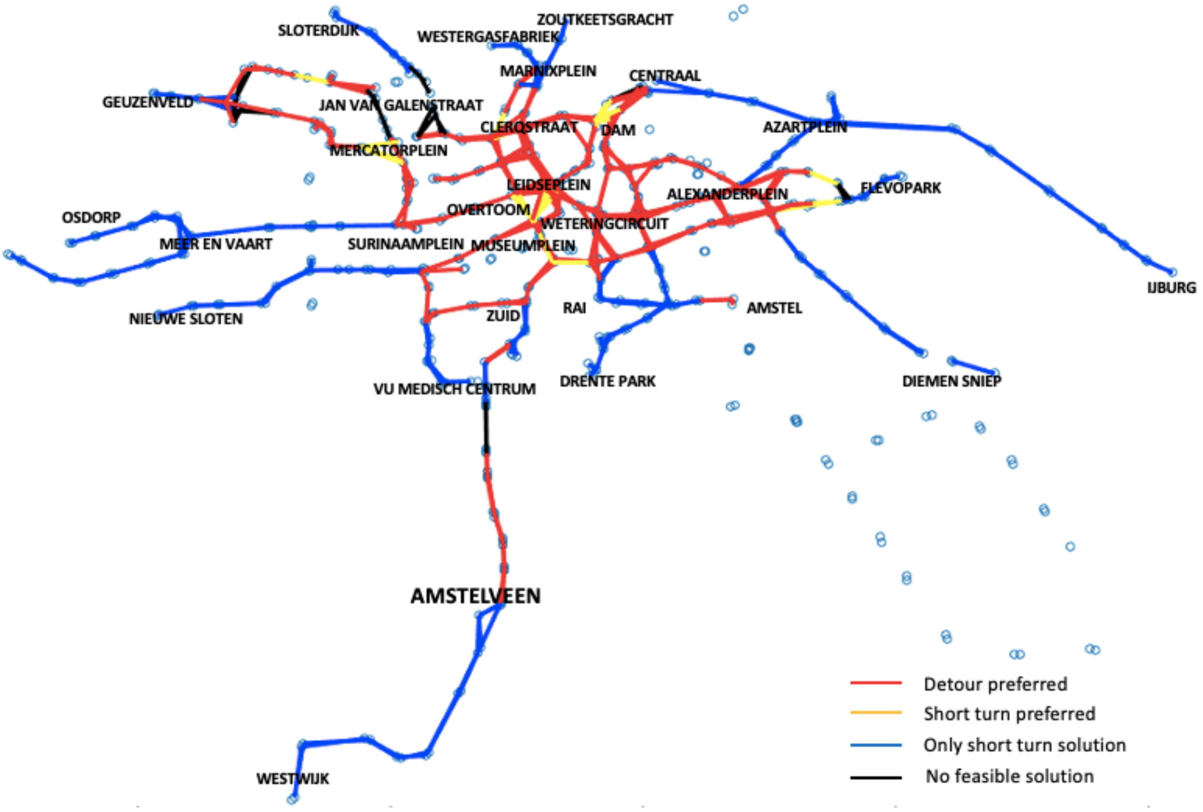

Figure 41 Rescheduling measure per disrupted link- Amsterdam tram network

- The plausible supply side adjustments for a disruption are sensitive to the bounds on extra travel time and extra travel distance. The bounds are calibrated based on the expert judgement of possible transit adjustments for different disruptions.

Higher the bounds on extra travel time and travel distance, lower is the possibility to get 'no feasible solution' as the algorithm increases its area of exploring new solutions.

Phase 3: Quantifying the passenger, operator, and societal impacts

The objective of this phase is to determine the benefit of a new rescheduling infrastructure to passenger, operator, and the society. The new rescheduling infrastructure is identified in the PT transport network which are either a junction connector, a crossover, a turning loop or a line connector. To quantify such benefits, the two scenarios are created and in each scenario is executed through phase 1 and phase 2 of the project. The base scenario (scenario 1) is the one with only disrupted link sets and the extended scenarios (scenario 2) are the one where the new link sets are tested with all the disrupted link sets. The utilities for both the cases are derived and by comparing the outcomes from each of the new link scenario with the base scenario, the benefits are calculated. These benefits help to answer the sub-question 3 which is as follows:

3. **How to quantify the passenger and operator impacts resulting from the supply adjustments with or without the new rescheduling infrastructure?**

The benefits for operator, passenger and authority are quantified using constants which monetize the output information from the model into euros. This makes it easier to quantify the impacts on passenger, operator and society and to compare them which is elaborated in chapter 4. The following conclusions could be drawn from this phase:

- Benefits to passenger are quantified by comparing generalized travel time saving and generalized travel distance saving due to the new link. Benefits to operator are quantified by comparing the production surplus which is total revenue gain (or loss) with the savings in operational cost. Demand regain due to the new link is used for quantifying the impact to the society.

- The generalized travel time, operational cost saving and revenue due to demand regain benefits the system as a whole. Benefit due to generalized travel distance is distributed benefit within the system as the reduction in fare from passenger's perspective is loss to operator's revenue.

- The monetized benefits are sensitive to the parameters such as value of time, operational cost per km average travel fare per journey, coefficient of demand elasticity and average fare per km.

- It is computationally expensive to compare the KPIs from both the scenarios and for all the disruptions, hence for the new rescheduling infrastructure case, the model identifies only those disruption sets where there is change of transit service and executes the KPIs for only those disruption sets.

- For every package of new link, the benefits are calculated. From the calculated benefits for the new link packages, it can be seen that for one two-hour evening peak period for Amsterdam tram network, the total benefit of a new link package to the all the passengers is highest which ranges around 50€, followed by the benefit to the operator which is usually around 25€ followed by societal benefits which is below 10€ considering the average frequency of disruption set as $4.78*10^{-4}$.

Phase 4: Quantifying the robustness of new link infrastructure during different disruptions

The objective of phase 4 of the project is to derive the worthiness of the new rescheduling infrastructure in PT network. It quantifies the robustness of new link infrastructure through the cost benefit analysis. By comparing the new infrastructure cost with the benefits of it on a time span of 30 years, it could answer the last sub-question of the project which is framed as:

4. **What is the method to identify the most beneficial new rescheduling infrastructure from all candidates rescheduling infrastructures that contributes to maximize the robustness for a large-scale public transport network?**

Comparing the cost with its benefits on a timeline of 30 years and deriving the net present value, the most beneficial ne rescheduling infrastructure could be find out. The following conclusions can be drawn from the phase 4 of the project.

- Comparing the monetized benefits to its investment and maintenance cost gives the idea whether it is worth investing in the new infrastructure. It also helps us to assess the time frame at which the benefits are expected to outweigh the cost of investment.

- Comparing the NPVs (Net Present Values) of the new infrastructures helps us to identify which amongst all the tested new infrastructures contributes to the maximum robustness value and is worth investing.

- The main cost that the new rescheduling infrastructure entails the construction cost during the first year which contributes for the higher percent of total cost. The benefits gained by the new rescheduling infrastructure is more or less equally distributed for the whole time period of 30 years.

