IMPLEMENTING
STATION-BASED BIKE-SHARING
IN STRATEGIC TRANSPORT MODELS

CREATING AN APPROACH TO COMBINE TOUR-BASED MODE-CHOICE AND MODELLING MULTIMODALITY

MASTER THESIS

CIVIL ENGINEERING - DEPARTMENT: TRANSPORT AND PLANNING

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PREFACE

In front of you is my final work as a student at the TU Delft. I am proud to present my thesis on the topic: Implementing station-based bike-sharing in strategic transport models. The research is conducted in collaboration with Sweco and the Delft University of Technology (TU Delft).

Without any doubt I can say that writing this thesis was my biggest challenge as a student. The field of strategic transport modelling was even more complex and contains many more facets then I thought prior to this thesis. However, after months of research and hard work the subject really caught my interest. In the end even leading to finding a job in the field of strategic transport modelling.

Performing this study would not have been possible without my supervisors.

I would like to start to thank my daily supervisor Henk Taale for the weekly meetings and effort on reading my work during the past months. His feedback and support really kept me on track to finalise this project. Then I would like to thank Adam Pel who was always willing to make time to answer my questions. His thoughts and critical feedback encouraged me to reconsider my research and kept me motivated. Finally I would like to thank Theresia van Essen and Niels van Oort for giving feedback during all progress meetings. Niels van Oort proved to be a very understanding and pleasant chairman to work with.

Then I would like to thank Sweco. Sweco gave me the opportunity to give some practical relevance to the research. After an interview with Guus Tamminga, he offered me to perform the research as an intern at Sweco. From that moment Guus Tamminga also functioned as an extra supervisor. It was a very pleasant experience to collaborate with Guus Tamminga and his input during the last couple of month helped me a lot to structure my report.

I would also like to express my gratitude to everyone else that contributed to the content in my thesis. Especially Frank Hofman, Maaike Snelders, Gijs van Eck, Rick van Grol, Peter Mijjer and Dick Bakker that shared their experience during a set of interviews.

Finally, my appreciation goes to my friends and family for their help and support throughout the years to successfully graduate and make my time as a student a joy.

EXECUTIVE SUMMARY

INTRODUCTION

Looking for more sustainable transport modes and improving accessibility is an essential topic for authorities. This raises the interest in multimodal trips. “Multimodal trips are trips using two or more vehicular modes between which a transfer is necessary” (Fiorenzo-Catalano, 2007). It offers the flexibility of private modes and, at the same time, the efficiency and high capacity of public transport modes (Van Eck et al., 2014). In the Netherlands, biking is already used for more than 50% of the trips to access the train. At the same time, using bikes for the last mile is less popular, with only 20% of the egress trips. (Jonkeren et al., 2018)This can be mainly contributed to limited availability of private transport modes at the egress-side of the trip. Shared mobility can be a solution for this problem. By facilitating the last-mile of a multimodal transport journey, multimodality can be promoted in order to compete with the car. In the Netherlands there is a nationwide bike-sharing system, especially designed to be an extension of the Dutch public-transport system (OV-fiets) (Bandeira, 2018). At most train-stations, there are shared-bikes to cover the last-mile of a train journey.

Authorities can be interested to make policies to promote the use of SB-bike-sharing in order to create a more sustainable transport system. Strategic transport modelling is a crucial tool in the decision-making process before implementing such policies (Van Eck et al., 2014). Implementing SB-bike-sharing in strategic transport models requires to combine two challenging topics.

- First of all, the model must be **tour-based**. A tour is defined as a trip chain starting at some location and eventually returning to the same location after a series of trips to perform activities (Hasnine & Nurul Habib, 2020). Modelling tours instead of trips makes it possible to capture consistency between multiple trips within a tour in order to model the fact that a person which uses a bike for the outgoing trip has to return the bike later in the tour.
- Secondly, the model must be **multimodal.** SB-bike-sharing is used in combination with other public transport modes. Therefore, bike-sharing has to be modelled, considering characteristics of the complete multimodal tour. This means that policies regarding SB-bike-sharing influences the demand for public transport and vice versa.

In transport planning practice, there is only one prevalent method that combines a tour-based mode choice and multimodality (Hasnine & Nurul Habib, 2020). This is the so called “Two-step-mode choice” approach. In this approach first a main tour-mode choice is modelled, multimodality is than modelled on trip-level, conditioned to the main-mode choice. The modelling software P.T.V Visum 2021 *(PTVgroup, n.d.)* uses a two-step mode-choice approach. This research hypotheses that the two-step mode-choice approach used in Visum has some important limitations to model the combination of tour-based mode choice and multimodality. SB-bike-sharing is used as an tangible case-study to illustrate and address this problem. This leads to two research objectives:

1. *Implementing SB-bike-sharing in the Visum two-step mode-choice approach to quantitively illustrate the limitations of modelling tour-based mode choice and multimodality in Visum.*
2. *Create an approach to combine tour-based mode choice and multimodality in order to address the limitations of the current Visum modelling approach.*

RESEARCH OBJECTIVE ONE

Implementing SB-bike-sharing in the software of Visum itself is a complex and time-consuming task. For this reason, this study replicates the Visum two-step mode choice approach in Excel. SB-bike-sharing is then implemented to the replicated model. Implementing SB-bike-sharing is done by adding extra transfer links to a multimodal transport network. The transfer links connect the biking network and the public transport network. The transfer links contain information about the transfer time, the transfer cost and the resistance to transfer between public transport and SB-bike-sharing. The replicated model is used on a theoretical case-study. The case-study uses a small-scale multimodal transport network consisting of 9 nodes. The scenarios tested in the case-study were designed to illustrate the limitations of the Visum two-step mode-choice approach. The two-step mode choice approach has the following three limitations:

The consistency limitation means that there is no consistency in the use of SB-bike-sharing. In reality, a person that uses SB-bike-sharing for the egress part of an outgoing trip, has to return the bike later in the trip to the same station. When there is no consistency, the person that used a bike could leave the bike at the activity location or could return the bike to another station. The case study further illustrated this problem. A situation is tested where the travel time for a public transport link is higher during the evening trip compared to the morning trip. The result is that more people decide to use SB-bike-sharing as an alternative travel option during the evening trip compared to the morning trip.

The aggregation limitation means that the model cannot consider person type specific preferences when modelling the demand for SB-bike-sharing. For this reason the model cannot consider that students are more likely to use the system compared to other person groups. This is illustrated in the case study by increasing the number of students in the population. More students resulted in more demand for public transport in general. However, the number of SB-bike-sharing users only increased proportionally to the public transport demand. This indicates that the correlation between the number of students and the demand for SB-bike-sharing is not explicitly modelled.

The travel demand problem refers to the fact that the model does not consider the relation between SB-bike-sharing and the demand for public transport. Promoting SB-bike-sharing is an interesting policy measure to increase public transport ridership. Nevertheless, the effect of this kind of policy measures cannot be tested with the current Visum approach, due to the travel demand problem. The case study illustrated the travel demand problem by decreasing the price for SB-bike-sharing. The Visum model clearly shows its limitations. The pricing only affected the number of SB-bike-sharing users and did not affect the demand for public transport in any case. Even when SB-bike-sharing was free of charge ,there was no change in the public transport demand.

All problems discussed can be generalised to other multimodal transport concepts and policies. The consistency problem is also a problem for park and ride facilities and for normal bikes. The aggregation problem is relevant to estimate the demand for multimodal transport in general. The travel demand problem is relevant for all promoting policies regarding multimodality. Examples of such policies are smooth transfers in park and ride facilities or improved biking lanes towards stations.

RESEARCH OBJECTIVE TWO

Research objective one discussed the problems of the Visum modelling approach. To address these problems, this study proposes "the tour-based mode-chain and station choice approach" (in short the tour-based mode-chain approach). The main difference compared to the Visum approach is that components that need consistency on tour-level are modelled at tour-level instead of trip-level. The model uses a set of discrete choices. The discrete choices are based on Random utility maximization principles. The choices upstream are all calculated based on the expected utility of choices downstream (Logsum). The decision making unit for the discrete choices are groups of people with the same characteristics .There is a set of three discrete choices:

- **The first choice** is what **pre-specified mode-chain** is used. There is assumed that there is only a limited number of multimodal mode combinations available. For this study the mode combinations used are: walk/public transport/walk, bike/public transport/walk, walk/public transport/bike and bike/public transport /walk. This means that the set of pre-specified modes is used in a tour. The walk/public transport/bike chain refers to a tour that uses walking at the access-side of a tour, public transport as its main transport mode and biking at the activity-side of a tour.

- **The second choice** is the **station choice**. People that use a (shared) bike to reach a station have to return to the same station as they used earlier in a tour. Consequently, the station choice has to be optimized at tour level in order to find the most efficient station considering the complete tour.
- **The last choice** is about using a **normal bike or SB-bike-sharing**.

The model performs the discrete choice models for complete tours. The input is derived from a shortest path algorithm through a constrained tour-based transport network. The optimization process is constraint per station and mode-chain. In the end this leads to attributes for each combination of stations and mode chains that is available in the choice-set. To find the available stations, the model looks with a maximal travel-time radius for the bike, what stations are available for each origin and destination.

The tour-based mode-chain approach is tested on the same case-study as the Visum approach. This gives the opportunity to test if the new approach can address the mentioned set of limitations. The results of the three scenarios were very promising:

- First of all, the case study **proves that the tour-based mode chain approach can deal with the consistency problem**. For the simple tour as well as the complex tour, the model gives consistent results. All bikes that are rented during the morning trip are returned in the evening trip to the same station.
- Secondly, the case study **proves that the tour-based mode chain approach can deal with the aggregation problem.** When the number of students increases, the model considers the correlation between the number of students and SB-bike-sharing usage.
- Lastly, the case study **proves that the tour-based mode chain approach can deal with the travel demand problem.** When the price of SB-bike-sharing decreased, the model estimated a significant increase of public transport demand. When SB-bike-sharing is free of charge public transport ridership increased with 16% compared to the situation with the normal price (€3,85). At the same time, free SB-bike-sharing results in 63% of the travellers that would use the shared-bike for their egress trip leg.

Given the results, this study concludes *that the "tour-based mode-chain and station choice approach" is capable of addressing the limitations of the current two-step mode choice approach. For this reason the new approach is from a theoretical perspective better capable to model the combination of tour-based mode choice and multimodality and is therefore more appropriate to model SB-bike-sharing.*

LIMITATIONS AND RECOMANDATIONS

This study also has some limitations. The approach used a frequency-based assignment procedure. To be able to better estimate transfer times it is suggested to combine the tour-based mode-chain approach with a hyper path assignment. Furthermore the approach to search for stations for each origin and destination must be reconsidered. When the current approach is used in a urbanized area, the number of stations in the choice set would grow substantially. Lastly there is a limitation that the method does not consider capacity constraints. Therefore it is suggested to test if the method is also applicable when performing multiple iterations.

Another important line of research is concerning the modelling effort of the tour-based mode-chain and station choice approach. The computational effort depends on the number of stations and mode-chains considered in the choice set. When assuming that each origin and destination have three station choices and four mode-chains available, the number of shortest path algorithms performed per origin destination pair is around 50. This means that for each origin and destination the model must also safe 50 extra matrices.

For future research it is suggested to applicate the tour-based mode chain approach to modelling park and ride facilities. Moreover, it is important to get better insights about computational applicability by using the model on a real case study.

INHOUD

1. INTRODUCTION

1.1 RESEARCH CONTEXT

The widespread use of private cars is causing problems for cities worldwide. In highly urbanized regions, there is continuously increasing travel demand, and at the same time, there are limited land resources (Tan, 2016). This combination can result in problems like travel time delay, unreliability, and greenhouse gas emissions (Van Eck et al., 2014). Therefore, looking for more sustainable transport modes and improving accessibility is an essential topic for authorities.

Authorities seek possibilities to increase the share of public transport and active modes like walking and cycling. Individually, these modes still cannot fully compete with private cars. Walking and cycling are only attractive modes for a limited spatial range and are vulnerable to bad weather conditions. Public transport does not offer the flexibility to provide door-to-door accessibility (Shelat et al., 2018b). However, combining private modes (like bikes) and public transport could be very promising. Public transportation access and egress time are an essential deterrent to transit ridership. This raises the interest in multimodal trips. “Multimodal trips are trips using two or more vehicular modes between which a transfer is necessary” (Fiorenzo-Catalano, 2007). It offers the flexibility of private modes and, at the same time, the efficiency and high capacity of public transport modes (Van Eck et al., 2014).

Good integration and coordination of transport modes make trips with multiple transport modes more attractive to travellers. For example, stations facilitate this by offering good parking facilities for bicycles, with easy and quick transfers to the train station (Brands et al., 2014). In the Netherlands, biking is already used for more than 50% of the trips to access the train. At the same time, using bikes for the last mile is less popular, with only 20% of the egress trips (Jonkeren, 2018) This can be mainly attributed to limited availability of private transport modes at the egress-side of the trip

The trend towards shared mobility offers an opportunity for this problem. In the Netherlands there is a nationwide bike-sharing system, especially designed to be an extension of the Dutch transit system (OV-fiets) (Bandeira, 2018). At most train-stations, there are shared bikes to cover the last-mile of a train journey. In contrast with free-floating sharing systems, the system requires users to return the bikes at the station where they rented it. This limits customers in their freedom to find and leave bikes at any place. However, it also gives an important advantage; bikes are distributed at stations which results in convenient transfers from public transport to the shared-bikes. During the rental period, users of the systems have complete freedom in the use of the bicycles and the place where they lock and park the bike (Bandeira, 2018). The certainty of the system makes station-based round-trip bike-sharing (from now on referred to as SB-bike-sharing) one of the most promising concepts to promote multimodal transport. The continuously growing demand of the SB-bike-sharing system confirms its market potential. In 2008, the nation-wide bike-sharing system was used for 0,5 million transport trips, in 2019 (before Covid 19) this number was 5.2 million transport trips (NS, 2019).

Authorities can be interested in making policies to promote the use of SB-bike-sharing in order to create a more sustainable transport system. Strategic transport modelling is a crucial tool in the decision-making process before implementing such policies (Van Eck et al., 2014). This is because strategic transport models are used to get insight into (uncertain) future conditions of the transport system. The models show the interaction between traffic supply conditions and traffic demand due to changing circumstances and input assumptions. For example, to see how the transport system reacts to economic, demographical, or land-use changes. Furthermore, transport models can be used to evaluate all kinds of policy measures with long term impact, such as the implementation of infrastructure (Bhat & Koppelman, 1999).

Strategic transport models are traditionally based on a sequential four- step procedure. In the first three steps the demand for transport is modelled and in the last step the modelled demand is assigned to a transport network. Modelling transport demand consists of modelling the number of trips, modelling destination choice and modelling mode choice. Transport modellers want to replicate travel behaviour to assess the effects of policies correctly. To be able to replicate behaviour as precisely as possible, transport models developed substantially through the years. Currently transport models may take many different forms. Depending on the modelling purpose, an appropriate modelling technique is chosen.

Modelling SB-bike-sharing is from a transport modelling perspective a challenging topic. It requires combining two transport modelling techniques. The first is focussed on realistically modelling the supply of SB-bike-sharing. As mentioned, the system requires users to return the bike to the station where they rented it. To do so, the model must consider complete transport journeys instead of separate transport trips. Tour-based modelling can in theory handle these kinds of problems. A tour is defined as: “a trip-chain which starts from a certain location (e.g. home) and returns to the same location after a series of trips (Bowman, Bradley, Shiftan, Lawton, & Ben-Akiva, 1998). Modelling tours instead of trips makes it possible to model consistency between different trips in a transport tour. Such consistency is that a person that chooses to rent a bike in the morning has to return the bike to the same station in the afternoon. Modelling tour-based mode choice is not an extensively studied topic. Therefore modelling methodologies often rely on simplifications in this regard. In those models a single transport mode is used for the entire tour. Those models do not consider that travellers in reality often use multiple modes within their transport tour (Hasnine & Nurul Habib, 2020).

This problem becomes evident when looking at demand characteristics of SB-bike-sharing. SB-bike-sharing is designed as an extension of the public transit network. This means that travellers use the system in general in combination with other transport modes. This introduces the other topic that is vital for this research, which is modelling multimodality. Many transport models rely on unimodal transport networks. Which means that it is not possible to switch modes during a transport trip or tour. In multimodal transport modelling the unimodal networks are connected at transfer stations (Van Eck, 2014). This makes it possible to combine multiple transport modes during the transport journey. This topic is challenging because it results in many transport alternatives to travel from an origin to a destination. When modelling a complete transport tour, the number of alternatives will be even higher, as travellers could choose to use different transport modes for their returning trip. To make a choice between different transport routes, characteristics of the complete journey must be considered. These are for instance elements like the time to reach a station (access-time), the time to travel from the station (egress-time), the transfer time between different transport modes, the resistance of a transfer and of course the in-vehicle time.

The last two sections show the challenge of the two different modelling requirements to model SB-bike-sharing. On one hand the model must guarantee consistency to model the fact that people have to return a bike to the place where they rented it. On the other hand the model must be able to consider multimodal transport tours. This makes it rather challenging to integrate SB-bike-sharing into strategic transport models.

1.2 THE PROBLEM STATEMENT

Currently SB-bike-sharing is not modelled in strategic transport models used in practice. This can be attributed to the fact that strategic transport models used in the Netherlands until recently did not have the functionalities to model multimodality in a tour-based model. As elaborated in the introduction, these are two essential modelling components to model SB-bike-sharing.