- For the case study of Amsterdam tram network, it could be concluded that investing for the new link package 6, 3, 11, and 13 is more beneficial than the rest packages as the payback period for these packages is earlier and the net present value at the end of year 2051 is higher than the net present value of the rest of the packages. It can also be seen that the slope of NPV of set 14 is steeper than the rest. Despite higher investment cost, on a longer time the NPV of set 14 would cross the rest of the packages. The comparison of NPVs for different set of new links is shown in the Figure 42 and the values of NPV is given in the Table 20.

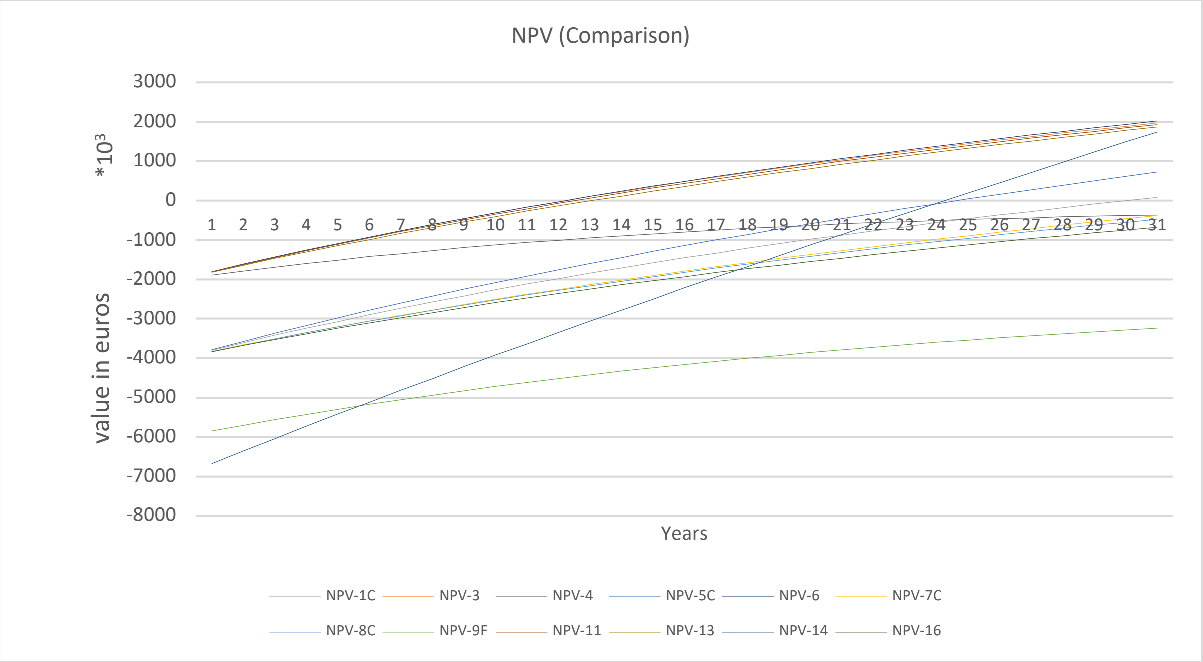

Figure 42 NPV Comparison

Table 20 NPV values for different link packages

Link Package Set	NPV value at the end of year 2051 (in *10^3 Euros)	Payback Year	Rank
6	2,022	2033	1
3	1,971	2033	2
11	1,927	2033	3
13	1,868	2034	4
14	1,737	2045	5
5C	725	2045	6
1C	81	2050	7
4	-368	--	8
7C	-381	--	9
8C	-473	--	10
16	-676	--	11
9F	-3,238	--	12

It is worth to note that there is no payback period for link set 4, 7C, 8C, 16 and 9F as the benefits never outweighs the cost on the timeline of 30 years. Although the benefits from these new rescheduling infrastructure set is higher than few other new rescheduling infrastructures, it is not always the case that the benefits outweigh the cost.

6.2 Policy Implications of the research project

From scientific point of view, this research project provides two main contributions. The first contribution is that it develops a method to identify the type of rescheduling measure needed during a disruption which could be either a short turn, a detour or if there is no feasible solution which is most suitable from a passengers' perspective. The second contribution of the research work is that the method finds out the worthiness of the infrastructural investments at various locations in PT network by calculating its Net Present Values.

The phase 1 of the project develops a method to generate the plausible candidate solution for both short-turn and detour for a disruption. This method could be used by the operators for operational decision making for supply side adjustments during an unpredicted disruption which can provide operator with candidate solution for short-turn and detour. The operator needs to give the disruption segment as an input and the model generates the plausible candidate solutions. Transit adjustment model being computationally less expensive can generate solutions fast which is handy during quick decisions.

The intermediate result of this model after execution of phase 2, provide insights to the operator regarding the most plausible supply side adjustment amongst short turn or detour. At this stage, the passengers' perspective for the decision making is also included. From the map which gives the suggestion for the most plausible supply side adjustment, operator can use it as a tool to assess the type of supply side adjustment to be used based on the location of the disruption.

The research work could be used for appraisal of new infrastructural investments. Through the project, the worthiness of an investment for an infrastructure in the network could be derived. It could be further developed to compare different infrastructure and its net present value over time and the expected year for generating a profit out of the investment. It could be also used to assess the benefits to the individual stakeholders. From a practical point of view, this research is beneficial to identify the worthiness of investment in new infrastructure and also on higher stages, this research helps to prioritize the investment decisions.

From the cost-benefit analysis for different new infrastructural links in phase 4, it can be seen that the investments are more worthy in those new link packages having only one set of new links than those sets having multiple sets. For example, the new rescheduling infrastructure package set 3 and 6 contains only one set of link which gives higher NPV at the end of 2051 as compared to other packages having multiple sets of links.

6.3 Recommendation for further improvement of the proposed methodology

This section of the chapter provides few recommendations to improve the proposed methodology for the project. Due to some limitations such as time and availability of the sources, there were few assumptions that were made in this project which could be further improved. These are as follows:

First, the overall methodology to derive the benefits of the new link could be improved and the results could be more accurate by adding an extra step of change in modal split due to changes in travel resistances. Since the travel resistances such as travel time and travel distance from a passenger's perspective changes due to changes in the transit services, there would be changes in the modal split ratios. The impacts on demand due to changes in the travel resistance is captured through demand elasticity in the modal but that does not exactly capture the essence of changes in modal split. In the case study of Amsterdam, the alternative modes that a passenger can use is either tram or metro otherwise they have to walk to the nearest stop to get access to the service. In reality, other transport modes such as buses or taxis also exist which is not considered in the passenger assignment model. This may have substantial impact on the passenger travel time and travel distance. The future works could supplement this research by considering the alternative modes for the passengers to travel from origin to destination. Calculating the disutilities of such paths with alternative modes during the passenger assignment can include the concept of multi-modality to this project.

Secondly, generating candidate solutions for the short turn and detour makes it more sensitive to the travel time and travel distance bounds. These bounds vary by the operators which depends on the disruption type and location. Making the travel time and travel distance parameters linked with the disruption type and location, the sensitivity of the transit adjustments could be reduced.