However, the municipalities of Groningen and Lelystad and the province of Utrecht recently shifted to the transport modelling software P.T.V Visum 2021 (P.T.VGroup, nd). P.T.V Visum is a popular strategic transport modelling software and used by many authorities worldwide. The approach is referred to as the "Visum" modelling approach. The modelling software combines the topics of tour-based modelling and multimodality and could therefore be an appropriate model to implement SB-bike-sharing. As municipalities mainly switch to new transport models to model new developments in the transport sector, it becomes relevant to see if the new type of transport models are indeed capable of modelling developments like SB-bike-sharing.

As became clear in the introduction, combining tour-based mode choice and multimodality is not a straight-forward task. The most prevalent option used in literature and in practice is the "Two-step-mode choice" approach. In this approach first a main tour-mode choice is modelled, multimodality is then modelled on trip-level, conditioned to the main-mode choice. Also the modelling approach in Visum uses a two-step mode choice approach to model multimodality. From analysing the approach, it becomes evident that there are three important limitations to realistically model the SB-bike-sharing system (later in the research explained in more detail):

- *There is no tour consistency in the choice for SB-bike-sharing*. This means that someone that bikes from a certain station on the outgoing trip does not always use a bike to return to the same station on the returning trip.
- *The demand for SB-bike-sharing is not influenced by different socio-demographics.* This means that It is not possible to consider that some person types and activity purposes are more likely to use SB-bike-sharing compared to others.
- *The demand for public transport is not influenced by SB-bike-sharing*. This means that policies regarding SB-bike-sharing would never influence public transport ridership in the model.

This research uses the mentioned limitation to model SB-bike-sharing as a tangible case to address a bigger problem of the current model of Visum. This problem is regarding the two step-mode choice approach, that is used to model tour-based mode choice and multimodality in Visum**.** This leads to two main research objectives:

1. *Implementing SB-bike-sharing in a two-step mode-choice approach to quantitatively illustrate the limitations of modelling tour-based mode choice and multimodality in Visum.*
2. *Create an approach to combine tour-based mode choice and multimodality in order to address the limitations of the current Visum modelling approach.*

The problem addressed in this research is relevant from an academic perspective as well as from a practical perspective.

1.2.2 ACADEMIC RESEARCH CONTRIBUTION

From an academic perspective the research contribution is purely focussed on combining the topics of multimodality and tour-based mode choice. The two-step mode choice approach is at this point in time (2021) an accepted methodology to combine multimodality and tour-based mode choice. Therefore, it is interesting for academics to get more insights about limitations of this approach.

More importantly, the created approach in this study will be a valuable addition to the current tour-based mode choice modelling methodologies. The created approach is designed to tackle the limitation of the two-step mode choice approach. For this reason, the created approach could become the new standard to combine multimodality and tour-based mode choice.

1.2.1 PRACTICAL RESEARCH CONTRIBUTION

From a practical perspective the research contributes by performing a first step towards implementing SB-bike-sharing to the current modelling approach of Visum. The two-step mode-choice approach that is used in Visum is also used in many other strategic transport models used in practice. This means that conclusions that are drawn about limitations of the two-step mode-choice approach are interesting for a wider public than just users of the PTV. Visum software.

Properly modelling the combination of multimodality and tour-based mode choice also has more applications than modelling SB-bike-sharing.

- To start with, modelling the use of the normal bike for multimodal journeys relies on the same modelling components. People that use a bike to reach a station on a daily basis will have to return to the same station later in the transport journey in order to perform the same transport journey the next day. This means that aside from modelling multimodality it needs to model consistency in the mode choice between multiple trips in a tour.
- Another important example is modelling park and ride facilities. Promoting the use of Park and Ride facilities receives a lot of attention by authorities nowadays. Park and ride facilities are used to transfer from the car to public transport. Hence, park and ride facilities facilitate multimodal transport. Besides, park and ride facilities require users of the system to return to the parking facility later in their transport journey.

The research is focussed on modelling SB-bike-sharing. Still, many of the conclusions that are drawn regarding limitations and opportunities to model SB-bike-sharing can be generalised to park and ride facilities and normal multimodal biking journeys as well.

1.3 RESEARCH QUESTIONS

The two research objectives are translated into a set of research questions. How the sub-questions relate to each other and answer the main research questions is explained in the research method in the following section. The following set of research questions will be addressed in this research:

How to create an approach that combines multimodality and tour-based mode choice in order to realistically implement SB-bike-sharing in strategic transport models?

The following sub questions will help to find an answer to the main research question:

1. What are the modelling requirements to realistically model SB-bike-sharing?
2. How can SB-bike-sharing be implemented in the Visum modelling approach?
3. What are the limitations of the Visum modelling approach looking at the requirements to model SB-bike-sharing?
4. How to create an approach that combines multimodality and tour-based mode choice?
5. Is the created modelling approach able to address the limitation of the current Visum approach to model SB-bike-sharing?

1.4 RESEARCH METHOD

This paragraph will elaborate what method is used to answer each of the research questions.

1. **What are the modelling requirements to realistically model SB-bike-sharing?**

- Finding characteristics about SB-bike-sharing. → (Literature)

Transport model try to replicate reality. Consequently, to model SB-bike-sharing, knowledge is needed about characteristics of SB-bike-sharing. Characteristics refer to characteristics from a supply perspective and a demand perspective. The supply perspective discusses characteristics from the system itself (such as the speed and price from the system). The demand perspective focusses on determinants for the demand of SB-bike-sharing.

- Categorization of important modelling choices within the field of strategic transport modelling. → (Literature)

There exist many different types of transport models. Depending on the modelling purpose an appropriate modelling technique is chosen. To find an appropriate approach to model SB-bike-sharing knowledge is needed about the choices that can be made within the field of transport modelling. To do so, there is made a categorization of transport models.

- Translate the characteristics of SB-bike-sharing based on existent modelling methodologies to a set of modelling requirements. → (interviews and literature)

Based on the categorization and the characteristics of SB-bike-sharing there is substantiated what modelling components are needed to model SB-bike-sharing. To get a better understanding about current practice in transport modelling a set of interviews was conducted with transport planning practitioners.

2. **How can SB-bike-sharing be implemented in the Visum two-step mode-choice approach?**

One of the research objectives is to substantiate the problems of modelling SB-bike-sharing with the Visum two-step mode choice approach. Implementing shared-mobility in the software of Visum itself is a complex and time-consuming task. Hence, there is chosen in this study to replicate the relevant modelling steps for the implementation of SB-bike-sharing in Microsoft Excel. There are tools in excel that make it possible to automatically optimize shortest paths. With repeated shortest path searches and all formulas used in the Visum two-step mode-choice approach it is possible to replicate this model. Relevant steps within the Visum approach refer to all steps that are related to the Visum two-step mode choice approach. Developing the Visum two step mode choice approach in Excel has two more advantages:

- It gives in depth insights in how the modelling procedure works. This can be used to identify and address limitations regarding modelling SB-bike-sharing.
- It makes it possible to make a new approach in the same software in order to compare both models based on the same case-study.

Developing the modelling steps is based on interviews with developers of the strategic transport model Stravem. Stravem is the strategic transport model of Utrecht and is developed in the software of P.T.V Visum 2021. Furthermore P.T.V Visum 2021 has a helping guide that gives an in depth explanation of all modelling steps in the model.

3. **What are the problems of the current Visum approach to model SB-bike-sharing looking at the modelling requirements**?

When SB-bike-sharing is implemented in the replicated model in Excel, it is possible to identify the limitations for the implementation of SB-bike-sharing in the Visum two-step mode choice approach.

This analysation will be substantiated based on a theoretical small-scale case-study. The case-study uses a multimodal transport network consisting of 9 nodes. The network is chosen in order to have:

- Enough explanative power to indicate the limitations of the Visum approach.
- Enough multimodal transport options from the origin to the destination.
- A feasible network size for shortest path algorithms in Excel.

The replicated Visum two-step mode choice approach with the implementation of SB-bike-sharing is used to simulate a set of three scenarios. The scenarios are formulated such that they can quantitively illustrate the limitations of the Visum two-step mode choice approach. Findings regarding limitations in the replicated model can be generalised to the real model of Visum.

4. **How to create a new approach in order to address the limitations of the Visum two-step mode-choice approach?**

This research wants to address the limitations regarding the two-step mode-choice approach to model SB-bike-sharing. Therefore a new method is created to combine multimodality and tour-based mode-choice. The new approach is created based on the following information:

- Existent studies to model multimodality. Next to the two-step mode choice approach that is used in practice there are also methodologies described in the literature. Therefore a literature study is performed to existent modelling methodologies to model multimodality.
- The requirements to model SB-bike-sharing.
- The limitations of the Visum two-step mode-choice approach to model SB-bike-sharing.

5. **Is the new approach able to overcome the mentioned problems of the Visum two-step mode choice approach?**

The new approach is also developed in Excel in order to perform the same case-study as the Visum two-step mode-choice approach. By simulating the same set of scenarios it is possible to draw conclusion about whether the new modelling approach can address the limitations of the two-step mode-choice approach to model SB-bike-sharing.

Based on this set of research questions conclusion can be drawn regarding the main question:

How to create an approach that combines multimodality and tour-based mode choice in order to realistically implement SB-bike-sharing in strategic transport models?

The conclusions drawn for SB-bike-sharing are in the conclusion generalised to other concepts that rely on a tour-based mode choice and modelling multimodality.

1.5 RESEARCH DESIGN

Literature research and interviews

Chapter 2 – Multimodal transport and SB-bike-sharing

Chapter 3 – Modelling requirements (Combining heterogeneity, tour-based mode choice and multimodality)

Chapter 4 – In depth literature about Tour-based mode choice modelling and multimodality

Problem description

Chapter 5 – Implementing SB-bike-sharing to the Visum approach

Method – New modelling approach

Chapter 7 – Explanation of the new modelling approach

Results – case study

Chapter 8 – Results of the new modelling approach (effects of interesting policy scenarios regarding SB-bike-sharing)

Conclusions and recommendations

RESEARCH PHASE AND LITERATURE STUDY

2. MULTIMODALITY AND STATION-BASED BIKE-SHARING

Transport models want to replicate reality as precisely as possible. This means that when SB-bike-sharing is implemented in strategic transport models, the models must be able to replicate characteristics of the system. Besides, the model must be able to recognize determinants for the demand of the system. For this reason, it is essential for this research to know characteristics of SB-bike-sharing. SB-bike-sharing is used to promote multimodal transport. Therefore this paragraph will start off by explaining something about multimodal transport and elaborate why multimodal transportation is an interesting development for authorities. Afterwards, there is discussion on how SB-bike-sharing can facilitate more multimodal transportation. Lastly, there is elaborated about characteristics of SB-bike-sharing from a supply perspective as well as from a demand perspective.

2.1. MULTIMODAL TRANSPORT TERMINOLOGY

This paragraph will explain what multimodal transport is and discuss some relevant terminology regarding multimodal transport trips for this study. First, it is important to understand the difference between uni-modal and multi-modal transportation.

- *Unimodal transport* journeys are characterized by the fact that there is only one transportation mode used to travel from an origin to a destination. Hence, most transportation by car is considered unimodal. People most likely have a car close to their origin and drive to a parking place nearby the destination. (Bandeira, 2018).

- "*Multimodal trips* are trips using two or more vehicular modes between which a transfer is necessary" (Fiorenzo-Catalano, 2007). "Vehicular modes", refers to the fact that walking is not considered as part of a multimodal trip. This is because walking is considered to be part of any trip. Next, transfers are an essential part of multimodal trips:
    - *Intra-modal* transfers are transfers within uni-modal public transport networks. transferring from one urban bus line to the other is an intra-modal transfer.
    - *Inter-modal* transfers are transfers between different transport service networks or modes, such as for instance between bike and train or bus and train. Hence, multimodal trips contain one or multiple intermodal transfers (Fiorenzo-Catalano, 2007).

An example of a multimodal trip with the main transport mode train is visualised in figure 2.1. Each multi-modal trip contains an access trip leg, a main trip leg and an egress trip leg.

- *The access trip leg* refers to the transport leg which is used to travel from the home-end origin to a station where a person can transfer to the main transport trip leg.
- *The main transport trip leg* is defined as the trip leg that covers the largest amount of the total trip distance.
- *The egress trip leg* is the part of the trip where a person travels from the station to the destination at the activity-side of a trip (Bandeira, 2018).

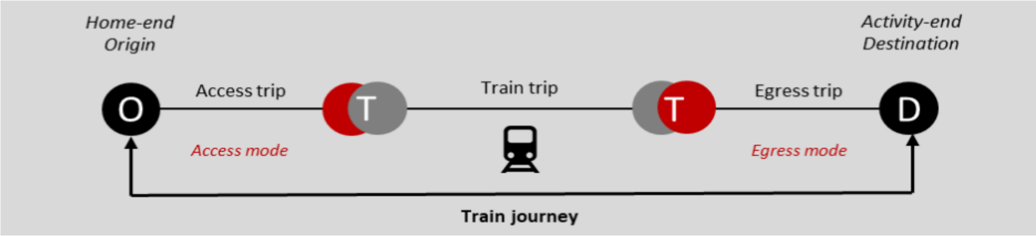


Figure 2.1: Multimodal transport trip with the main transport leg Train retrieved from (Bandeira, 2018)

2.2 STIMULATING MULTIMODAL TRANSPORTATION AT THE EGRESS-SIDE

This paragraph substantiates the attractiveness of multimodal transport and argues that there is latent multimodal transport demand at the egress-side of transport trips.

The reason that multimodal trips receive a lot of interest by authorities in many west European countries is that it offers the flexibility of private modes and, at the same time, the efficiency and high capacity of public transport modes (Van Eck et al., 2014). Unimodal trips by public transport lack flexibility to offer door-to-door accessibility. Active modes like biking are only attractive for a limited spatial range (Shelat et al., 2018b). Figure 2.2 illustrates how combining the two can result in a transportation mode that can compete with the car. Consequently, promoting multimodal transport could in the end result in reducing road traffic congestion and increasing public transport use (Fiorenzo-Catalano, 2007).

Despite its potential, multimodal trips in the Netherlands only account for around 3% of the total number of trips. Because multimodal trips are on average relatively long with 41km, the total share of multimodal transport represented in transport kilometres is around 10% (Van Nes et al., 2014; Shelat et al., 2018a).

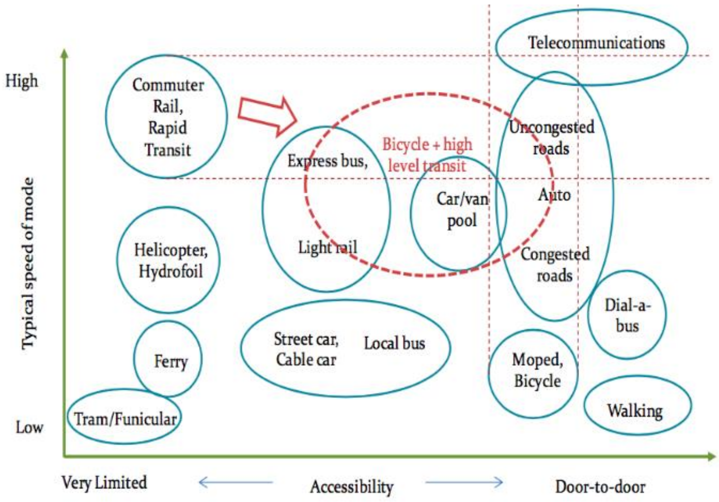


Figure 2.2: Comparison between multimodal transport (bike + high level transit) and other modes of transportation in terms of speed and accessibility, retrieved from (Shelat et al., 2017)

Combining biking and high level transit is one of the most promising combinations of multimodal transport. Biking can, compared to walking, significantly increase the catchment area of transit stations, and for this reason overcome the first and last-mile problem of the high level transit modes. This means that regions with limited public transport accessibility become better accessible. The median access distance is 550m and 1,8Km for walking and biking respectively. The median egress distance is 600m and 2.4Km for walking and biking respectively (Shelat et al., 2017).

The potential of combining high-level transit and the bike is in the Netherlands confirmed by the high share of people that bike towards train-stations. The numbers are retrieved from the Dutch mobility penal KIM (kennisinstituut infrastructuur en mobiliteit) (Jonkeren et al., 2018):

- *The share of people using a bike to access the train station in the Netherlands is around 55%.*
- *The share of people using a bike to egress the train station in the Netherlands is around 20%.*

As can be seen, the number of people biking at the egress-side of a transport trip is relatively low. This has to do with the fact that people often have no private bike available at the egress-side of a transport trip. There can be concluded that there is most likely a latent demand to use a bike at the egress side of multimodal transport trips (Jonkeren et al., 2018).

2.3 STATION BASED BIKE-SHARING AS SOLUTION

This paragraph substantiates that station-based bike-sharing is used as a solution for the latent demand at the egress-side of transport trips and will explain characteristics of SB-bike-sharing from a supply perspective.

Given the fact that authorities want to stimulate multimodal transport, it is interesting to search for policies that can stimulate biking at the egress-side of public transport trips. There are three main options to bike at the egress-side of public transport trips. First is to park a bike at the activity-side of a transport trip. The second option is to have a folding bike that people carry with them on the main trip leg. Lastly, people can use shared-mobility.