Third, to identify the most plausible supply side solution, the supply side adjustments per disruption is modelled considering two adjustments which are short turn and detour. Consider a disrupted segment where multiple lines are disrupted because of it. The model generates a short turn solution where the most plausible short turn is modelled for all the multiple transit lines, and a detour solution where the most plausible detour is modelled for all the multiple transit lines. In the next step, the disutilities to the passengers are calculated for these two sets of solutions. The project does not include those sets where one of the disrupted transit line is having a short turn as a candidate solution and other disrupted transit transit line is having a detour. This generates more solutions for the operator to adjust the services during a disruption which could be future research topic.

Fourth, in chapter 3, the suggestion to the operator for disruption in Amsterdam tram network for the most plausible supply side adjustment is based on the 2 hours evening peak period data. For both transit adjustment and passenger assignment, a static model is used (based on one single time period) whereas the tactical and operational decisions made by the operators are sensitive to time. It is suggested that for future research, dynamic or quasi-dynamic models could be used for providing suggestions for operational decisions.

Fifth, in chapter 3, modelling the most preferred transit assignment is totally based on the disutility the passengers in having without looking into account the beneficial transit assignment for operators. Although the bounds to extra travel time and extra travel distance have been used, it does not properly capture the operator’s perspective at this stage for the beneficial transit adjustment. For example: assume a disruption where both short turn and a detour candidate solution is possible. According to the model, say that the disutility of short-turn is more than disutility of detour and hence detour is preferred, but on the contrary, the operator finds short turn less operationally expensive than detour. The results generated by the model could contradict the operator’s decision. This could be improved by considering the operational cost per km to operator at this decision stage of the most plausible supply side adjustment.

Sixth, while modeling the disrupted link set packages which is based on the links entering and links leaving the coupled nodes (stop IDs) on upstream and downstream respectively, there exist few links in the network infrastructure which are not disrupted at all as they are nodes containing the link have not been coupled. So, for such links, the recommended supply side adjustments are not modelled.

Seventh, in passenger assignment model, a discrete choice model is applied on only 3 generated paths. For more accurate results, it is recommended to generate higher number of alternative paths per OD pair. Also, for making the passenger assignment computationally stable, the reassigning paths is done for those OD having demand higher than 0.1. This makes the assignment slightly biased towards the paths having higher flows.

Eighth, in chapter 4 the methodology caters of manually finding the incomplete junction connectors, plausible link connectors and crossovers which could also be modelled by searching the stops near the junctions which are not connected with each other and hence making it more flawless. This could be done by pairing all the upstream and downstream stops of a line and searching for the missing stop in the whole sequential arrangement of stops for a line. Another method could be by using the buffer function in GIS software and pairing the stops within the buffer, looking for the existence of link between these stops.

Ninth, in the chapter 4 of benefit quantification, only few KPI's per stakeholder are considered where there exist other unobserved benefits of new links. Currently the benefits are biased on lower side, and it is recommended that the using more KPI's relating to network indicators and service availability indicators could include the unobserved benefits of the new link. In this project, to include societal benefits, a proxy indicator of demand regain due to the new rescheduling infrastructure is used which does not properly capture the societal benefit. It is suggested that indicators which capture the accessibility of a region such as BBI (Bereikbaarheidsindicator) as used by Dutch Ministry of Infrastructure (Rijkswaterstaat, 2017) or spatial based accessibility indicators such as Contour cumulative opportunity measure or Joseph and Bantok's potential model can be used to capture the societal impacts more effectively. Also, the qualitative benefits could also be included in the model. For future research, more insights could be collected for assessing the benefits for various actors. To derive the benefits of the new link, it is recommended to perform detailed research on the types of benefits not only the identified stakeholders but also other benefits such as environmental benefits.

Lastly, in chapter 5, it is assumed that the frequency of disruption for all the disrupted link packages is same. It is recommended that more detail frequency of disruption per link package could be included by assessing it with the total link length of all the links in the link package with the total length of network. Other influencing parameters for the frequency of disruptions could be the number of switches per link or the number of bridges per link as these factors make the link vulnerable to the disruption.

For further research, the robustness value of new rescheduling infrastructure at the network level could also be analyzed by assessing the network topological indicators such as network connectivity (γ-index), network meshedness (α-index), network directness, betweenness centrality, node closeness centrality as discussed in Cats (2017), robustness indicator metric, effective graph conductance as suggested in Wang et al. (2015) for Amsterdam tram network for the base network and for the network with new links.

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Appendix

Appendix 1: Lower-bound threshold value decision process

To reduce the processing time for re-run of path generation for every disruption, the re-run of path generation is constrained to only those paths who has the demand flow more than or equals to 0.5 passengers. The decision of the lower bound threshold value for the flow is decided aiming to reduce the total number of od-pair for the rerun of model but to capture at least 80-85% of the demand. For the following 5 disruptions, the various threshold value of demand are tested which gives the promising threshold value of 0.5 which can capture at least 80% of the total demand. It also reduces substantially the path generation process for the number of OD pairs but capturing at least 80% of the demand. The threshold number of 0.5 passengers is taken into consideration. The following graphs shows the variation of number of od pair and the demand percent captured.

1. For disruption between Rhijnvis Feithstraat and J.P. Heijestraat

Table 21 Threshold value decision for disruption between Rhijnvis Feithstraat and J.P.Heijestraat

Threshold value	OD Pairs	OD Pair percent	OD demand	OD demand percent	Time (s)	Solution
8	52	1.34	805.33	29.94	129	ST
5	111	2.85	1185.75	44.08	165	ST
2	295	7.59	1650.17	61.35	293	ST
1	475	12.22	2014.99	74.91	481	ST
0.5	726	18.67	2227.23	82.80	662	ST
0.4	830	21.35	2302.42	85.60	893	ST
0.1	1815	46.68	2687.36	99.91	1557	ST
0	3888	100	2689.90	100	3446	ST

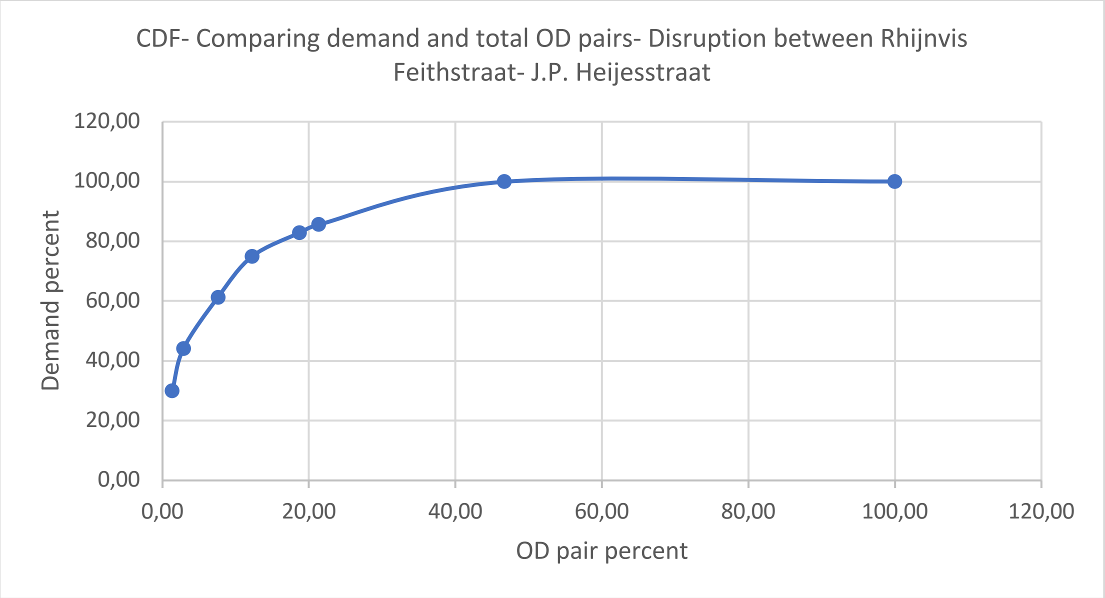

Figure 43 CDF- Comparing demand and total OD pairs- Disruption between Rhijnvis Feithstraat- J.P. Heijesstraat

2. For disruption between 1e Con. Huygensstraat and J.P. Heijesstraat

Table 22 Threshold value decision for disruption between 1e Con. Huygensstraat and J.P. Heijestraat

Threshold value	OD Pairs	OD Pair percent	OD demand	OD demand percent	Time	Solution
8	100	2.05	1574.1	31.02	193	ST
5	195	3.99	2172.2	42.81	279	ST
2	438	8.96	2977.9	58.69	539	ST
1	741	15.17	3565.45	70.27	857	ST
0.5	1317	26.95	4215.15	83.07	1365	ST
0.1	2998	61.36	4888.9	96.35	3880	ST
0	4886	100	5074	100		ST

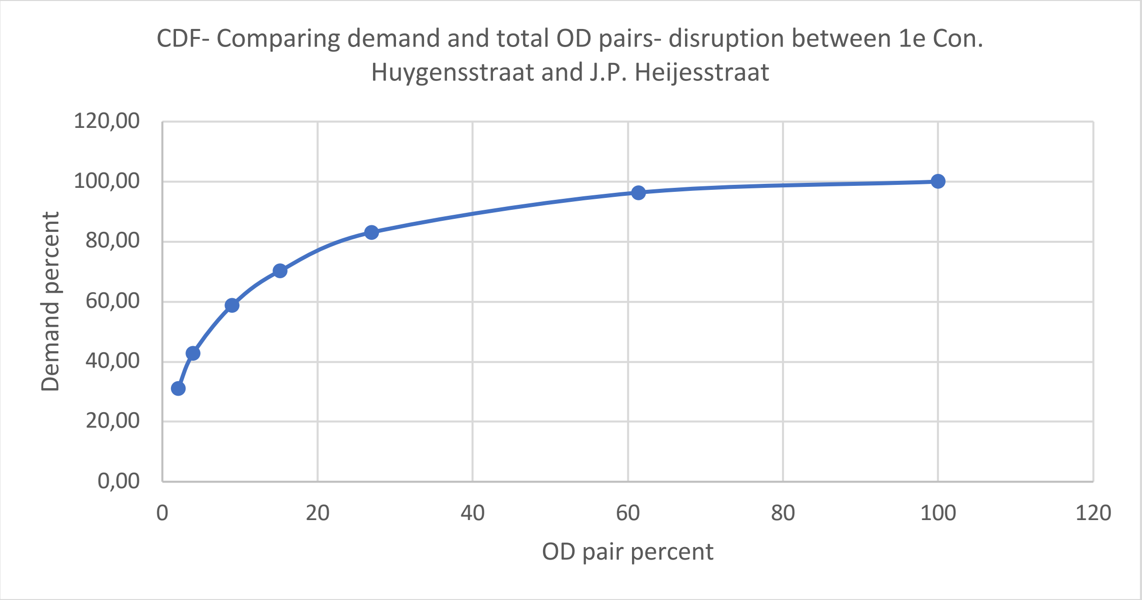

Figure 44 CDF- Comparing demand and total OD pairs- disruption between 1e Con. Huygensstraat and J.P. Heijesstraat

3. For disruption between Zeeburgerdijk and Javaplein

Table 23 Threshold value decision for disruption between Zeeburgerdijk and Javaplein

T.Value	Time	Demand	Demand %	OD pairs	OD pair percent	Solution
5	61.38	77.78	49.3	6	8.45	Detour
1	92.55	98.29	62.3	10	14.08	Detour
0.5	119	124.77	79.08	20	28.17	Detour
0.2	146	146.08	92.59	45	63.38	Detour
0	181	157.77	100	71	100	Detour

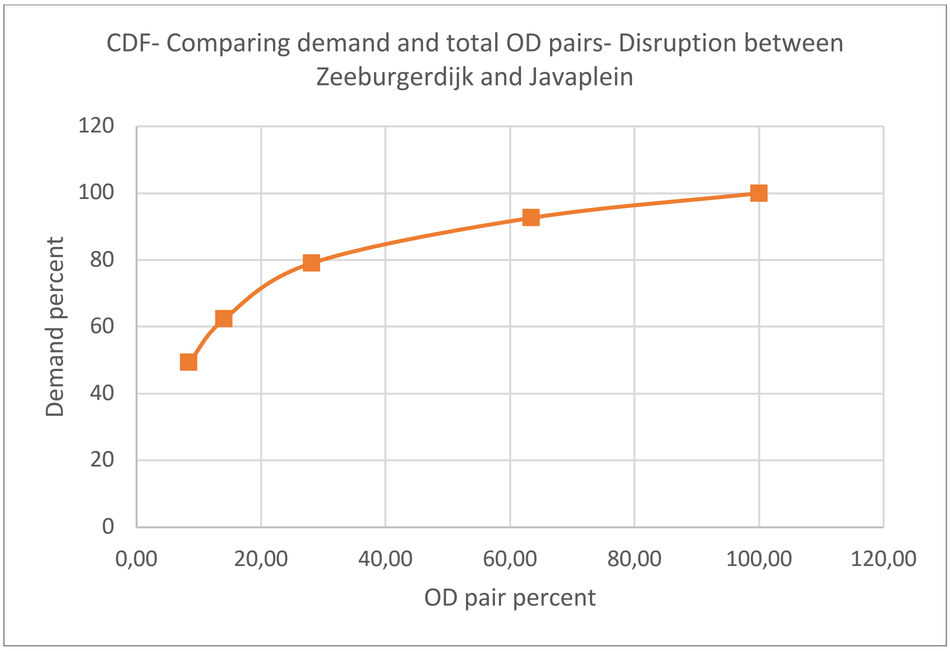

Figure 45 CDF- Comparing demand and total OD pairs- Disruption between Zeeburgerdijk and Javaplein

4. For disruption between Mr. Visserplein and Artis

Table 24 Threshold value decision for disruption between Mr. Visserplein and Artis

Threshold value	Time	Demand	Demand %	OD Pair	OD pair percent	Solution
8	69	152.26	42.12	4	2.02	Short turn
5	80	197.12	54.53	10	5.05	Detour
1	85	285.14	78.88	38	19.19	Detour
0.5	123	321.28	88.88	67	33.84	Detour
0.2	187	346.95	95.98	136	68.69	Detour
0.1	244	361.44	99.99	197	99.49	Detour
0	245	361.48	100	198	100	Detour