" Shared mobility is the shared use of a vehicle, bicycle, or other low-speed modes that enable users to have short-term access to transportation modes on an "as-needed" basis, often serving as a first- or last-mile connection to other modes, such as public transit" (Shaheen & Chan, 2016).

The first two mentioned options have important disadvantages. When high shares of public transport users would park a bike at the activity side of a transport trip, it would give capacity problems to the bike-parking facilities. On the other hand, when high shares of people would use a folding-bikes it would take up lots of space in the public transport vehicles.

For this reason, promoting shared-mobility is an interesting opportunity for authorities. In the Netherlands there is a nation-wide bike-sharing system called *"OV-fiets",* that was specifically designed as an extension of the public transport network to cover the last-mile. The system proves its potential, in 2019 there were 5.2 million transport trips with the OV-fiets (NS, 2019). The system also contributed to the increase of biking at the egress-side of transport trips from around 11% in 2008 to around 20% in 2020 (Jonkeren et al., 2018).

Bikes are rented out *at fixed locations*. Therefore the system is considered as a Station-Based system, and from now on the system is referred to as SB-bike-sharing. There are currently bikes available at almost 300 locations in the Netherlands. These are mainly train stations. However, there are also bikes available at some bus, tram and metro stations, city centres, and at some park and ride facilities (Bandeira, 2018).

Furthermore, the system is characterised by the fact that it is *a round-trip system*. This means that a person who rents a bike has to return the bike to the same location. What makes the system attractive is the fact that a person can *unlimited use of the bike during the rental period*. It is also possible to *lock and park the bike at any place* a person wants. Besides, the bikes are completely *similar to conventional bikes* and have no special tires (Bandeira, 2018).

The system is designed mainly for Dutch travellers, as it is required to own a public transportation card to be able to use the system. For those who have a transportation card, the subscription is free of charge. Each time that someone wants to use the system *it costs €3,85 per day*. The bike has to be returned within three days (Bandeira, 2018).

This research focuses purely on SB-bike-sharing. There are also other shared mobility systems available on the market. The most important alternative for SB-bike-sharing are free-floating sharing systems; those systems give no parking restrictions for their vehicles. This means that people can leave the vehicles anywhere they want.

From a multimodal perspective, station-based sharing gives advantages. Companies and authorities can place the sharing stations strategically to serve as an extension of the public transport system. With free-floating sharing, there is no guarantee that vehicles are available at public transport stations. This can result in longer access times to the sharing system. Furthermore, when people use the free-floating system to reach an activity location, they have no certainty that this transport mode is still available for their returning trip.

2.4. DEMAND CHARACTERISTICS OF SB-BIKE-SHARING

This paragraph elaborates what socio demographics, trip elements and mode characteristics influence the potential use of SB-bike-sharing.

In a research on determinants of the willingness to use shared mobility Arendsen (2019) summarizes a set of decisive factors that influence the mode choice. First of all, characteristics of the available transport modes play a role, then there are factors related to the trip that a person wants to make and lastly there are factors that are related to the traveller itself.

- *Mode characteristics*. This refers to the characteristics of the transport mode itself. Choosing between different transport modes is often a trade-off between *travel time* and *travel cost*. The travel time for a specific trip depends on characteristics of the trip, but also on the speed of a transport mode. Next to the quantitative characteristics of a transport mode also qualitative elements such as the convenience of the transport mode can play an important role (Arendsen, 2019).

- *Trip characteristics*. This refers to characteristics of the transport trip that a person wants to make. Depending on *the trip distance*, people are more likely to use a certain transport mode. The bike is for example mainly used for relatively short transport trips. Besides, each trip has a certain *travel motive*. The travel motive refers to the type of activity a person wants to perform. For some travel motives people are willing to travel a longer time compared to other motives. This is indicated by *the value of time*. Also the *type of urban area* where a trip is performed can be a decisive factor. In dense Urban areas people use more public transport (Arendsen, 2019). Also external factors influence the trip and with that also the mode-choice. For example the weather can influence the choice for a certain mode.

  Last but not least, for *multimodal transport trips* it is important *to consider characteristics of the complete door to door transport journey*. For example the distance of the main-transport trip leg is an influential factor for the chance that a person uses a bike for the first or last mile. People are more willing to bike to a station when the main-transport trip leg also has a significant length. Lastly people also consider the *type of stations* that are available during a transport trip. Some stations make the combination of biking and public transport more attractive than others (van Mil et al., 2020).

- *Socio demographic characteristics.* Socio demographics relate to characteristics of the traveller itself. This can for example be the *age, gender, education level, income and vehicle ownership.* Also less straightforward characteristics can be considered. An example can be how *familiar a person is with a technical development* or what his *attitude is towards new technological developments.* (Bandeira, 2018).

Given these three general determinants for mode choice it is interesting to see what the most decisive factors are for the use of bike-sharing. The research of Arendsen (2019) points out that the familiarity of shared mobility is an important determinant for the use of the system. People are relatively familiar with bike-sharing in the

Netherlands due to the OV-fiets. For the shared bike they indicate that costs and travel time aspects such as the transfer time and biking time are important factors. The sensitivity of the cost of the system is even higher compared to conventional public transport modes . In addition, characteristics of travellers must be considered. In general young people that use the train for commuting are more likely to use shared mobility.

In the research of Bandeira (2018) they conclude that the cost of the system and the reliability of having shared-mobility available at the egress side of a transport trip are the most decisive factors. Moreover, the access time to the system, the egress time and the reliability to have the bike available at the end point of the trip also have a significant influence. The OV-fiets are currently mainly used for trip motives that are associated with visiting friends and family members (42%). Business and work related trips are less often the trip-motive (18%). An important reason can be that people find the OV-fiets at this point too expensive for daily use (Bandeira, 2018).

There is also research into the modal shift as a result of different bike-sharing systems (Ma et al., 2020). This research indicates that the use of the OV-fiets 36% percent less walking trips, and that 60% used the tram and bus less than before. Also the relation between the OV-fiets and an increase of train-use was confirmed. Train use increase was reported for 16% of the OV-fiets users. The most important factor to use the OV-fiets instead of other modes was saving time. The research also suggests that a good connection between public transport and the OV-fiets as well as subsidies can encourage commuting people to use the OV-fiets more often.

2.5 CONCLUDING REMARKS

Multimodal transport is used to let public transport compete with the car. Because of the low shares of people that bike at the egress-side of transport trips, SB-bike-sharing has the potential to promote multimodal transport.

Important supply characteristics of SB-bike-sharing are that:

- The system is *station-based*, which means that the system is only rented out at predetermined stations
- The system is *round-trip based*, which means that people that rent a bike have to return the bike where they rented it.
- The system *charges per day and not per trip*.
- The bikes of the system are completely *similar to normal bikes*.

Important determinant for the supply of SB-bike-sharing are categorized in mode characteristics, multimodal trip characteristics and socio-demographics.

- *Mode characteristics* such as the speed and the price of SB-bike-sharing are important factors for the use of the system.
- *Multimodal trip characteristics* refer to all elements that are part of the door to door journey. Examples are the trip motive, the trip distance, the main transport leg, the access and egress transport leg and the station choice.
- *Socio demographics* refers to personal characteristics that influence the demand for SB-bike-sharing. SB-bike-sharing is for example mainly used by students.

3. THE STRATEGIC TRANSPORT MODELLING REQUIREMENTS

Given the characteristic of SB-bike-sharing as discussed in chapter 2, this chapter will substantiate the strategic modelling requirements to model SB-bike-sharing. Strategic transport models are used to get insight into future conditions of the transport system. For example, to see how the transport system reacts to economic, demographic or land-use changes. They are also used to evaluate the effect of different scenarios on the transport system. Transport modellers want to replicate travel behaviour to assess the effects of policies correctly. To be able to replicate behaviour as precisely as possible, transport models developed substantially through the years. Currently transport models may take many different forms (Kwak, 2010). Depending on the modelling purpose, an appropriate modelling technique is chosen. This chapter starts with an overview of all needed modelling characteristics to model SB-bike-sharing. Then, all requirements are discussed individually in the following paragraphs. This chapter will give an answer to the research question:

1. What are the modelling requirements to realistically model SB-bike-sharing?

3.1 THE TRANSPORT MODELLING CATEGORIZATION

Table 3.1 categorizes choices for transport modelling methodologies. This paragraph elaborates about the modelling requirements for SB-bike-sharing. This is done based on interviews with experts and practitioners in the field of strategic transport modelling.

Modelling transport is about finding a balance between the needed functionality, modelling detail and modelling accuracy on one side and building effort, computational effort and data needs on the other side. To get an understanding of current practice in the transport modelling market, interviews were held with transport planning practitioners. Interviews were performed with practitioners working for commercial parties as well as practitioners working for the Dutch authorities. The list of practitioners interviewed and the topics discussed during the interviews can be found in the appendices A.

Table 3.1: Categorization of transport modelling strategy choices

Modelling topics:	**Option 1**	**Option 2**	**Option 3**	**Option 4**
Aggregation of supply	**Macro supply modelling**	Micro supply modelling	(Agent-based)	
Aggregation of time	**Static modelling**	Dynamic modelling		
Unit of travel Demand	Trip- Based	**Tour- Based**	Activity-Based	(Agent-Based)
Behavioural Aggregation	Aggregated demand	**Disaggregated demand**	Individual demand	
Modelling Multi-modality	Unimodal modelling	**Multimodal modelling**		

3.2 STATIC MACROSCOPIC MODEL

This subparagraph explains that the fact that the transport model used for this study is static and macroscopic, follows from the objective of the research to implement SB-bike-sharing into strategic transport models.

We want to implement SB-bike-sharing to strategic transport models in order to have a tool to see how policies regarding SB-bike-sharing influence the transport system. As an illustration, the model should estimate the effect of lowering the price of bike-sharing on the number of cars on a road section. In order to do so, transport supply and transport demand relations are essential. This kind of relative long-term supply and demand relations belong to the field of strategic transport models (Calvert et al., 2016)

The interviews showed that strategic models in the Netherlands always rely on static input data and present traffic macroscopically. Even the most advanced approach on the Dutch market, called “Feathers”, uses static input data and has a macroscopic network representation (Snelder, M, Personal communication, 05-10-2020).

Macroscopic supply models calculate average traffic flows analytically, this is based on the traffic demand and travellers route-choice. It describes traffic by concepts like density (vehicles per meter), traffic flows (vehicles per second) and average speed (meter per second). Because the model does not consider individual vehicles, more detailed traveller choices like lane choice, speed and following distance are not considered.

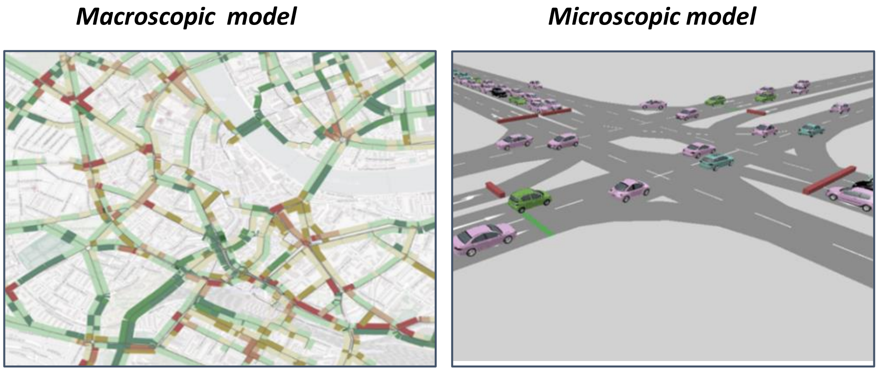


Figure 3.1: Difference between macroscopic and microscopic transport models (Calvert et al., 2016)

Static assignment models calculate average conditions during a longer period of time regarding the traffic demand, the traffic costs and the route choices. In static assignment models, the traffic volume is directly calculated based on stationary Origin and destination matrices. The inflow of a particular link always equals the outflow. When the inflow increases, the travel time also increases.

The reason that strategic transport models in the Netherlands are stationary is that dynamic models need detailed input data and are computationally heavy. Dynamic models need every small time window (approximately every 5 minutes) input data on origins and destination relations of travellers. This kind of detailed information is hard to gather, especially when testing scenarios in the long term. Similarly, modelling dynamics is computationally heavy because it has to model each time window a separate network state.

As microscopic simulation models are dynamic by nature, the same problems go for this type of model. Moreover, running simulations goes hand-in-hand with stochastic outcomes. When testing scenarios, different model outcomes can result from the different scenarios or can be caused by the stochasticity of the model. Therefore, many model runs are needed to obtain average results. This will lead to high computational effort and calculation times for reliable model outcomes (Rasouli & Timmermans, 2014; Miller, 2018).

Agent-based models are currently also not feasible to use for strategic transport planning. Those models have the same problems regarding stochasticity. Moreover, agent-based models demand detailed input data, which is not only costly, but also difficult to acquire (Omer et al., 2010).

3.3 TOUR-BASED MODELLING

This paragraph substantiates that given the fact that SB-bike-sharing has round-trip constraints, that the model used for this study should be tour-based.

The unit of travel demand refers to the choice if a model explains travel demand based on trips, tours or activity schedules. Demand for transport arises because people want to perform activities in different locations ((Miller, 2018)Activities can have different purposes: like working, doing groceries, sporting, but also being at home. The movement between two different activities is called a trip. A tour is defined as a trip chain starting at some location and eventually returning to the same location after a series of trips to perform activities (Hasnine & Nurul Habib, 2020). When a person starts at home, is going to work, and after work is doing groceries before returning home again, this is referred to as one tour. This tour consists of 3 different trips (home – work, work – groceries, groceries – home). Travel demand can also be modelled as a result of the combination of activity schedules. A tour stops when a person returns to its start location (mostly home). However, after a person comes home, this person could decide to perform another activity. It is possible to include this choice within one activity schedule.

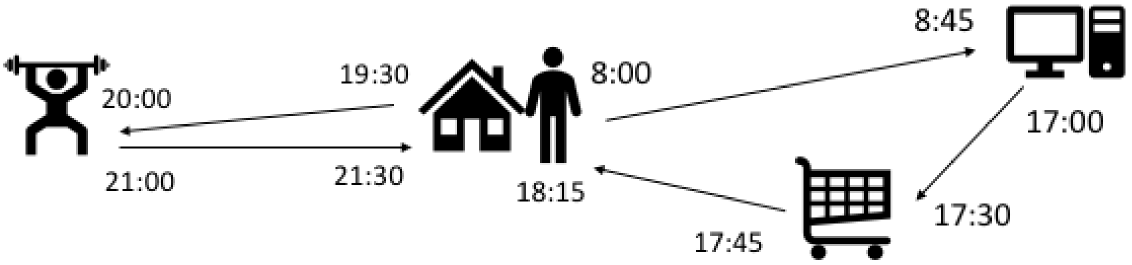


Figure 3.2: 1 Activity schedule with 2 tours and 5 trips

One of the characteristics of SB-bike-sharing is that it is a Round-trip sharing system. This means that travellers have to return the bike at the station where they rented it. In transport modelling jargon, travellers use the shared bike for multiple trips within a tour. This is visualized in figure 3.2. First, the bike is used to reach destination A, in the second trip, the bike is used to reach destination B, and in the third trip, the bike is used to return to the train station. This makes it for three reasons important to consider tours instead of trips:

- As previously stated, tour-based models can model consistency between multiple trips within a tour. This means that the model can restrict people to use the same transport mode for multiple transport trips in their tour. As the bike-sharing system obligates people to return the bike to the station where they rented it, this consistency is essential to replicate the sharing system. A tour-based model can, in theory, capture this effect. In Figure 3.2, the model would constraint the traveller to only allow the tour on the left side.

- Next to modelling consistency, a tour-based model can better capture the attractiveness of SB-bike-sharing. In reality, one of the reasons to use the shared bikes is that they give the flexibility to perform multiple trips at the activity side of a tour. Hence, people that perform multiple activities before returning home are most likely to use the system. This effect is only captured when modelling tours instead of separate trips.

- Lastly, a trip-based model would have difficulties modelling the financial aspect of the bike-sharing system. People pay when they rent a bike for a complete tour. It is hard to capture the price when modelling trips, as you do not know in advance the number of trips that a person makes during their transport tour. When it would be sure that a tour consists of two trips, the price in the trip-based model could be half the price of the system. However, there are also many tours with more than two trips, making the price per trip even lower (the price for a tour divided by the number of trips).

Altogether it is apparent that the model should model tours instead of trips. Modelling only tours or complete activity-schedules is a trade-off between data availability and the needed functionality. Activity-based modelling frameworks rely on individual activity schedules. Especially when making long-term predictions, those individual activity schedules are hard to estimate. Besides, it is questionable if modelling consistency between multiple tours within a day is necessary. The bike-sharing system is intended for use on the activity side of a trip. Thus, people usually return the bike before going home. Assuming this is the case, the use of SB-bike-sharing is fully captured within one tour and can be modelled with a tour-based model.