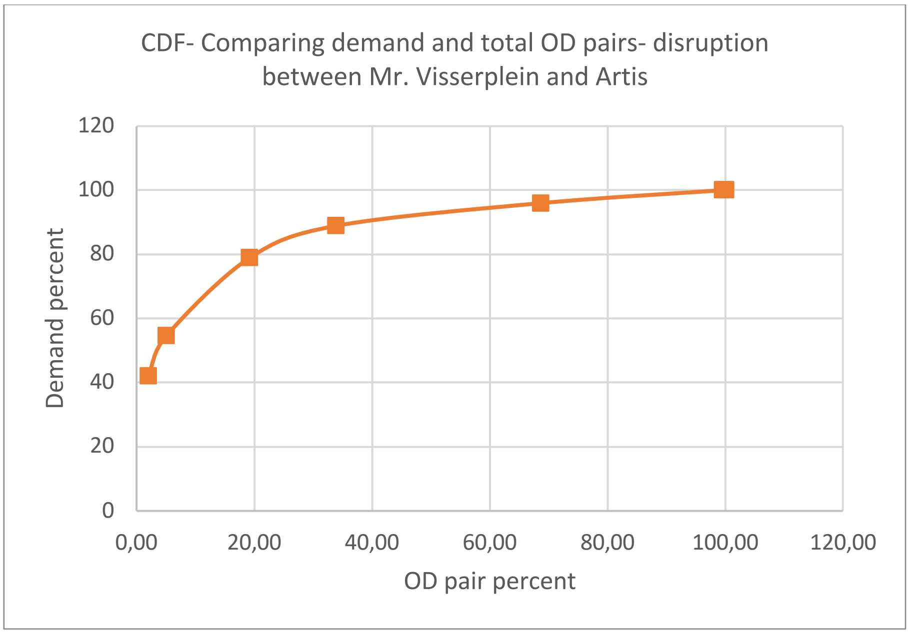

Figure 46 CDF- Comparing demand and total OD pairs- disruption between Mr. Visserplein and Artis

5. For disruption between Wiltzhanghlaan and Molenwerf

Table 25 Threshold value decision for disruption between Wiltzhanghlaan and Molenwerf

T Value	Time	Demand	Demand %	OD Pair	OD pair percent	Solution
8	104	700.92	31.86	41	2.51	Detour
5	144	915.2	41.6	74	4.53	Detour
1	438	1584.66	72.03	380	23.26	Detour
0.5	646	1756.7	79.85	586	35.86	Detour
0.2	1180	1994.3	90.65	1066	65.24	Detour
0.1	1703	2199.78	99.99	1634	100	Detour

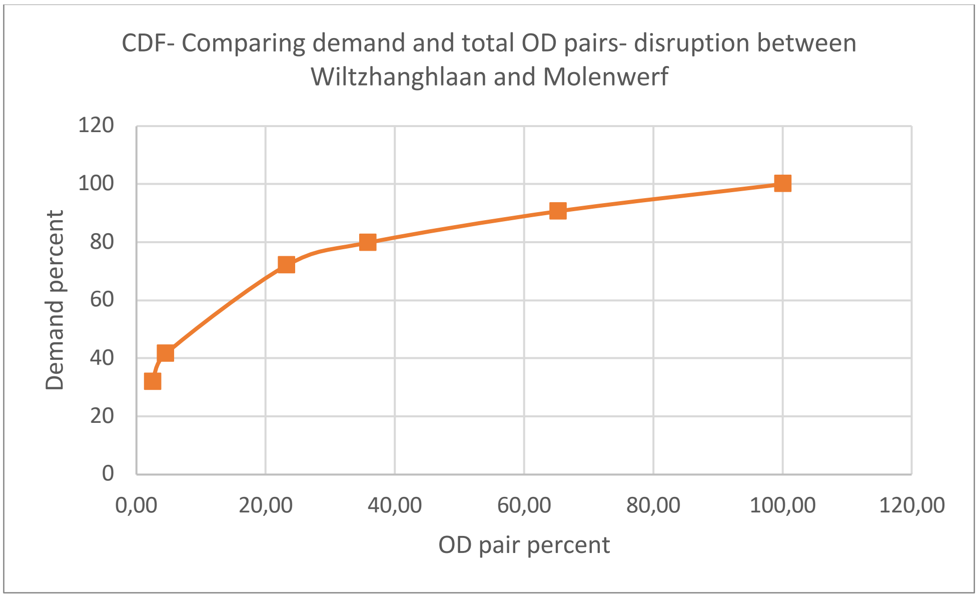

Figure 47 CDF- Comparing demand and total OD pairs- disruption between Wiltzhanghlaan and Molenwerf

Appendix 2: Cost-Benefit graphs for set of new links

This appendix gives the cost of the new infrastructure and the monetized benefits gained over a time of 30 years till 2051. As soon as the benefit line crosses the cost line, the net present value starts to become positive which tells that from that particular point of time, the benefits outweigh the cost, and it is worth investing in that new infrastructure. The figures below show the cost-benefits graph for the new infrastructure.

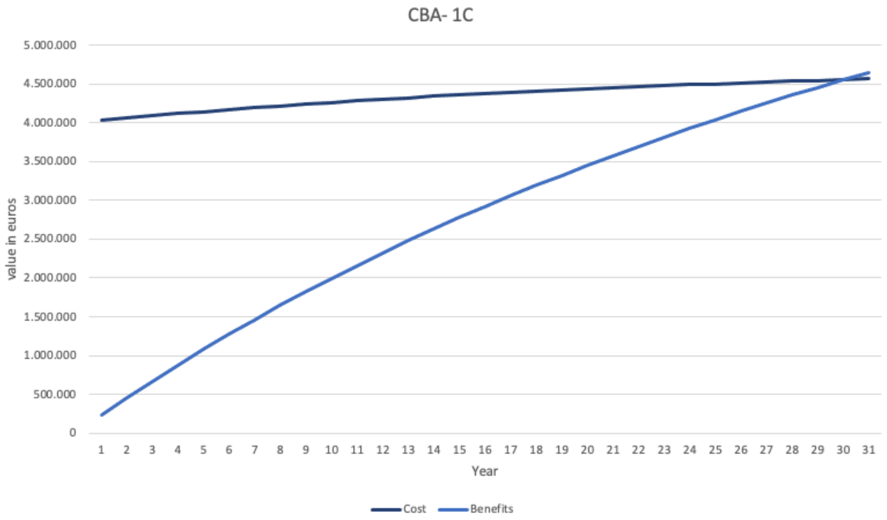

Figure 48 CBA for link package 1C

The benefits for link package 1C outweigh the cost of investment at 29th year which is 2050.