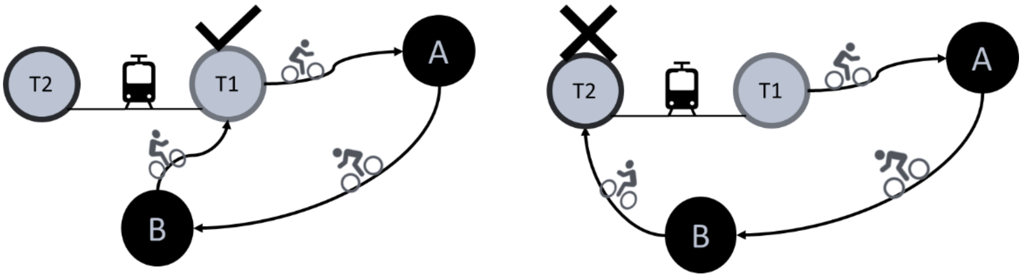


Figure 3.3: Consistency constraint, tour at the left is permitted, tour at the right is not

3.4 MODELLING HETEROGENEITY

This subparagraph substantiates that because of different perceptions regarding SB-bike-sharing it is important to model heterogeneity in the population with a disaggregated model.

Another characteristic of transport models is the level of behavioural aggregation. The behavioural aggregation level refers to what models see as the decision-making unit in the model. This can be an individual (microscopic), a group of people with the same characteristics from a certain area (disaggregated) or all people from a certain area (aggregated). The different levels of aggregation are visualized in figure 3.4.

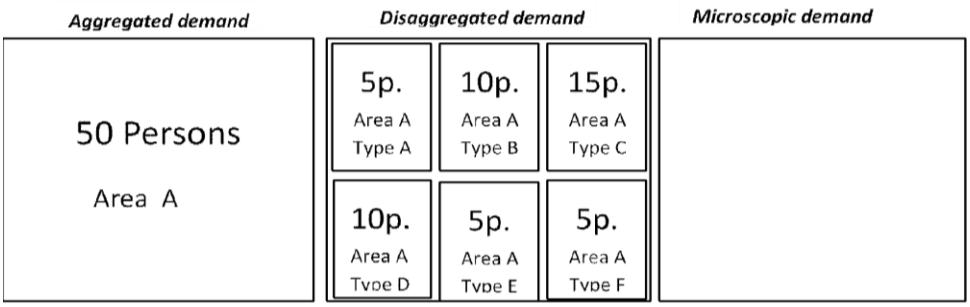


Figure 3.4: Visual representation of behavioural aggregation levels

Modelling different perceptions regarding the SB- bike-sharing system within a population is essential. Social demographics are an important determinant for the use of the system. This refers to the fact that some groups are more likely to use the bike-sharing system than other groups. Likewise, for some activity purposes, there is also a higher chance that travellers use bike-sharing. This kind of differences in user preferences can be modelled in disaggregated modelling methodologies. When students have an intrinsic preference for bike-sharing, the model deals with this by setting the parameters for this group accordingly (changing the mode-specific constant). In the same way, the model can consider intrinsic preferences to use bike-sharing for specific activity purposes. This is visualized in figure 3.5; different person groups and activity purposes will all affect the chance that a traveller uses the bike-sharing system.

Within the disaggregated transport models, it is possible to model at a microscopic demand level or at a group level. Again, this is the trade-off between modelling detail and data availability. So if modelling at the group level seems appropriate, this is the preferred option. Looking at the current literature on characteristics of users and potential users of the SB-bike-sharing system, it is noticeable that user characteristics of the system are not available at a high detail level. This means that even when the model would have the functionality to model at the individual level, there is no information available on how this would affect the bike-sharing system. This shows the difference between modelling detail and modelling accuracy. Even though modelling on the micro-level is more detailed, it is not necessarily more accurate.

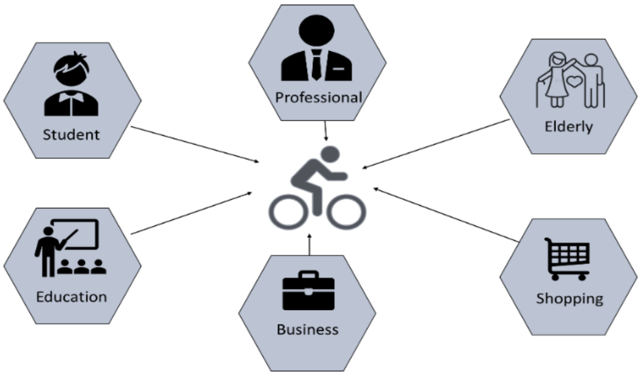


Figure 3.5: The reason to model disaggregated, user specific characteristic and activity purposes can be considered when calculating the demand for SB-bike-sharing.

3.5 MULTIMODAL MODELLING

This paragraph substantiates the reason that the model used in this study must be able to model multimodality.

Lastly, transport models can be distinguished in unimodal or multimodal models. In unimodal models, the transport model assumes that only one transport mode is used during a tour or trip. In multimodal models, it is possible to change modes during a transport tour. This difference is visualized in **figure 3.6**.

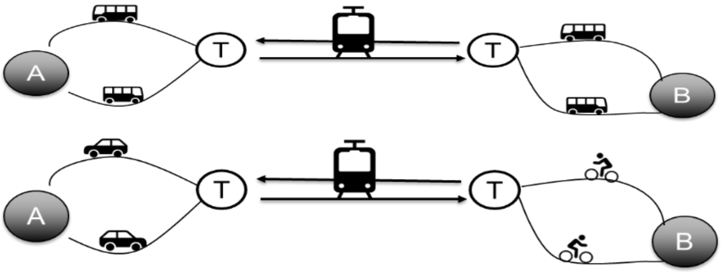


Figure 3.6: Unimodal transport trip above (with public transport) versus a multimodal transport tour below (combining public transport with car and bike)

To realistically model the demand for SB-bike-sharing modelling, multi-modality is a vital component of the modelling strategy. As pointed out, the bike-sharing system is used to promote multimodal transport. Accordingly, the system is used in combination with other public transport modes so that they work complementary to each other. Stimulating the use of public transport will also influence the use of SB-bike-sharing and vice versa. Therefore it is essential to model both systems in relation to each other in a multimodal model.

In figure 3.7 a multimodal trip is illustrated within each stage of the trip determinants for the use of the trip chain. First, there is an access trip leg with a certain travel time. Then there is a transfer with a certain transfer time and transfer resistance. Followed by the transit trip itself with a number of transfers and with certain cost and travel time. When the transit leg is finished, travellers will transfer to the egress mode, which is in this case, the shared bike. The transfer again has specific resistance and transfer time. As bike-sharing has a price, this transfer also contains information about the price of the system. The last measurable determinant would be the travel time with the shared bike. Next to measurable components, there are also external factors and personal preferences playing a role in choosing a multimodal trip.

As can be noted, the transfers are important determinants for the attractivity of the trip chain. Therefore the multimodal models include transfer links in their transport networks. Those transfer links contain all essential information about the transfer times and resistance. Transfer resistance depends on multiple factors, like the mode that is used to access or egress a station but also the type of station that is used to transfer between modes. Hence, implementing SB- bike-sharing in a multimodal transport model would mean that new transfer links are added to transfer from the Transit network to the bike network.

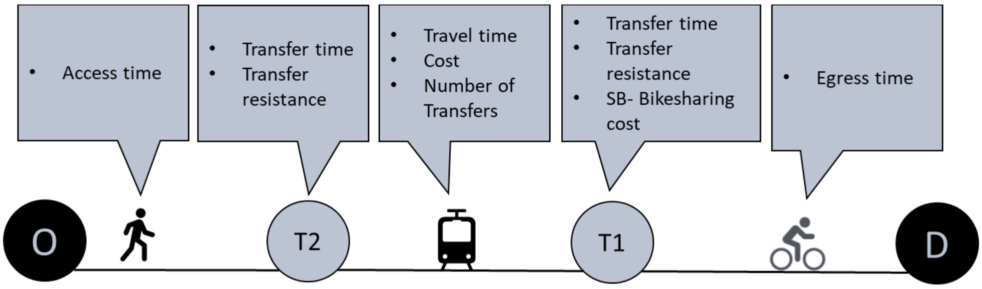


Figure 3.7: Characteristics of a multimodal trip with SB-bike-sharing

3.6 CONCLUDING REMARKS

This chapter substantiated what strategic transport modelling characteristics are needed to properly model SB-bike-sharing. Because this research is focused on strategic transport models it became evident that the model used for this study has a macroscopic representation of traffic demand and will use static input data. Besides there are three important modelling requirements following from the SB-bike-sharing characteristics:

- **The model is Tour-based** to model consistency in the use of SB-bike-sharing. The model can only consider the fact that a person has to return a bike to a particular station, when considering tours instead of trips.
- **The model is Disaggregated** to model the fact that persons have different perceptions regarding SB-bike-sharing. One type of person is more likely to use the system compared to other types.
- **The model is Multimodal** to consider attributes of complete transport tours in the choice of using SB-bike-sharing. Policies regarding the public transport networks should influence the use of SB-bike-sharing and policies regarding SB-bike-sharing should influence the use of public transport.

Modelling tours instead of trips and modelling multimodality are individually both extensive researched topics. However, the problem of this research arises from the combination of the modelling characteristics. Modelling multimodality in a tour-based model is a challenging task. For this reason the next chapter will look at what approaches are currently available.

4. RELEVANT MODELLING TOPICS GIVEN THE TRANSPORT MODELLING REQUIREMENTS

Chapter 3 substantiated that the strategic transport model that is used to model SB-bike-sharing must be Tour-based, must be able to model multimodality and should be disaggregated. This chapter explains some important concepts for this type of model based on literature research. First of all, the type of modelling structure for disaggregated tour-based transport models is explained. These are the so-called Random Utility maximization models. Those models rely on attributes obtained from transport networks. Therefore, paragraph 4.2 explains how those transport networks are presented in strategic transport models. Paragraph 4.3 will discuss how people choose their transport modes and routes, based on uni-modal transport networks. Paragraph 4.4 will elaborate why modelling multimodality is more challenging compared to modelling uni-modal mode choice. Multimodality is mainly researched by academics with a focus on trip-based models. For this reason paragraph 4.5 elaborates about trip-based methodologies to model multimodality. Modelling multimodal tours is more challenging, for this reason it is interesting to see what approaches are available to model multimodality from a tour-based perspective, this is discussed in paragraph 4.6. This chapter mainly functions as the theoretical background to understand some modelling concepts in the remaining part of this research.

4.1 RANDOM UTILITY MAXIMIZATION MODELS (RUM-MODELS)

Transport models that are disaggregated and tour-based rely in general on principles of random utility maximization. Therefore this paragraph explains how this kind of choice structure works.

Random utility maximisation models (RUM models), model the trade-off that individuals make to compare different alternatives with each other and in the end choose the alternative that maximises his or her welfare. As passengers always make a choice between a discrete set of alternatives, the RUM models are a type of discrete choice models. Many choices within the discrete choice models are interdependent. This is represented in a hierarchical manner.

Figure 4.1 is an example of a hierarchical representation that can be used to model tour-based models. At first there is chosen for a particular location (F, I, etc.) for the main activity of the tour. Next, based on the main-activity location there is a certain chance to use each transport mode. The fact that the mode choice is conditioned on the main location choice, results for instance in that people would not use a bike to reach a destination that is too far away. This example shows that the choice-set downstream heavily depends on choices made upstream.

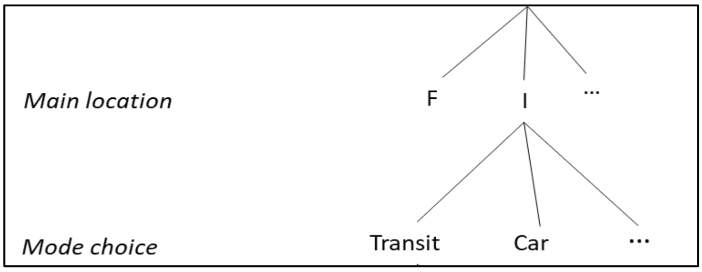


Figure 4.1: Example of a discrete choice modelling structure

Travellers are assumed to choose the alternative that maximises their perceived utility from a set of alternatives, which is called the choice set i. Passengers do not know the true utilities, this is expressed by a random term ε_j in the utility function. Sources of error in the utility are for example missing variables, unobserved taste variation, measurement errors and incorrect function forms. The total utility is expressed by the formula:

$$U_i = V_i + \varepsilon_j$$

In which V_i is the systematic part of the utility function. The following formula is used to derive this systematic part of the utility function:

$$V_i = ASC_i + \sum_{m \in i} \beta m X m$$

As can be seen, the systematic part consists of the attributes from a certain travel alternative m, plus some model parameters β_m. The model parameters can be derived by survey data, revealed preference or borrowed from other models. The attributes from an alternative are derived from input data and from the transport network. This can for example be the travel time, travel distance or travel cost for different transport modes to travel between an origin and a destination. How those transport networks are presented and used to obtain attributes is explained in the next two paragraphs. Next to these attributes there is an attribute which is called the Alternative Specific Constant (ASC). The ASC contains difficult to measure factors like reliability or safety.

As most tour-based models are disaggregated, perceived utility can be person type specific. This means that parameters can be different for different person groups. As an example, varying parameters makes it possible to make students more sensitive to high Public transport fares. Also intrinsic preferences for certain modes for a specific person group can be included this way. This is done by changing the ASC for this particular person group. Dummy variables are used to change the utility functions in this regard.

Based on the utilities, choice probabilities to choose a certain alternative can be estimated. The chance that alternative i is chosen from the choice set C , depends on the chance that the utility of alternative i is higher than all other alternatives. This is mathematically expressed as follows:

$$P(i:C) = Prob\,(U_i \geq U_j, \forall\, j \subset C)$$

Depending on the distribution chosen for the error term different formulas for the mode choice probabilities are used. For most travel demand mode choice and destination choice models including this study a Gumbel distribution is assumed. This leads to the so called multinomial logit model:

$$P\,(i : C) = \frac{e^{Vi}}{\sum_{\forall j} e^{Vj}}$$

An important assumption in this type of model is that the error terms are independently and identically distributed (IDD). This means that when the utility of a certain alternative changes it will have the same proportional effect on the probabilities of choosing other alternatives, while being equal. This assumption does not always hold. When alternatives share unobserved similarities there is correlation between the error terms. For instance, when a train connection is made more attractive, this will affect the probability of other Public transport alternatives more than it would affect probabilities of choosing a car alternative.

The IDD assumption is relaxed by using nests within the MNL-model. This is called the nested logit model and assumes that certain choices are conditioned to other choices. The chance that an alternative i within nest n is chosen is conditioned to the chance that nest n is chosen.

$$P_i = P_{(i\,|\,n)} * P_n$$

The utility of nest n contains the log sum of the alternatives within the nest plus some utility factor representing the shared attributes of the alternatives in nest n. Choices upstream in figure 4.1, are often based on the log sum of available alternatives downstream. The log sum is a measure for the maximum expected utility that is possible within the lower-level choices in nest n. The log sum is given by:

$$ln\left(\sum_{j\in n} exp\; exp\;\; (V\;(n)/\theta(n))\right)$$

Combining the formulas, gives the formula for the probability of choosing alternative i out of alternatives j within nest n, in the choice set of all nests m. In this formula "$\theta(n)$" represents a dispersion parameter, specific to each nest, which reflects the correlation between alternatives within the nest. The closer to zero, the higher the shared unobserved factors between the alternatives in a nest. Notice that when the dispersion parameter is one, the formula becomes similar to the Multinomial logit structure..

$$P(i)=\frac{\exp\left(V_{i|n}/\theta_n\right)}{\sum_{j\in n}\exp\left(V_{j|n}/\theta_n\right)} * \frac{\exp\left[V_n+\theta_n \ln\left(\sum_{j\in n}\exp\left(V_{j|n}/\theta_n\right)\right)\right]}{\sum_{\forall m}\left[\exp\left[V_m+\theta_m \ln\left(\sum_{j\in m}\exp\left(V_{j|m}/\theta_m\right)\right)\right]\right]}$$

4.2 REPRESENTATION OF THE TRANSPORT NETWORK

This paragraph will briefly discuss the concept of transport networks and the difference between private transport networks, public transport networks and multimodal transport networks. This is based on a more extensive explanation by Fiorenzo-Catalano (2007).

Transport models use information about travel times, distances and other characteristics of travel alternatives to calculate travel choices of travellers in the discrete choice models. This kind of information is obtained from transport networks. Transportation networks make use of graph models. An example of such a graph G is presented in figure 4.2. A transport network consists of a finite set node N, and transport links L. All nodes and links have certain attributes. Nodes represent for example intersections, where it is possible to change to multiple links. Links on the other hand contain information about the travel distance and travel time. Transport links are often directed, to represent the fact that there are one-way roads and that travel times in the opposite directions can vary. This means that for a two way road section there are transport links for both directions. An example of a simple transport network is presented in figure 4.2. In this network the length (l) and cost (c) of the links is included (Fiorenzo-Catalano, 2007).

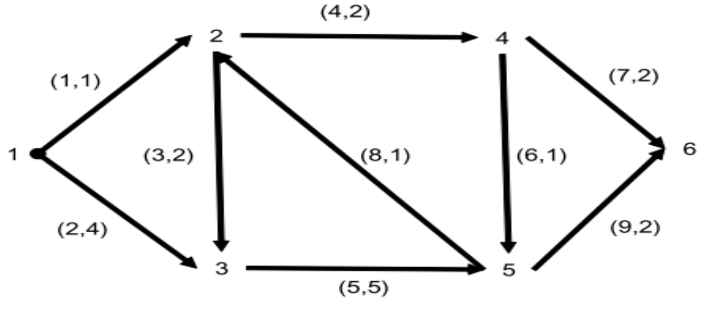


Figure 4.2: Graph (G), with 6 nodes (N) and 9 links (L) between the nodes with attributes (l,c) (Fiorenzo-Catalano, 2007)

A path in a graph is the sequence of consecutive links that connect an origin node with a destination node (so examples of paths from node 1 to node 6 are from 1 to 3 to 5 to 6 but also from 1 to 2 to 4 to 6 etc.). Summing the attributes of the consecutive links in the paths gives the attributes of a specific path. Origins and destinations are represented by a special type of nodes. These are so-called centroid nodes. Centroid nodes are connected to the transport network with connectors. This link represents the phase that people have to travel from their origin and destination to a physical element on the transport network.