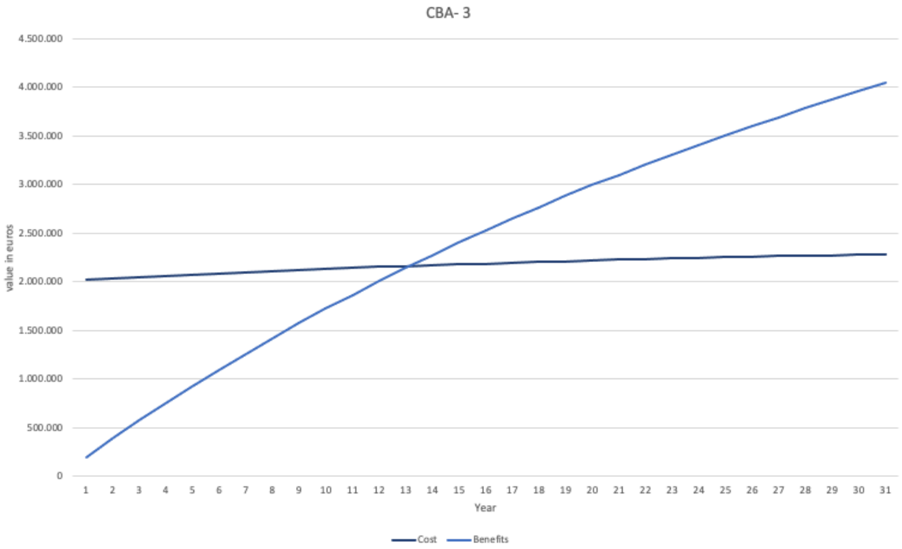

Figure 49 CBA for link package 3

The benefits for the link package 3 outweigh the cost of investment at 13th year which is 2033.

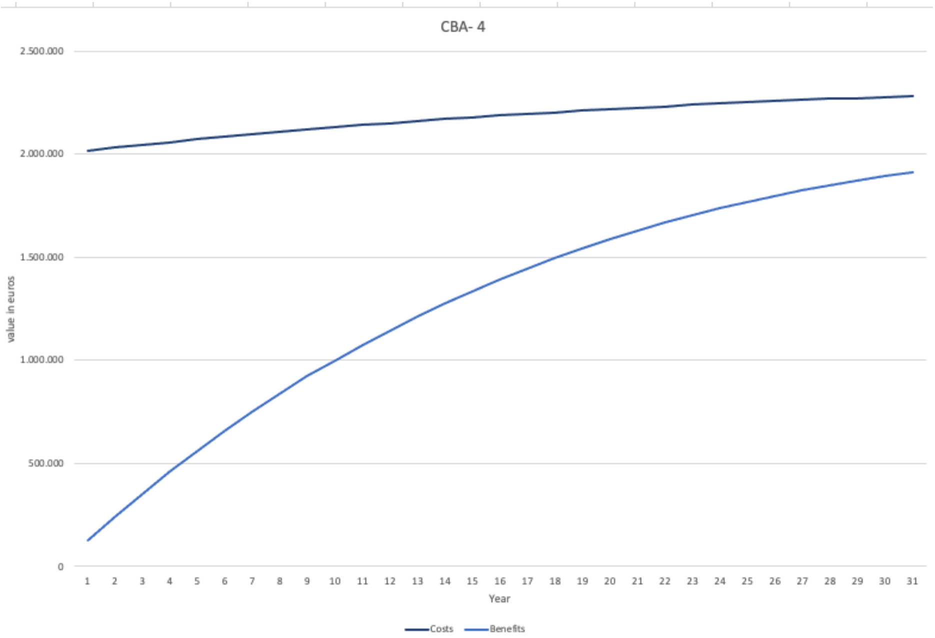

Figure 50 CBA for link package 4

The benefits for the link package 4 do not outweigh the cost of investment.

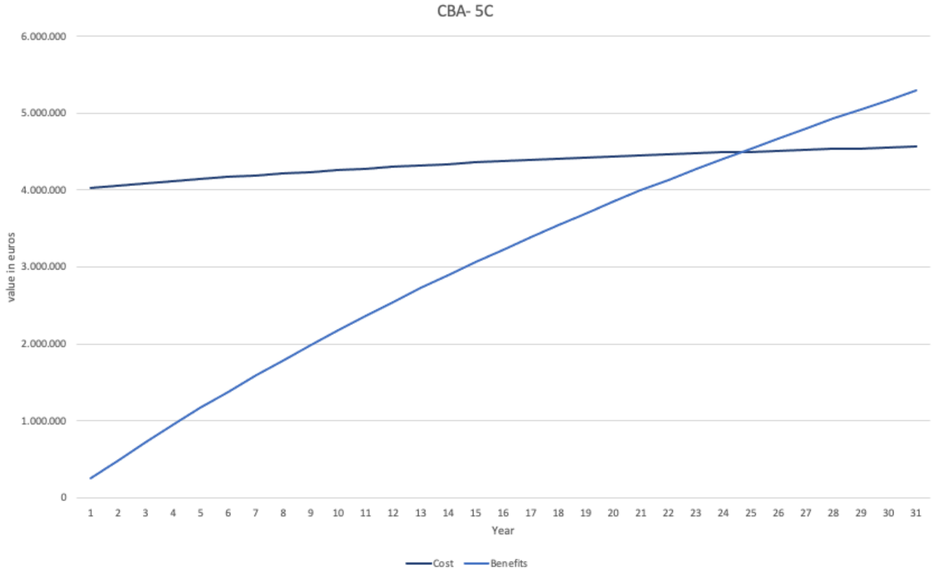

Figure 51 CBA for link package 5C

The benefits for the link package 5C outweigh the cost of investment at 25th year which is 2045.

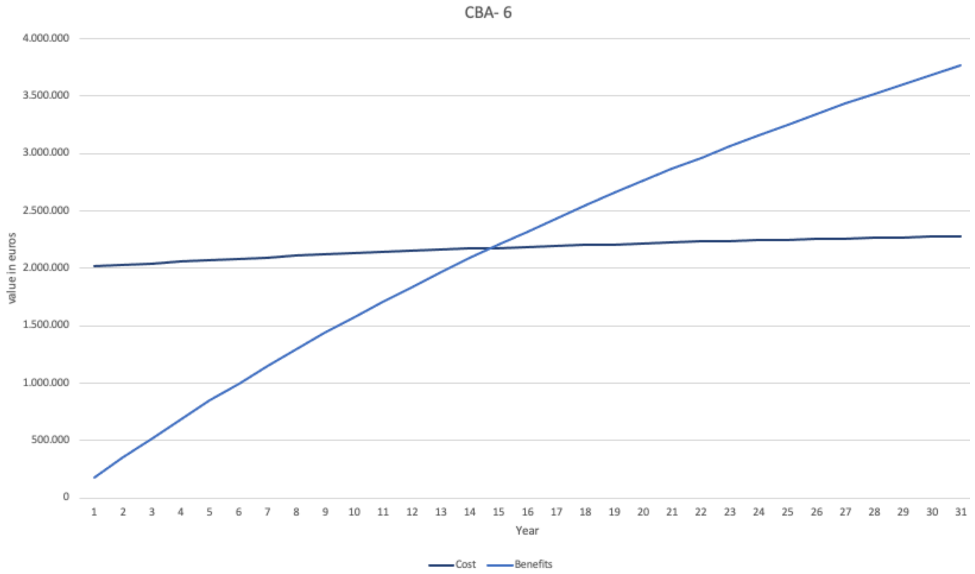

Figure 52 CBA for link package 6

The benefits for the link package 6 outweigh the cost of investment at 15th year which is 2035.