Because car networks and public transport networks have different characteristics. Transport networks are distinguished in so called continues services and discontinues services:

- *Continuous transport networks* can be accessed every moment and at a finite number of locations. Examples of such a continuous service are those of private car and bike networks.
- *Discontinued services are transport networks* that can only be accessed at a limited number of stations, and have different service lines which all follow predetermined time schedules. Public transport networks are discontinued.

Modelling discontinuing services is more challenging. This is because of the fact that the time dimension plays an important role and the fact that transfers between multiple service lines are necessary. In such transport networks extra links are added to represent the fact that people board or alight a service line and that vehicles have dwell time at public transport stations. The boarding links contain information about waiting times to different service lines. Such a node and line structure is presented in figure 4.3.

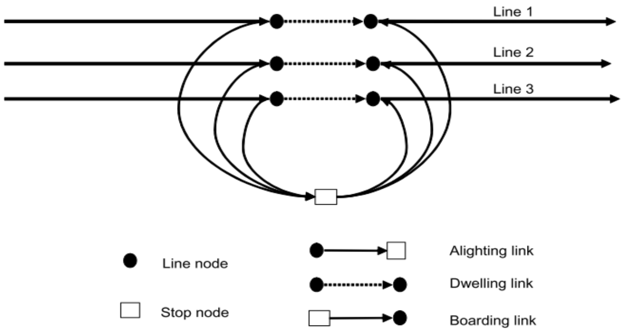


Figure 4.3: links and nodes in discontinues transport networks, retrieved from (Fiorenzo-Catalano, 2007)

There are two important approaches to deal with these waiting times:

- *Frequency based models* which describe public transport networks based on frequencies and average headways of different service lines. This means that there is no distinction between individual runs in a transport service. Waiting times for transfers and departures are directly derived from the service frequency. The assumption is that there are high-frequency service lines. This means that passengers do not consider exact departure times for arriving at a Public transport stop. For this reason, it is assumed that passenger arrivals are uniformly distributed (Fu et al., 2012). The waiting times are therefore assumed to be half the headway, so a service frequency of 10 vehicles per hour, results in a waiting time of 3 minutes ((60/10)/2=3) (Tan, 2016).
- *Schedule based models* explicitly consider that transit time-tables have not only a discrete place (stops) but also discrete times (the schedule) (Gentile et al., 2016). In timetable-based assignment procedures, it is assumed that travellers consider the service time-table in their route choice. This makes time-table based assignment procedures especially more appropriate for low-frequent services. Passengers make in that case, a conscious decision to arrive just before departure times at the station. (Tan, 2016) Moreover, some transfer can in reality have a perfect connection while other transfers might not. In a time-table

based assignment, this difference is considered, while in a frequency-based assignment, transfers to lines with the same frequency are assumed to have the same transfer time.

In contrast to uni-modal networks, *multimodal transport networks* have to combine continuous and discontinuous services. In such multi-modal transport networks the path between an origin and destination also involves choices about the transport modes and boarding and alighting stations. Different transport networks must in this case be connected with extra transfer links. However, this can be done with multiple approaches. How multimodality can be handled will be explained in paragraph 4.4 to 4.6.

4.3 MODELLING UNI-MODAL MODE CHOICE AND ROUTE CHOICE

This paragraph explains the concept of mode-choice models and route-choice models for Uni-modal transport networks.

Without considering multimodality, modelling the mode choice component is based on attributes obtained from the unimodal transport networks. Figure 4.4**,** shows an example of this kind of modelling structure in a study of van Eck (2014). The model assumes that there are only two transport modes available; Car and Transit.

Given an origin and a destination in the unimodal transport networks, the model has to generate a path. Generating paths can be done by route-search algorithms. This is for example based on a shortest path algorithm which minimizes the route cost. The route cost is then a weighted sum of important attributes for the travel paths, such as travel time, travel distance and monetary cost. Another option is that the utility is based on multiple possible travel alternatives and uses a generalized value for the travel cost.

With the utility values for the transit and car alternative, the model can calculate how the travellers are distributed between (in this case) transit and car with a multinomial logit model. Given the mode-shares, the next step is to assign the transport demand to the transport networks. Assigning the transport demand to the transit network is based on route-choice models.

Route-choice models consist of two steps. Travellers do not necessarily use the path with the least route cost. Therefore multiple routes need to be generated. The first step generates the set of possible routes. The second step calculates how the travel demand is distributed across the generated routes.

There are different algorithms available to generate the set of routes. For an overview one can read the study of Prato to different types of route-choice models (2009). Most methods repeatedly search for shortest paths, while varying circumstances in the transport network. Another line of reasoning is that paths have to fulfil a set of behavioural rules to be included in the choice set, using a branches and bound algorithm.

Calculating the exact route-choice is a challenging task. For good and robust utility and parameter estimation the route-sets must be reasonably large (between 70 and 100 is regarded as common practice). Because of the large route-set there are complicated correlation structures (Prato, 2009). High correlation between alternatives has influence on route-choice probabilities. To deal with this issue transport models rely on modifications of the logit structure or on a method which is based on “generalized extreme values”. Again, for an extensive explanation of the methods one can read the study of Prato (2009).

Once the traffic is assigned to the transport network, travel times in the car network can change as a result of congestion effects. Because of this, the distribution of the mode-shares could change as well. Therefore, the model contains a feedback loop to iteratively reach an equilibrium for the mode shares.

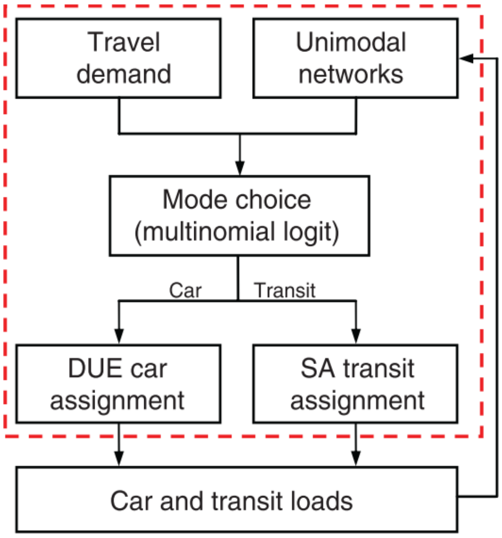


Figure 4.4: Modelling mode choice for Transit and Car (van Eck, 2014)

4.4 CHALLENGES TO MODEL MULTIMODALITY

The model used for this study is multimodal instead of unimodal. This paragraph distinguishes three categories of modelling challenge when considering multimodal transport networks instead of uni-modal transport networks.

Modelling multimodality is characterized by a multimodal transport network consisting of multiple transport modes (train, bus, tram, metro, car, bike and pedestrians) and transport services (different public transport lines) in which there is calculated what transport modes and routes travellers use to reach their destinations. This is different compared to the route-choice models in Uni-modal models where only one transport mode is used for the entire path. Van Eck (2014) describes three categories of modelling challenges. The first involves challenges in the route-set generation. To model the chance that a person uses a specific path, first the model must know what set of multimodal paths is available. The second challenge involves the calculations of people that use all generated paths. Based on attributes of the generated paths there is a chance that travellers use each multimodal path. The last set of challenges involve obligatory changes to the transport network

- Generating the set of routes is more complex in case of multimodal models. This is because there is a *wider set of travel alternatives available*, as multiple modes can be used in one transport trip. To generate all possible combinations of modes and routes, the choice set can become very large. Moreover, when modelling multimodality, it becomes *essential to track mode availability*. Sometimes a transfer to a certain transport mode is not possible because the transport mode is on the particular point of the trip not available (think of a transit-car-transit trip).

- More travel alternatives, also result in a more complicated route choice model. In multimodal transport trips the choice for transport modes and transport routes becomes an integrated choice; *the mode choice and route choice are heavily correlated*. Moreover, the multimodal transport choice involves many extra choice dimensions, such as choosing access and egress modes and boarding and alighting stations. These extra choice dimensions will result in a higher variety of traveller perceptions, *so heterogeneity in the population becomes more important to consider*. The higher number of choice dimensions and travel alternatives also leads to *more complex correlation structures between unobserved factors* of different travel alternatives. Lastly, *the attractiveness of a trip leg depends on the composition of the complete transit trip*. To reach an activity location, travellers are more likely to use the bike as an access mode, compared to using it as an egress mode. The parameters have to be set accordingly. This means that the model needs information about whether a trip is home-based or activity-based. For a trip towards home, the parameters are exchanged, as it is more likely for people to use a bike for the egress trip leg.

- Also the transport network itself needs adjustments. Transfers become an essential part of the choice for a multimodal transport trip. *Therefore the resistance of a specific transfer needs to be considered.* This depends on factors like the transfer time, parking cost, walking time and the risk of missing a transfer. Also *capacity problems* play an important role in this regard. When parking facilities are overcrowded this will influence the shares of people using the particular facility.

4.5 TRIP-BASED METHODOLOGIES TO MODEL MULTIMODALITY

Because modelling multimodality is mainly researched from a trip-based perspective, the first two trip-based approaches to handle multimodality are described. The first approach pre-specifies popular mode-chains. The second approach integrates the mode choice and the route choice to one modelling step in a so-called "super-network". The pre-defined trip chain approach is widely used, the super-network approach has a sound explanation of travel behaviour but is so far not applicable in practice.

4.5.1 PRE-DEFINED TRIP CHAINS

The first approach prespecifies mode-chains as additional artificial modes. These mode-chains consist of a specific combination of access and egress modes with Public Transport in between. Transferring between private modes and public transport modes is allowed at pre specified transit stops with corresponding links between the set of modes (Van Eck et al., 2014). The links to transfer between modes contain information about the transfer resistance. A study from Brands (2014) is used as a guideline for this approach. There are some limitations in the number of mode-chains that can be pre-defined to keep it computational traceable. In the research of Brands the following mode-chains are defined:

- Walk – Transit – Walk
- Bike – Transit – Walk
- Car – Transit – Walk
- Walk – Transit – Bike
- Walk – Transit – Car

The utility of each mode-chain is determined with the so-called Zenith algorithm. This algorithm contains the following modelling steps as cited from Brands et al. (2014):

1. *"For every origin and every destination the set of relevant stops are calculated. This set of stops could be different per access/egress mode. The set is bounded by using various constraints."*
2. *"For every stop in the network a set of relevant interchange stops are calculated. This set of stops is bounded by a walking distance constraint."*
3. *"For every destination zone in the network the shortest path tree is built backwards, starting at the relevant egress stops for the given destination. Paths are built backwards while following the entire line with a label setting algorithm. The various options to reach a stop are limited by constraints. The utility is calculated using a logit equation."*
4. *"From the set of stops reached in the previous step and based on the blended utility, the process is repeated until a given maximum number of interchanges."*
5. *"Based on the paths between the stops and the predetermined access and egress legs, the total chain for different access and egress modes is calculated. "*

The approach is based on a popular method to model Transit in frequency-based assignment methodologies. It assumes that people have an optimal strategy to travel from a boarding station to an alighting station. A strategy specifies all lines that bring a traveller closer to a destination. Passengers are assumed to be divided over the transit line, proportional to the generalised cost of each transit line (Brands, 2015). The total utility to travel between a set of stations is then obtained by summing the utilities of all transit lines in the strategy.

From each station, the travel time to the origin and destinations are based on a shortest path algorithm with the transport mode that is used to access and egress the station. The available stations depend on the mode that is used to access or egress the station.

The sum of the generalised cost to access the boarding station, egress the alighting station, and to travel between the set of stations, gives the total generalised cost from an origin to a destination (with a particular mode-chain and a specific set of stations). Summing the utilities for all possible stations with the log sum, gives the expected utility for each mode-chain.

This makes it possible to calculate mode shares. The structure to model the mode-shares is shown in figure 4.5. The mode choice structure is almost similar to the mode-choice used for unimodal models. However, there is one important difference. There is correlation between all mode-chains that use Transit, for this reason the model uses a nested logit model. First there is chosen between car and transit, then within the Transit nest there is chosen between the different mode-chains.

Looking at the set of multimodal modelling requirements there are some limitations of the pre-specified-trip chain approach. To start with, the method will always miss out on some of the plausible mode-chains. Next, the approach does not capture the fact that mode and route choice is an integrated choice in multimodal transport trips. Then, the model approach is not capable of handling the correlation patterns between the multimodal alternatives, and finally the model is not able to fully capture mode availability constraints and trip-dependent leg properties.

Nevertheless, the pre-defined mode-chain approach is used extensively in transport planning practice. This has to do with the fact that it is a relative easy adjustment compared to the classical modelling approaches (Van Eck, 2014). Moreover, the approach is computationally feasible and is easier for the model parameter estimations (Brands, 2015).

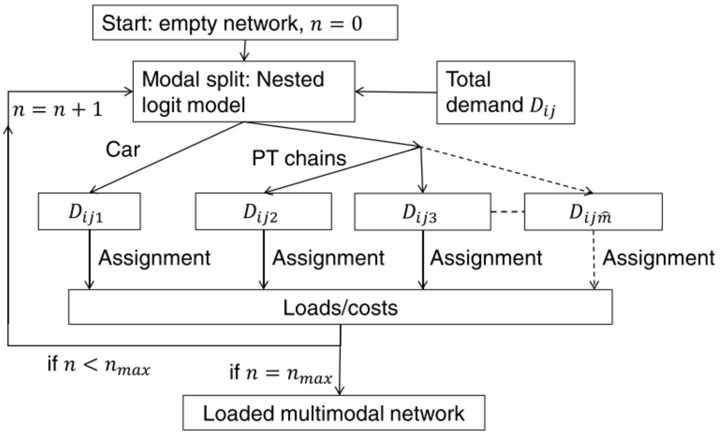


Figure 4.5: Pre-set mode-chains approach (Van eck. Et al, 2014)

4.5.2 SUPER-NETWORK APPROACH

The second approach is the so-called “super network approach”. In the super network, generated routes not only describe the sequence of links, but also the corresponding combination of modes used for the chosen route. The approach is characterized by the following modelling setup: There is an a-prior generation of the choice set and the mode and route choice is modelled simultaneously. The modelling approach is visualised in figure 4.6. The route-set is generated in the multi-layered super network. Transport networks of all modes are connected with artificial links. The network representation is visualised in figure 4.7. All origins and destinations are connected to the pedestrian layer. This implies that all travel paths involve a transfer from the pedestrian layer to the particular mode. The artificial links are the dotted lines between the set of layers. Those artificial links contain information about the transfer resistance (Fiorenzo-Catalano, 2007).

The generated routes contain different transport paths to travel from an origin to a destination. These can be unimodal alternatives, for example by only using the car (not considering the walking leg to the car), but also multimodal alternatives that use multiple layers to reach a destination. In the end a route-choice model will determine the number of travellers using each generated route alternative. With these route shares, also mode shares are obtained. Hence, the route and mode choice step are modelled simultaneously (Van Eck. et al, 2014).

For academics the super network approach is an interesting method. This is because it is a very sound explanation of human travel behaviour. This is substantiated by the fact that the super network approach meets all challenges that are mentioned in section 4.4. Still, the super network approach is not used in practice. The reason for this is twofold. First of all the method results in high computation times. This is a consequence of the fact that there exist many path alternatives in such a multi-layered network. Even more important is the problem that parameter model estimation becomes impractical due to simultaneous mode choice and route choice modelling (Van Eck, personal communication, 26-09-2020).

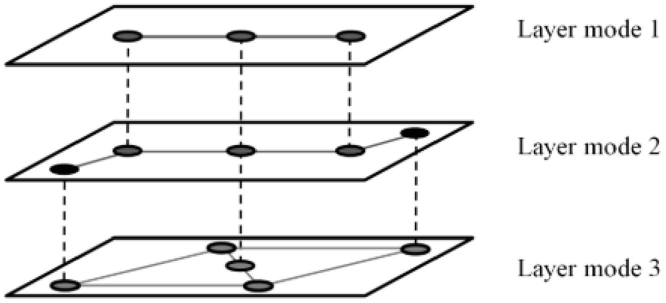


Figure 4.6: Visual representation of super network approach, transfer links presented with the dotted line

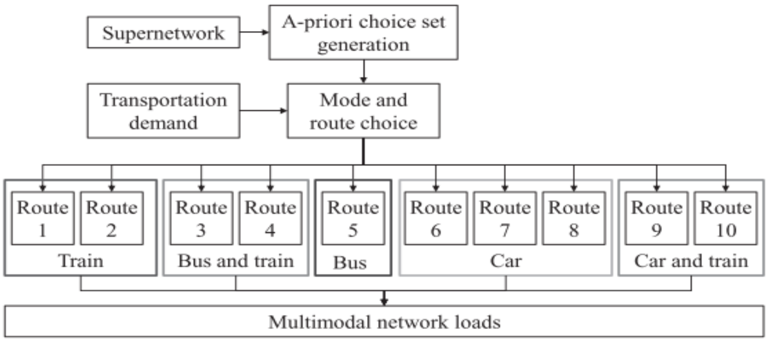


Figure 4.7: Super Network modelling structure, simultaneous route and mode choice modelling

4.6 TOUR-BASED METHODOLOGIES TO MODEL MULTIMODALITY

The transport model used in this study must be able to model multimodality in a tour-based context. However, the mode-choice component is not extensively researched for tour-based models yet. This results in the fact that there is only one approach extensively used in transport planning practice, namely the main-tour mode choice and conditioned trip level mode choice approach.

4.6.1 INTRODUCING TOUR-BASED MODE CHOICE

In contrast to the trip-based models as discussed in the previous paragraphs, tour-based models consider the mode-choice of complete tours. This makes it possible to model consistency between multiple trips within a tour as discussed earlier. However, in a review to all tour-based mode choice methodologies from Hasnine and Nurul Habib (2020) there is pointed out that the mode choice component is a limited researched topic. For this reason most tour-based models used in practice and literature, often rely on simplified tour-based mode choice or even on a trip-based mode choice.

The simplified tour-based mode choice assumes that only a single mode can be used during the entire tour. The limitation of this approach is visualized in figure 4.8. In reality there is a substantial number of cases where travellers use more than one mode in the complete tour (Hicks et al., n.d.). This is especially prevalent in situations where people perform multiple activities. Nevertheless, in case of a simplified mode-choice model, people that use a car to reach a destination will also use a car for the remaining trips within the transport tour. This simplification is made in order to limit the number of available mode choice alternatives to keep the models computationally applicable (Hasnine & Nurul Habib, 2020).

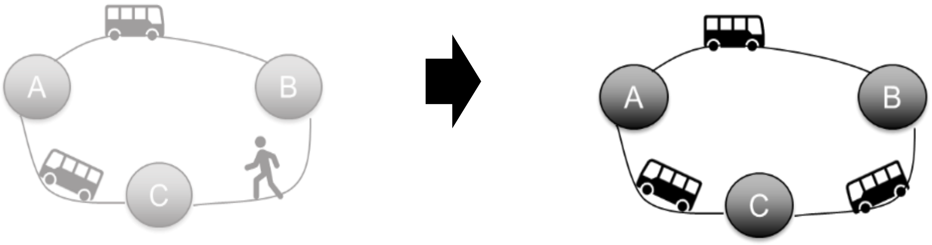


Figure 4.8: The problem of simplified tour-based mode choice models, on the left a feasible mode-chain in reality and on the right how it is modelled with a simplified mode-choice model

When modelling multimodality the situation becomes even more challenging. Since each trip can contain multiple transport modes, the number of possible alternatives will rise even further. There is only a limited body of literature that tries to tackle this problem. The coming subparagraphs will elaborate about current efforts.

4.6.2 TWO STEP MODE-CHOICE APPROACH, MAIN-TOUR MODE CHOICE AND CONDITIONED TRIP-LEVEL MODE CHOICE

The most prevalent option to model multimodality in tour-based mode choice models is the main tour-mode choice with a conditioned trip-level mode choice approach. The mode-choice component is modelled in two steps, for this reason this method is referred to as the “two step mode-choice approach”. This type of modelling approach is easily implemented in tour-based models which use principles of Random Utility Maximization. This is because it also uses a hierarchical choice structure. The model assumes that there is a main-tour based mode choice. This main-mode choice does not change during the tour, as illustrated in figure 4.8. Given this main-mode choice and other modelling steps such as the location choice, the model choses mode-choice on trip level.

The mode-choice on trip level can use techniques to model multimodality which are used in trip-based approaches. However, the mode-choice is restrained to the main-mode choice. This means for example that a person that uses public transport as the main-mode choice will always have a public transport leg on trip level. Still, the person can on trip-level decide to bike to a station or choose to walk to the station.

This also shows the limitation of this modelling approach. Consistency between access and egress modes within a tour is not explicitly modelled. Therefore mode availability constraints are not considered for the access and egress trip legs.

Despite the consistency problem of access and egress modes, the main tour-based mode choice and conditioned trip-based mode choice is the only method that proved its applicability in transport planning practice. As this research wants to create an applicable approach to model SB-bike-sharing the next chapter will perform a case-study to this approach to see whether it is appropriate to model the SB-bike-sharing system.

4.6.3 COMBINATORIAL LOGIT

Hicks et al. (n.d.) uses a standalone combinatorial logit model to consider all feasible mode combinations in a tour. A tour mode combination is feasible if it fulfils some constraints regarding the mode availability. To make this possible, the model tracks car status during a tour. This for example means that when someone uses a car to reach a destination the car status at the destination is “available” for the next trip. If someone parked the car earlier in the trip at (for example) a park and ride, the car status is “not available” for the subsequent trip. When the car is “parked” at a P+R, the model saves the P+R location in order to know where the car has to be picked up later in the tour. By tracking the vehicle’s status the number of feasible mode combinations is significantly truncated (Hicks et al. n.d.).

Given the “car status” for each trip in a tour there is reconsidered what transport mode is used for the next trip in the tour. This makes the approach cumbersome as it results in many alternatives. This is especially the case in tours with more than two trips or when multimodality is considered. The approach of Hicks skips for this reason an explicit choice set generation. Instead the model uses a recursive logit algorithm, which is an advanced technique that makes route and mode choices on link level instead of making choices at trip or tour level. The recursive logit is not applicable at large scale networks due to high computational times (Meyer de Freitas, 2019).

4.6.4 DYNAMIC TOUR-BASED MODE CHOICE MODEL

The Dynamic tour-based mode choice model designed by Hasnine and Habib (2020) assumes that the tour-based mode choice is performed in multiple sequential discrete choices. Each choice in the dynamic model is conditioned to previous choices and has a future expectation term. The model is history dependent in the sense that it also knows the vehicle status in different stages of the model. The future expectation term considers the fact that an individual maximises his or her future choices while making a current choice.

This is expressed by a separate parameter, which is a measure of the importance of future choices, compared to current choices. In case a person would choose for SB-bike-sharing in the morning, the choice would be based on the fact that the person currently wants a bike, but at the same time, the person would consider the fact that he or she has to return the bike. The relative importance of the fact that he or she has to return the bike is expressed by the future expectation parameters. This seems a theoretical sound explanation of human travel behaviour Hasnine and Habib (2020).

However, the method is currently also not applied in transport planning practice. This can be explained by the fact that this method results in very complex choice structures. This makes the approach computational challenging and also makes parameter estimation complicated. Each trip in the tour is conditioned to earlier mode choices in the tour. For this reason for each situation different parameters have to be estimated.

Also the dynamic mode choice model proposed by Hasnine and Habieb (2020) does not explicitly consider station choice and park and ride choice.

4.6.5 OPTIMIZING PARK AND RIDE LOCATION IN A DYNAMIC TOUR-BASED MODEL

A research from Khani et al (2014) specifically focuses on optimizing the park and ride location choice in a tour. They argue that when daily travel is modelled in the form of complete tours, it is important to consider park and ride location explicitly and constraint travellers to return to their park and ride location. The best park and ride location for the morning trip is not always the best location for the returning trip. This makes the problem a tour-optimization problem instead of a trip-optimization problem. There is an algorithm developed that enumerates all possible park-and-ride locations and searches for the location with the lowest generalised travel cost on tour level. The approach was designed for dynamic models, still the concept is also applicable for static models.

The concept is here simplified, to explain it in a static context. The park and ride assignment model assumes a combination of two multi-modal shortest path problems. The concept is shown in figure 4.9.

1. From the origin, a shortest path algorithm is used to find the travel times with car to multiple park and ride facilities, this travel time is labelled with l_1.
2. From the destination a backward shortest path algorithm is used to find the Transit travel time from each park and ride to the destination, this travel time is labelled with l_2.
3. The travel time from the origin to each park and ride "o" and from the park and ride to the destination are added together $C_o = l_1+l_2$.
4. The same procedure is used to find C_i, to travel from the destination to the origin again using each park and ride "i".
5. Then the total travel cost for each park and ride facility is calculated with $C_t=C_o+C_i$. The optimal park and ride location is the park and ride facility with the minimal cost $C_{t.}$

A problem of the current approach in the study of Khani et al. (2014) is that it only tackles the mode choice for a simple tour with one main destination.

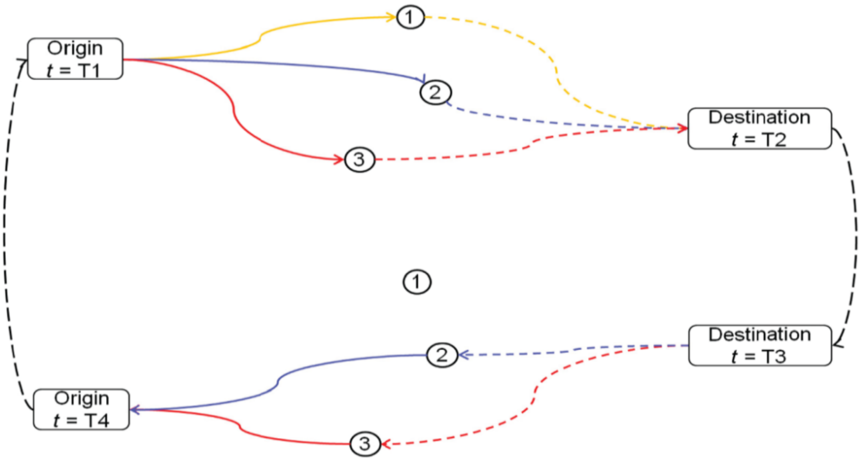


Figure 4.9: Optimizing P+R choice on tour level (Khani et al., 2014)

4.6.6 MULTISTATE SUPER NETWORK

The most advanced approach that is available in the literature is the so-called Multi-state Super network. This approach was originally developed by Arentze and Timmermans (2004) and further enhanced by Liao et al. (2014) in multiple studies. A review of all progresses and processes is given in Liao et al. (2014). The multi-state super network could be seen as the activity-based counterpart of the normal super-network approach. The method assumes that a wider range of decision-making processes can be represented by links and nodes. Therefore performing activities are also represented by a link between a set of nodes. Going through such an activity link means that a person stays at the same location, but transfers from one activity state to the other. The transport network is copied as many times as there are activities during a tour. Driving to an activity link and going from one state to the other state means that at that point an activity is performed. In the end a person that performs a tour searches for the optimal tour in the multi-state-network while performing a set of activities in between.

A schematic overview of this approach is shown in figure 4.10. Note that each hexagon represents a transport network. Each row represents different activity states and each column represents different vehicle states. Going from a new activity state or vehicle state is possible with the arrows that connect the hexagons. Note that each arrow goes to the same corner of a hexagon as where it came from. This means that a transfer from vehicle states or activity states always happens at the same location. The dotted hexagons represent Transit and walking links, the solid borders represent the car network.

The start of the optimizations is at home when none of the activities are performed. The tour ends when the person is home again and both activities are performed. The order of the activities and the location choice is not predetermined and is part of the optimization process. Furthermore, the person is free to choose whether he or she carries bags or leaves it at the car or at home during the tour. Each path through the multi-state-super network is a solution that is consistent with a set of constraints and uses the opportunities given by the physical transport network (Arentze and Timmermans, 2004). Finding an optimal path is based on a standard least-cost path finding algorithm.

Due to lots of research that has been performed on the multistate super-network, the efficiency of the algorithm increased significantly. However, the model is still far from applicable in practice. Because all decisions are made in the integrated network, model estimation will not be feasible. Furthermore, computation times rise significantly with the network size, due to the many network copies. Currently, all applications of the Multi-state super network rely on deterministic choice models. This means that they completely ignore the fact that travellers have not full information, and different perceptions, regarding travel alternatives. For this reason the multistate super network is considered a “state of the future”.

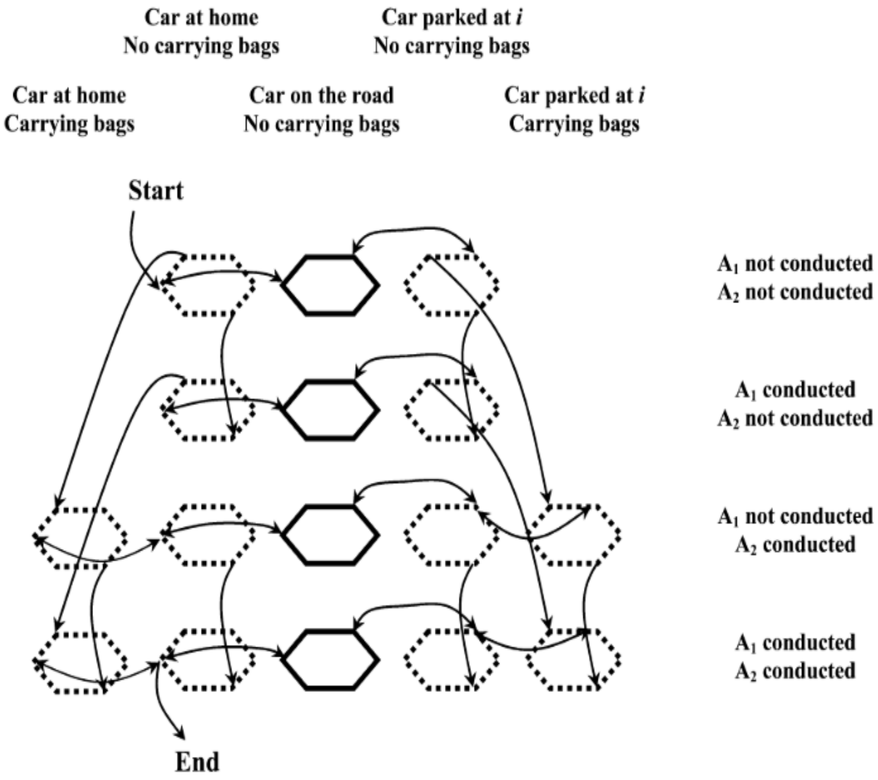


Figure 4.10: The concept of the multi-state super network

4.7 CONCLUDING REMARKS

This chapter mainly functioned as research to obtain theoretical background knowledge to understand modelling concepts which are important for the remaining part of this study. First of all there is elaborated about random utility maximization models which are extensively used in tour-based methodologies. The chance that a certain alternative is chosen is for this reason obtained by the Multinomial logit function. When alternatives share unobserved factors the function is changed to a nested logit function.

Next there is discussion that the input attributes that are used to model the utility of different transport modes are derived from the transport networks. In order to obtain paths in the network, the model uses path-search algorithms. Based on the utility of the different transport modes, shares of people that use each transport mode car are calculated.

Modelling multimodality comes with extra modelling challenges. These are challenges regarding the generation of the transport trips, challenges to calculate the choice models, and challenges to model demand and supply interactions.

There are two trip-based methodologies to model multimodality; The pre-specified trip-chain approach and the super network approach. The pre-specified trip-chain approach is widely used in strategic transport modelling practice. The super network approach is theoretical (looking at the modelling challenges) a very interesting approach but is not used in practice.

There are six different efforts discussed to model multimodality in tour-based models. Only one of those efforts is widely used in transport planning practice. This is *the two-step mode choice approach*. The model assumes that there is a main-tour based mode choice. This main-mode choice does not change during the tour. Given this main-mode choice and other modelling steps such as the location choice, the model chooses the multimodal mode-choice on trip level. This means for example that a person that uses public transport as the main-mode choice will always have a public transport leg on trip level. Still, the person can on trip-level decide to bike to a station or choose to walk to the station. This also shows the limitation of this modelling approach. Consistency between access and egress modes within a tour is not explicitly modelled. Therefore mode availability constraints are not considered for the access and egress trip legs.

SB-bike-sharing is all about modelling consistency between access and egress trip legs. Therefore, it is expected that modelling SB-bike-sharing with the two-step mode-choice approach also has its limitations. This shows the problems that will be addressed in this research. The only approach that is available in transport planning practice to model multimodality and tour-based mode choice is still not appropriate to model SB-bike-sharing. The problem is further substantiated in the next chapter.

The other approaches to model multimodality in tour-based mode-choice models can be used to create a new modelling approach in chapter 6.

PROBLEM DESCRIPTION

5. IMPLEMENTING SB-BIKE-SHARING IN THE MODELLING PROCEDURE OF P.T.V VISUM 2021

This chapter will research how SB-bike-sharing can be implemented to a strategic transport model that is used in practice. The strategic transport model used for this case-study is the transport model of P.T.V Visum 2021 (PTVgroup, n.d.). PTV Visum 2021 is one of the world leading software packages for strategic transport modelling. The software package is provided by the PTV group. The modelling software is used by the municipalities of Groningen and Lelystad, and the province of Utrecht in the Netherlands. Besides, there are many other users of the model worldwide(PTVgroup, n.d.). The model is in theory an appropriate model to implement SB-bike-sharing. This is because the model fulfils the modelling requirements as pointed out in chapter 3; the model is tour-based, disaggregated and is able to model multimodality. However, as elaborated in chapter 4, current models that combine multimodality and tour-based mode choice in general rely on the "two-step mode-choice approach". The "two-step mode-choice approach is not able to model mode choice consistency for access and egress transport modes. For this reason the hypothesis is that there will also be some problems to properly model SB-bike-sharing when using the modelling procedure of Visum.