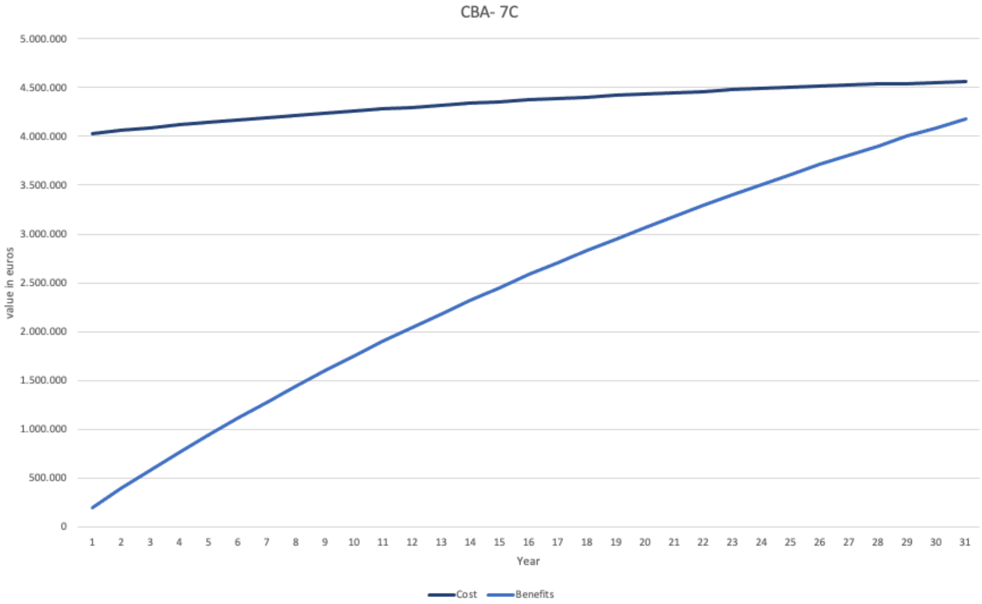

Figure 53 CBA for link package 7C

The benefits for the link package 7C do not outweigh the cost of investment.

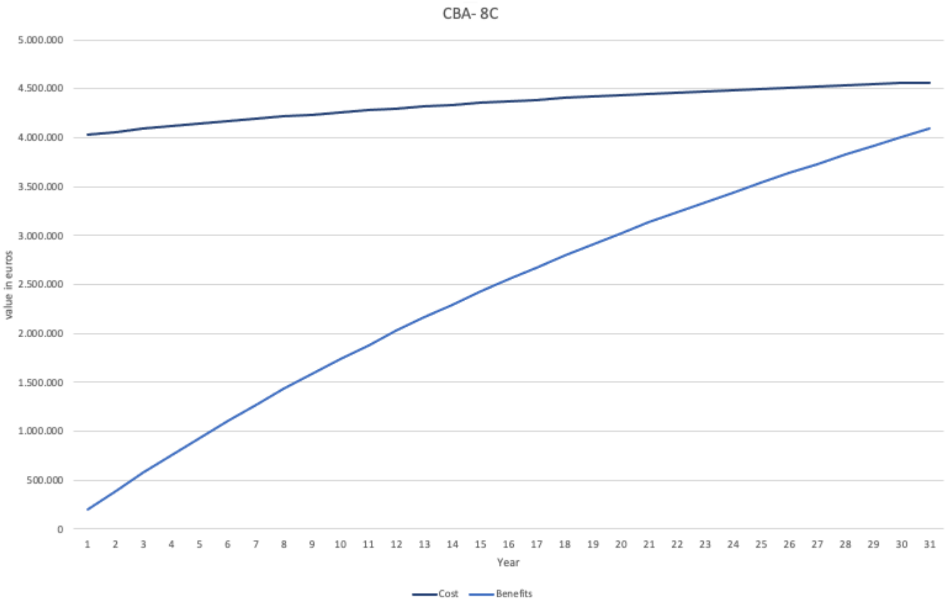

Figure 54 CBA for link package 8C

The benefits for the link package 8C do not outweigh the cost of investment.

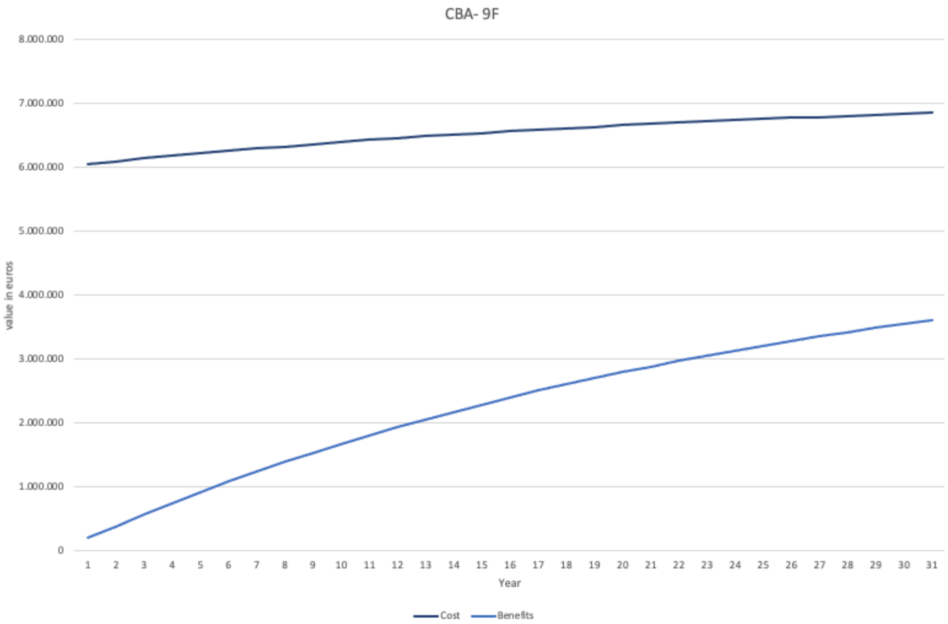

Figure 55 CBA for link package 9F

The benefits for the link package 9F do not outweigh the cost of investment.

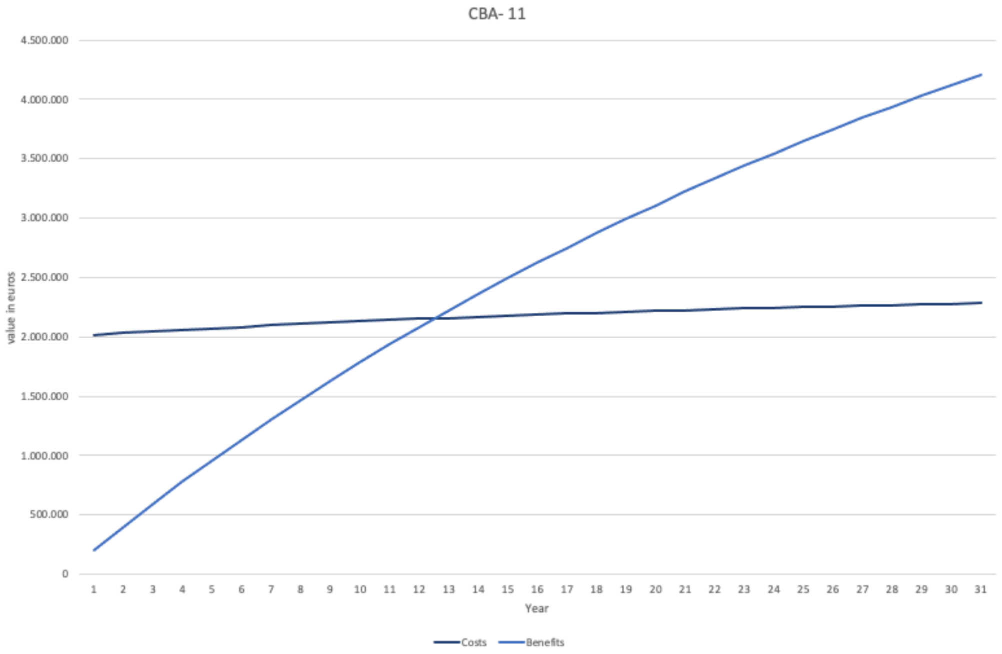

Figure 56 CBA for link package 11

The benefits for the link package 11 outweigh the cost of investment at 12th year which is 2033.