Implementing shared-mobility in the software of Visum itself is a complex and time-consuming task. Hence, it is chosen for this study to replicate the relevant modelling steps for the implementation of SB-bike-sharing in Microsoft Excel. Relevant steps refer to all steps that are related to the two-step mode choice approach in Visum. When SB-bike-sharing is implemented in the replicated model in Excel, it is possible to analyse limitations for the implementation of SB-bike-sharing in the real modelling software of Visum. This analysation will be substantiated based on a small-scale case-study in chapter 7.

This chapter will first give a brief explanation about how the complete modelling procedure of Visum works. Then, there is elaborated how the relevant modelling steps for the implementation of SB-bike-sharing are replicated. Lastly there is explained how SB-bike-sharing is implemented to the model. This chapter will contribute to reaching the first research objective.

- *Implementing SB-bike-sharing in a two-step mode-choice approach to quantitatively illustrate the limitations of modelling multimodality in Visum.*

Furthermore this chapter answers two of the sub questions:

2. *How can SB-bike-sharing be implemented in the Visum modelling approach?*
3. *What are the limitations of the Visum modelling approach looking at the requirements to model SB-bike-sharing?*

5.1 EXPLANATION OF THE VISUM MODELLING PROCEDURE

This paragraph explains how the complete modelling procedure of Visum works. This gives some understanding about how the mode-choice components are related to the rest of the modelling procedure.

Figure 5.1 summarises the modelling steps of the Visum modelling procedure. This explanation is based on the PTV Visum manual. The explanation of the complete modelling procedure is briefl, as only the mode-choice components are relevant regarding the scope of this research. There are three factors that determine the activity location and mode choice:

- The first factor is the **tour generation** (left side of the figure). This is based on the number of people living in a particular area combined with their activity schedules. An activity schedule is a set of activities that is performed in a transport tour. There exist simple transport chains that only contain one main activity but also more comprehensive chains that contain main-activities and multiple sub-activities. As not all persons have similar activity patterns and travel preferences, different person types are distinguished within each zone. This is based on socio economic data like gender, age and income.

- Then there is a **zonal attraction** (middle of the figure). This is a measure for how attractive a zone is to perform a particular activity within an activity schedule. When there are a lot of offices in a zone but there are less shops, the area is attractive for the activity work but less attractive for the activity shopping.

- The last important factor is the **skim-matrices**. In skim-matrices data is stored about attributes that are used to calculate travel resistance. There are different skim-matrices for each transport mode. These are for example attributes like travel time, travel distance and travel cost to travel between an origin and a destination. Hence, the skim-matrices are derived from the transport network.

The three factors described are input for the **RUM-models** (RUM-models are explained in paragraph 4.1). The first layer of the RUM-models is the location choice. To determine the **activity location distribution**, a formula is used with a positive relation with the zonal attraction and a negative relation with the associated travel utility. The travel utility is obtained by taking the log-sum of the utilities of the different transport modes. By multiplying the location distribution with the generated tours coming from each zone, the numbers of persons travelling between each origin and destination is calculated. This is saved in origin and destination matrices (OD-matrices). The location distribution is person type and activity purpose specific.

Mode choice is modelled based on utility values of the different transport modes. The utility value of each transport mode is calculated with utility functions and attributes stored in the skim-matrices. Based on the mode utilities, mode shares are obtained and the location distribution is distributed across the transport modes. At the end leading to persontype and activity purpose specific OD-matrices per transport mode.

Sub-activity location is also modelled based on a formula with a positive relation with the zonal attraction and a negative relation with the associated travel utility. The location for the sub-activity is chosen conditioned to other activity locations in the tour (including the home-location) and the mode-choice. This means that the location is determined such that it is efficiently located considering the complete tour. For example a person that goes shopping on the trip from work to home, will search for a store that results in a small detour considering the work and home location.

Time of day slicing divides the matrices for all transport tours to different time frames across the day. All matrices were until this point persontype and activity purpose specific. In the **Aggregating matrices** step, All matrices are summed to obtain one matrix for the complete population per transport mode. In the end, this will lead to trip-based OD-matrices per transport mode and per time frame.

Modelling Multimodality calculates the number of people using each access and egress mode to go to a certain station or park and ride facility. The mode choice specific matrices are adjusted to consider the multimodal trips.

After the adjustments, the **Assignment** step assigns the traffic to the transport network. This is based on people's route-choice between the origins and destinations. The assignment step results in new travel times and costs for the road network; therefore, multiple iterations are performed until convergence is reached. The travel times for public transport, bike and walk keep similar for every iteration.

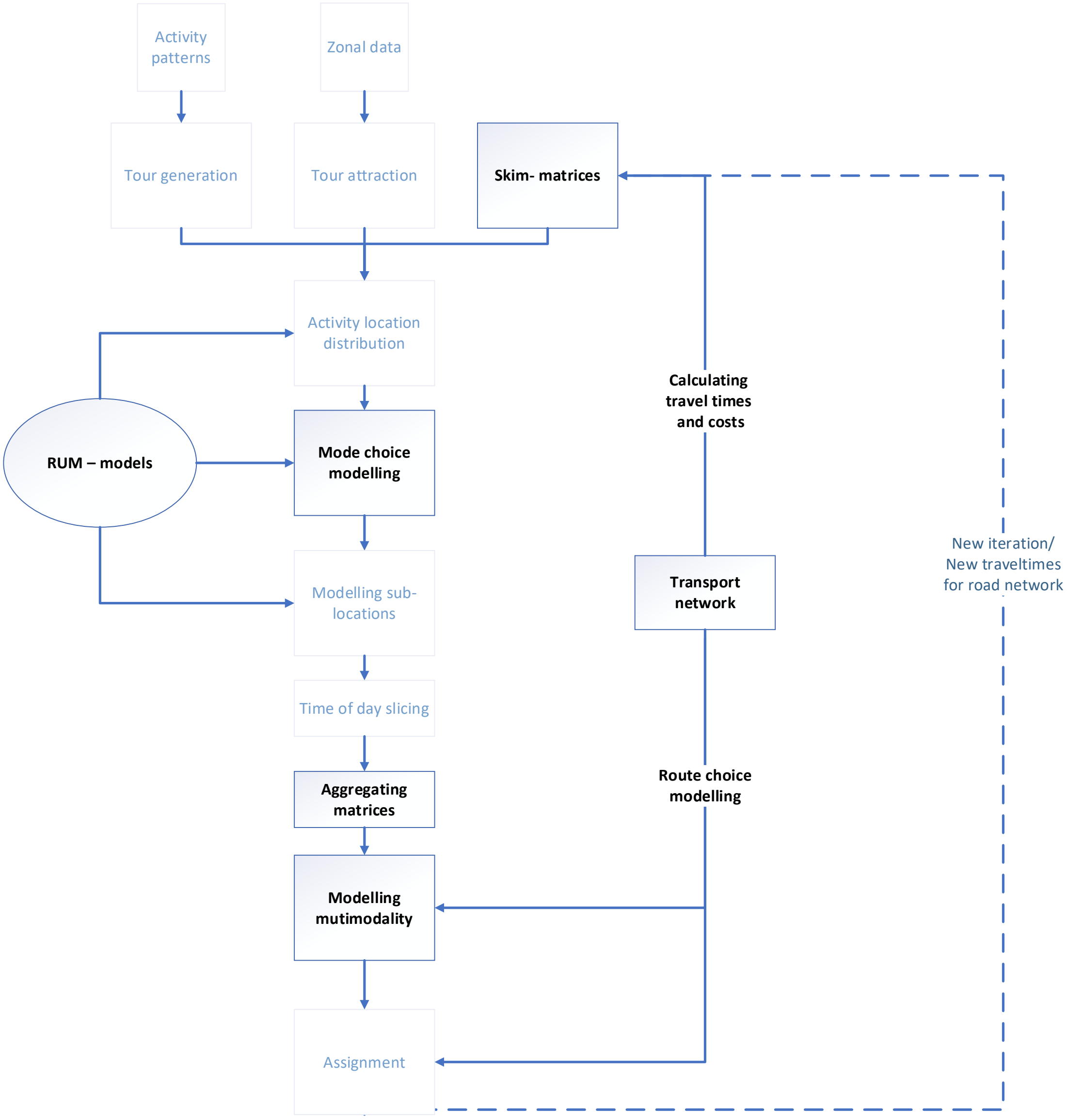


Figure 5.1: The modelling steps of the Visum modelling procedure, all steps that are related to the two-step mode-choice approach are highlighted

5.2 DEVELOPING THE TWO-STEP MODE CHOICE APPROACH USED IN VISUM

This paragraph will explain how the modelling components that are related to the two-step mode-choice approach are replicated in Excel. When only the highlighted steps in figure 5.1 are presented, figure 5.2 is obtained. Instead of calculating the location distribution the model assumes that the persontype and activity purpose specific OD-matrices are input for the model. The fact that the mode-choice approach used for this study is called the two-step mode-choice approach can also be seen in the figure. First the main-tour mode choice is calculated and later the trip-based multimodality is modelled. Multimodality is only modelled for all trips that use public transport. This means that the other modes directly proceed to the assignment step. When all steps are performed, OD-matrices are obtained that can be assigned to the transport network. The assignment step itself is not modelled in the replicated model for this study. This also means that the feedback loop is not considered.

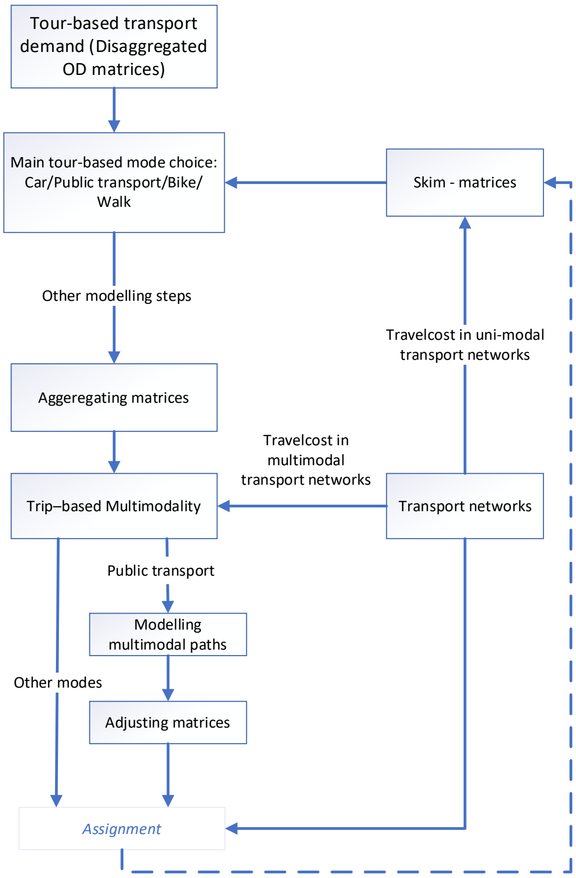


Figure 5.2: The two-step mode-choice approach replicated in this research. The modelling procedure is based on the procedure as used in Visum

5.2.1 THE UNI-MODAL TRANSPORT NETWORKS

The transport networks that are used to calculate the main-tour-based mode-choice are different compared to the transport networks that are used to model multimodality on trip-level. This is because the transport networks used to calculate the main-mode choice are uni-modal. For each transport mode there is a separate uni-modal transport network. There are no transfer links available to transfer between the different uni-modal transport networks. As an example, the transport networks that will be used for the outgoing trip in the case-study in chapter 7 are illustrated in figure 5.3. In reality and in transport models used in practice there are different transport networks used for each time-frame during the day, as travel times could vary. For this study it is assumed that the transport networks for the different time frames are similar.

All transport networks consist of a set of nodes N and links L as elaborated in paragraph 4.2. Each link L has a travel cost C to travel between each node v and w. The origin i and destination j are assumed to be in Node A and Node I respectively. As can be seen, it is assumed that there is an intrazonal travel time to cover the last mile, once one arrives at the nodes. To cover this last-mile, travellers can only use private transport modes (walk, bike and car), for this reason the last mile in the public transport network is also covered by walking.

The public transport network used in this study will be frequency-based. As elaborated in chapter 4, this means that the discontinuity of public transport is handled based on knowledge about the travel frequency of the Public transport lines. The waiting times are assumed to be half the headway of the frequency of a specific public transport line. Frequency-based assignment approaches assume relative high-frequency service lines, in which passengers do not consider exact departure times for their travel decisions.

When modelling multi-modality some of the transport networks will be connected with transfer links. How this process works is explained in paragraph 5.3

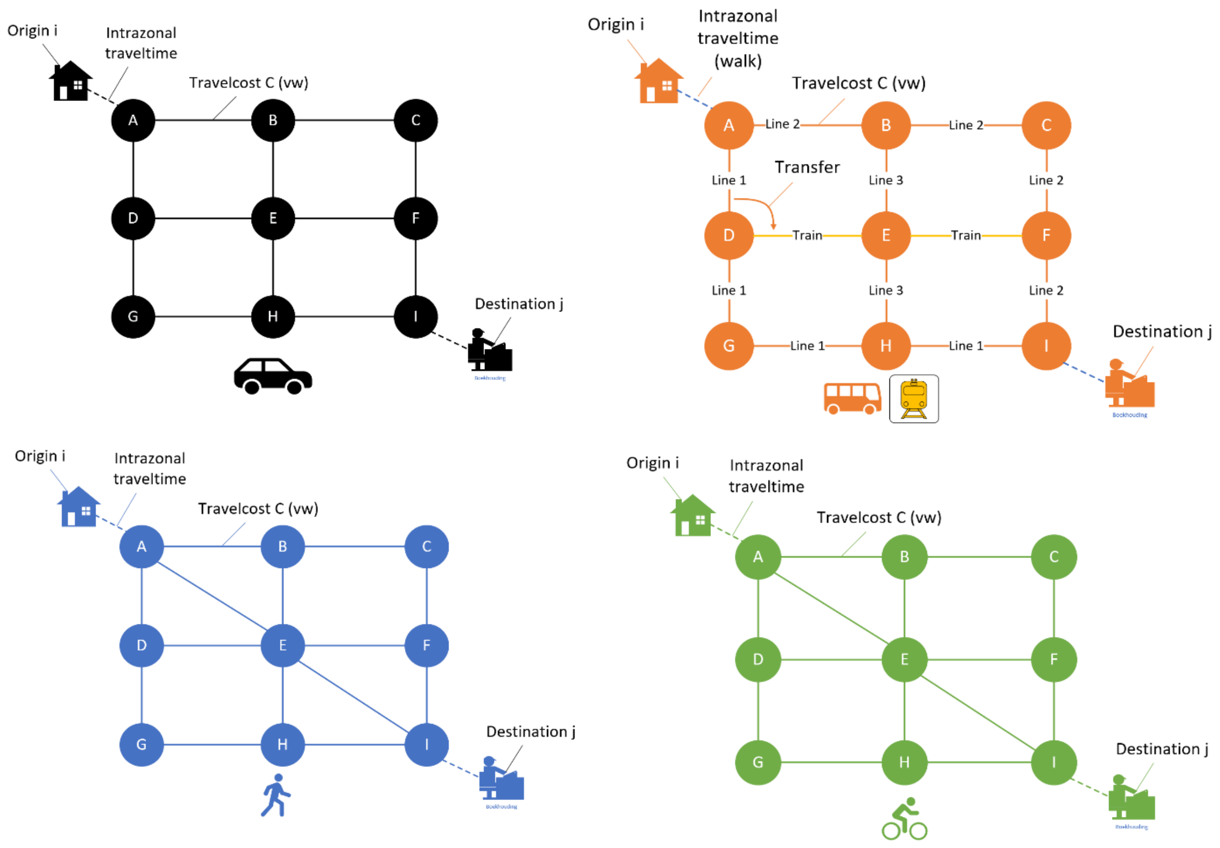


Figure 5.3: Unimodal transport networks for each transport mode

5.2.2 SKIM MATRICES

The transport network is used to obtain values for the skim-matrices, this is the first step in the development of the transport model as can be seen in figure 5.4. This sub-paragraph discusses how the values in the skim-matrices are obtained.

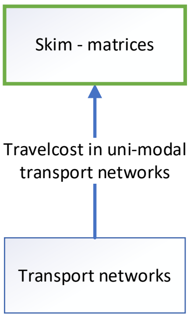


Figure 5.4: Using the transport networks to obtain Skim-matrices

All attributes that are assumed to influence the decision behaviour of passengers are stored in Skim matrices for every OD pair. The attributes for skim-matrices are obtained by generating paths for all transport modes. In the Visum transport model only the attributes of the path with the lowest weighted costs in the unimodal transport networks is stored in the skim-matrices. For this reason, the transport model for this study uses a shortest path algorithm which minimizes the weighted cost to generate paths for each transport mode. The shortest path algorithm used is the Simplex algorithm in Excel. This algorithm searches for the shortest path in a transport network given a cost function C(vw) to travel with a link between a node v and w. The shortest path is the set of links X(vw) between the transport nodes that give the lowest cost to travel from an origin node (i) to a destination node (j). The mathematical heuristics of this shortest path problem is given by the set of functions below. How this shortest path algorithm works in Excel is illustrated in appendices B.

$$\min \sum_{(v,w)\in \mathrm{A}} C\,(vw)X(vw)$$

$$\mathit{Subject\ to}:$$

$$1)\ \sum_{w|(\mathrm{i,w})\in \mathrm{A}} X(iw) = 1$$

$$2)\ \sum_{v|(\mathrm{v,j})\in \mathrm{A}} X(vj) = 1$$

$$3)\ \sum_{w|(\mathrm{v,w})\in \mathrm{A}} X(vw) - \sum_{v|(\mathrm{u,v})\in \mathrm{A}} X(uv) = 0\ \forall\, v\ \in \mathrm{V} \setminus \{i,j\}$$

$$4)\ X(vw) \in \{0,1\} \qquad\qquad \forall\ (\mathrm{v,w})\ \in \mathrm{A}$$

Formula 1.1: Shortest path heuristics (Yu & Yang, 1998)

The weighted cost function for car, bike and walking are simplified and only contain the travel time as an attribute. For Public transport there are multiple factors that influence the attractivity of an alternative. Travel cost and the number of transfers can play an important role in the choice for a travel path. Therefore the weighted cost function is given by the formula below.