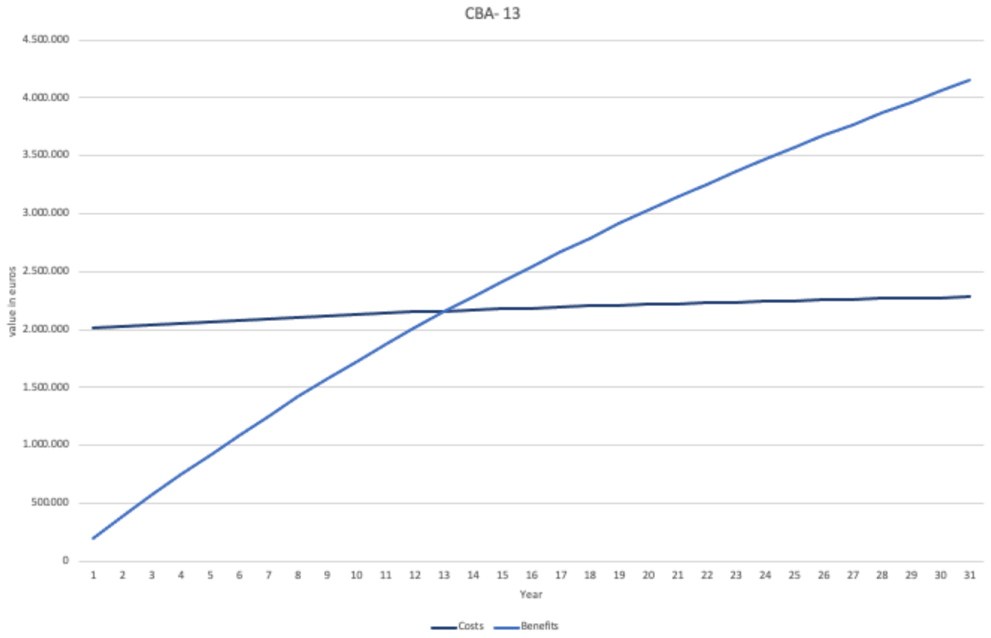

Figure 57 CBA for link package 13

The benefits for the link package 13 outweigh the cost of investment at 13th year which is 2034.

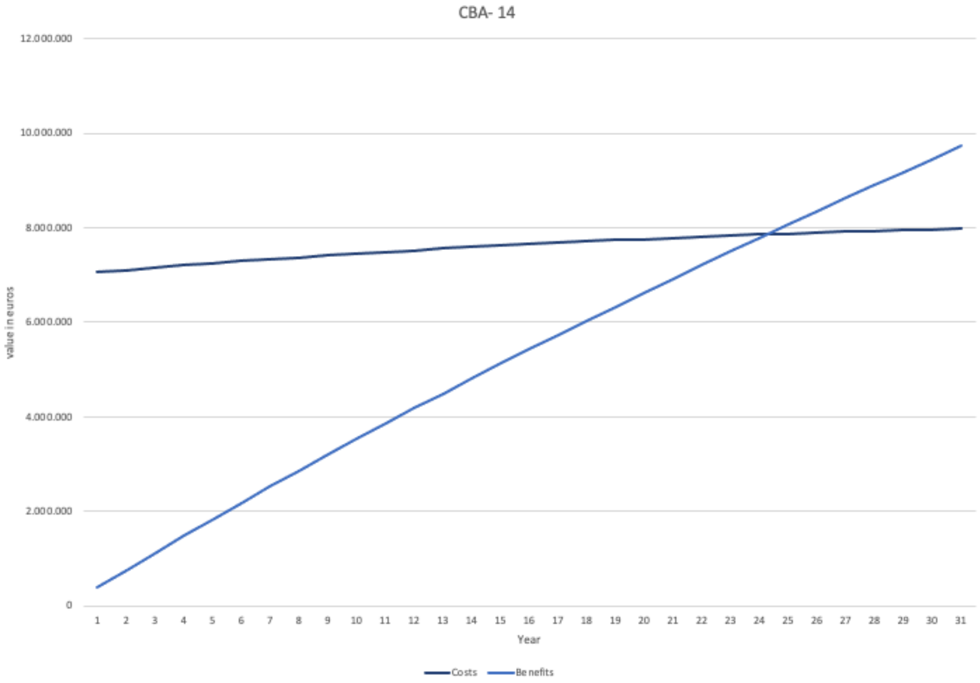

Figure 58 CBA for link package 14

The benefits for the link package 14 outweigh the cost of investment at 24th year which is 2045.

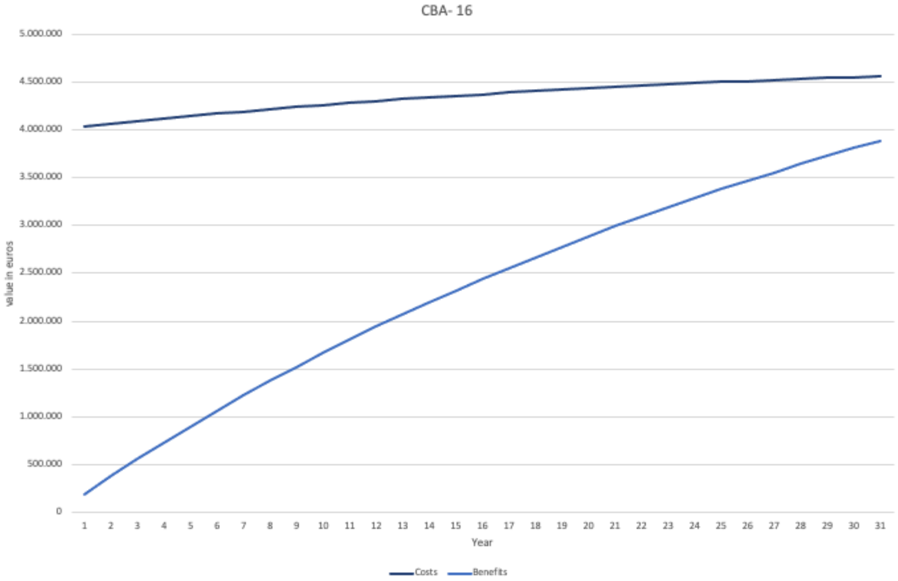

Figure 59 CBA for link package 16

The benefits for the link package 16 do not outweigh the cost of investment.