The shortest path algorithm generates paths between a set of nodes i and j. However, within each origin and destination node there is assumed that people also have to cover a small distance to reach the activity locations.

The travel cost between a set of nodes i and j, together with the intrazonal cost for nodes i and j gives the total travel cost to travel from i to j (i is in this case node A and j is node I). An example of a possible shortest path in the public transport network is visualised in figure 5.5.

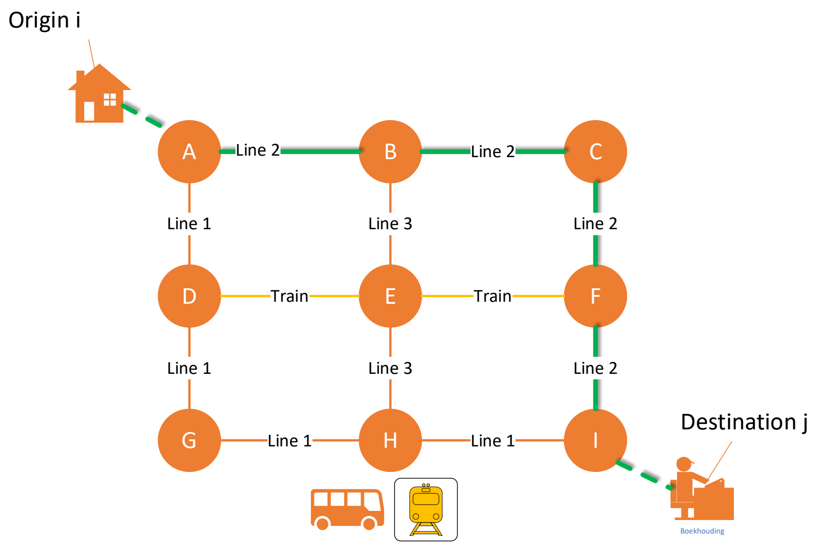


Figure 5.5: Example of a generated path between an origin i and destination j

The model of Visum is a tour-based model, accordingly the complete tour determines the travel resistance. For the replicated model there is assumed that travel times for the car, bike and walk network are similar for the outgoing and returning trip. Because of this assumption, the skim-matrix for the outgoing trip can be multiplied by two, to obtain the skim-matrix for the complete tour. For the Public transport network, it is assumed that the travel times could vary between the two trips. This is chosen because transfer times can be different for the outgoing and returning trip.

The generated shortest-tours give in the end the attributes for the skim-matrices. For public transport there are many components that determine the utility. Therefore all these components that are relevant have to be saved in skim-matrices. An example of a set of skim-matrices is shown in Appendices B. All components that are saved are summarized and explained in table 5.1.

Table 5.1: Calculation of Skim-matrix components Public transport

The access time	Time to walk to the station for the outgoing trip and walk back from the station for the incoming trip.
The egress time	Time to walk from the station to the destination for the outgoing trip and to walk from the activity-location to the station for the incoming trip.
The in-vehicle time	The time that is spend in the vehicles, also excluding tranfer time.
the transfer time	The total time to transfer between different Public transport lines.
The number of transfers	The total number of transfers.
The fare	The price of the Public transport tour.

5.2.3 MODE CHOICE MODELLING

The next step in the model development are the mode choice models. The mode choice models use information about the number of travellers between each origin and destination in combination with the skim-matrices to find the number of travellers using each transport mode between an origin and destination.

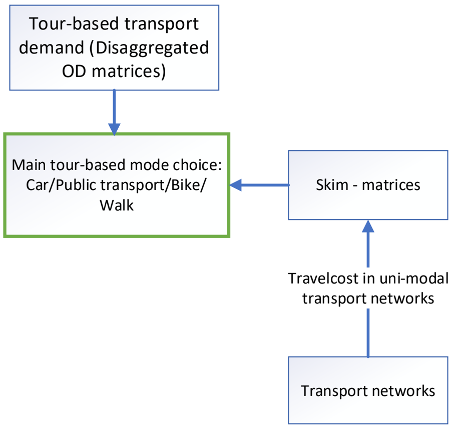


Figure 5.6: Development of the main tour-based mode choice step

The utility for using different transport modes can be derived by using the attributes obtained in the skim-matrices and multiplying it with specified parameters. To represent the fact that all person types have different perceptions regarding their preferred travel alternative, the model uses dummy variables. Besides, travellers' opinions vary for different activity purposes. For instance, a working trip has a higher value of time than a recreational trip or a shopping trip. For this reason, the parameters in the functions are activity specific. This also results in a separate matrix V_{ij} for each activity purpose and person group.

The utility functions, presented in table 5.2, are simplified compared to what is used for application purposes and is available in other studies. This is because estimating exact mode choice models is outside the scope of this research. Instead, the functions should have enough explanative power to show mechanisms of the Visum two-step mode-choice approach. The parameters for each utility function and activity purpose are presented in the case-study in chapter 7. An example of an obtained result from the utility calculation is given in Appendices B.

Table 5.2: Utility function of the different transport modes

Car	$V_{car} = ASC_{car} + \beta_1 * Tt_{car} + \beta_2 * Ct_{car} + D_{nca} * ASC_{nca,\ car}$
Public transport	$V_{PT} = ASC_{Public\ transport} + \beta_3 * Tiv_{Public\ transport} + \beta 4\ (Ta_{Public\ transport} + Te_{Public\ transport}) + \beta 5 * Ttr_{tranist} + \beta 6 * D_{tc} * Ct_{Public\ transport} + \beta 7 * Ntr_{Public\ transport} + D_{st} * ASC_{st\ ,Public\ transport}$
Bike	$V_{bike} = IF(ASC_{bike} + \beta 8 * Tt_{bike} + \beta 9 * Ct_{bike}$
Walk	$V_{walk} = ASC_{walk} + \beta 4 * Tt_{walk}$

Table 5.3: Name of the variables in the formulas

Formula	Variables
ASC	Alternative specific constant
Tt	Travel time
Ct	Travel cost
Tiv	In-vehicle time
Ta	Access time
Te	Egress time
T_t	Transfer time
Ntr	Number of Transfers
D_{nca}	Dummy - no car available
D_{st}	Dummy – student
D_t	Dummy – Public transport cost

The mode shares P^m_{ij} to travel with mode m between zones i and j, can be obtained by the multinomial logit model. This means that it is assumed that all modes are complete distinct alternatives. In the end this gives a new matrix P^m_{ij}. By multiplying the number of travellers coming from zone i with the share of people travelling from i to j, the number travellers F^m_{ij} from i to j can be obtained. The results of calculating mode-choices is presented in Appendices B.

$$Pm(ij) = \frac{Exp(Vm(ij))}{\sum_{r \in M} Exp(Vr(ij))}$$

$$Fm(ij) = F(ij) * Pm(ij)$$

$Fm(ij)$ = *Number of people that travel with mode m from i to j*
$Pm(ij)$ = *Probability to travel from i to j with mode m*
$F(ij)$ = *Total number of people travelling from i to j*
$Vm(ij)$ = *Systematic utility of mode m travel between i and j*

5.2.4 AGGREGATING MATRICES

Given the results of the mode-choice models, the next step in the modelling procedure is to transform the tour-based matrices to trip-based matrices that can be assigned to the transport network. This step is called aggregating matrices as indicated in figure 5.7.

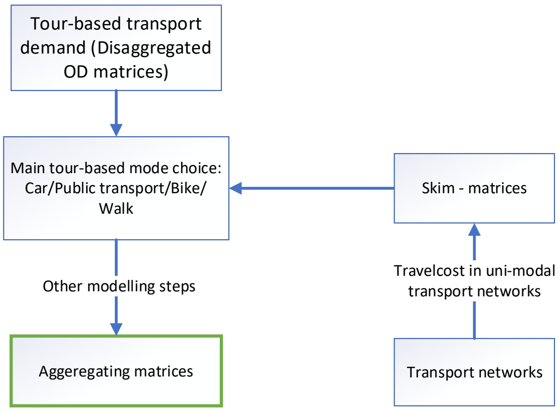
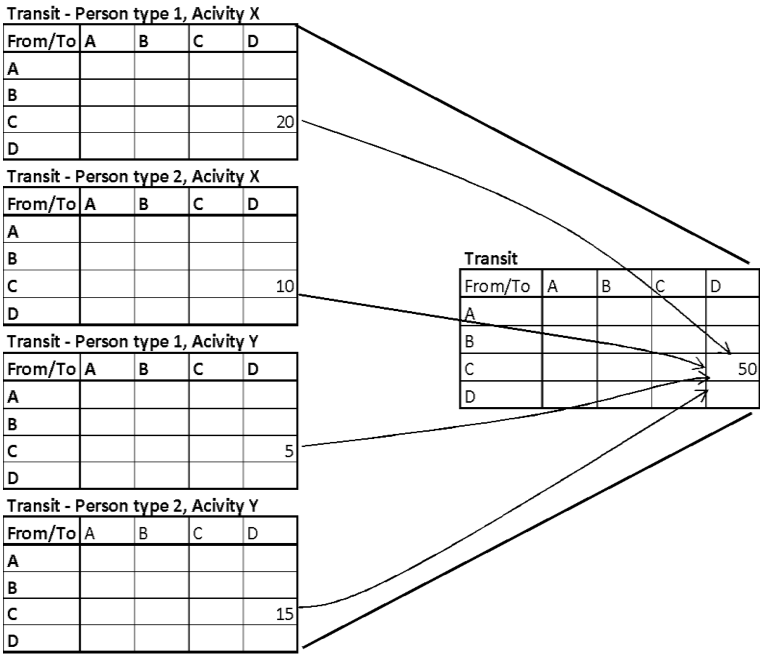


Figure 5.7: Development of aggregating matrices

To make this transformation, first the trips within a tour are divided across different time frames. The time of day slicing step is simplified in the modelling procedure of this study. It is assumed that every tour only consists of morning trips and evening trips. All trips coming from home, going to a destination are assumed to be morning trips. All trips coming from the activity location, going to home or to sublocations are assumed to be evening trips.

With the information about the number of trips within the tour that is performed in the morning and the evening, the tour-based matrices are split up into trip-based- morning and evening matrices. By summing the number of travellers per person type and activity purpose for each destination, the matrices are aggregated to one morning and evening matrix per transport mode. The evening matrix is different compared to the morning matrix, as the evening matrix contains sub-trips. How the process of aggregating matrices works is visualised in figure 5.8.



Transit - Person type 1, Acivity X

From/To	A	B	C	D
A				
B				
C				20
D				

Transit - Person type 2, Acivity X

From/To	A	B	C	D
A				
B				
C				10
D				

Transit - Person type 1, Acivity Y

From/To	A	B	C	D
A				
B				
C				5
D				

Transit - Person type 2, Acivity Y

From/To	A	B	C	D
A				
B				
C				15
D				

Transit

From/To	A	B	C	D
A				
B				
C				50
D				

Figure 5.8: Aggregating matrices, the number of travellers using transit for each person type and activity purpose are summed to one matrix representing the whole population

5.2.5 MODELLING MULTIMODALITY

Given the number of Public transport trips in the aggregated matrices the multimodality is modelled. This is the last step in the development of the Visum transport model as the assignment step is not modelled. The components that are modelled in this step are indicated in figure 5.9.

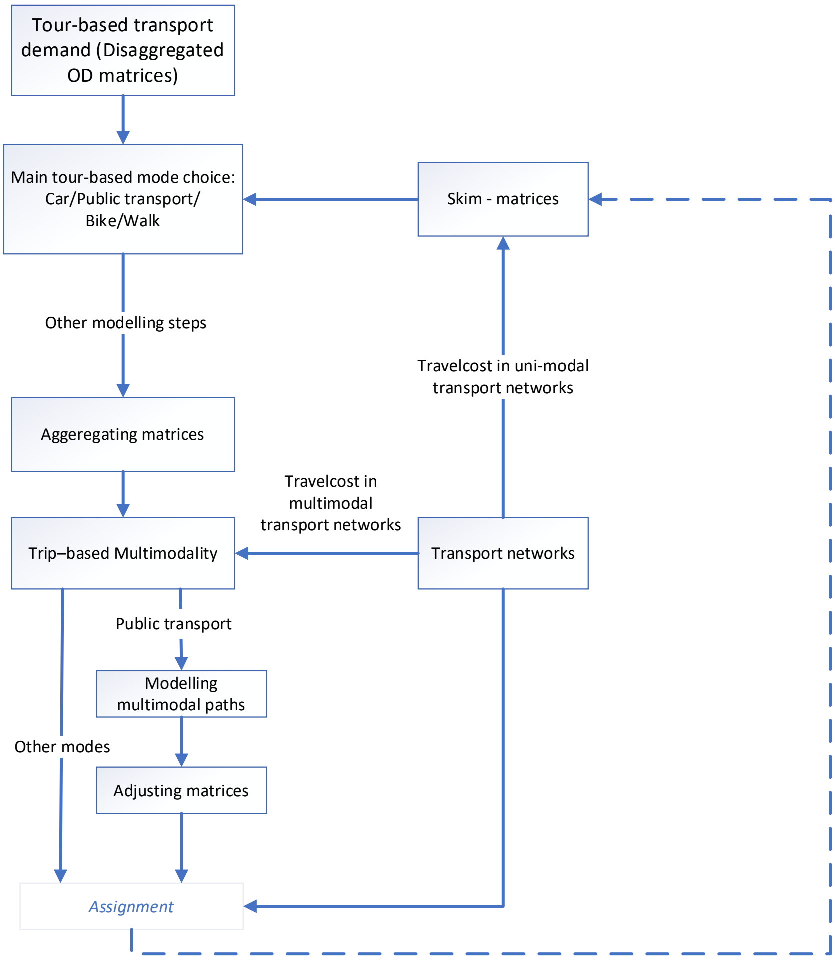


Figure 5.9: Modelling multimodality in the replicated Visum two-step mode-choice approach

It is assumed that multimodal transport trips can combine biking, walking and Public transport. Modelling multimodality consist of four steps:

- **Creating a multimodal Public transport network**. First the uni-modal public transport networks, used to generate skim-matrices are adjusted by connecting the bike network with the Public transport network with transfer links.
- **Route-set generation algorithms**. Then, based on the new network, multiple routes are generated using route-set generation methods. This means that a new algorithm is used, that not only gives the shortest path, but generates multiple paths.
- **Route-choice models**. The next step is to calculate the shares of travellers that use each generated path. For this process the model uses route-choice models.
- **Adjusting matrices**. Lastly, with the obtained route shares, the aggregated matrices F^m_{ij} are adjusted.

MULTIMODAL PUBLIC TRANSPORT NETWORK

Figure 5.10 and figure 5.11 show examples of the multimodal Public transport network for a trip from A to I and for a trip from I to A. Only nodes where it is possible to transfer are included in the multimodal transport networks. This could be transferred to different Public transport lines, but also transferred between the bike network and the Public transport network. Further it is noticeable that there are direct biking links between H, F and the working location in I. This is because station I has no biking facility, so a transfer from Public transport to bike is not possible in this zone.

All multimodal route-choice models, between each origin and destination, are in this study modelled as a separate directional graph. It is chosen for a directional graph because the network size grows significantly by adding bike and walk links to the network. As a consequence, reducing the network size to keep the optimization problem feasible in excel is desirable. In the directional graph only transport links are added that full fill some logicality constraints:

First of all, detours are prohibited. In the replicated model it is considered a detour when an alternative needs two more links compared to the fastest travel option. Secondly, there is a maximal travel time to access or egress with the bike from public transport stations. The maximal travel time is a percentage of the time to bike directly between the particular origin and destination. For this reason station E is not included in the multimodal transport networks. How long travellers want to bike to a station also depends on the characteristics of the Public transport station. Some stations have better facilities than other stations, for example better (bike) parking places. This is expressed by “type one” stations and “type two” stations. “Type one” stations are assumed to be preferred by travellers.

The networks in figure 5.10 and 5.11 are transformed to an shortest-path optimization problem. All routes start from A, representing the house in figure 5.10, then people choose to walk or bike and optimize their route until they reach I, where they end the trip at the desk. Each set of links in the network with a certain transport mode m is a trip leg Z^m. Transfers in the different zones are modelled as illustrated in figure 5.12 for zone D. All red lines are transfer links. Travellers can bike to zone D and transfer to the train or B/T/M 1. The other option is that they arrive with B/T/M 1 and transfer to the train or stay in B/T/M 1.

The bike and walk links (indicated as A_w and A_b) have the same travel times compared to the unimodal transport network that is used to obtain skim-matrices in paragraph 5.2.1. The transfer links contain information about transfer times, starting cost for a public transport mode and transfer resistance. How the transfer links are added to the model in Excel is presented in Appendices C.

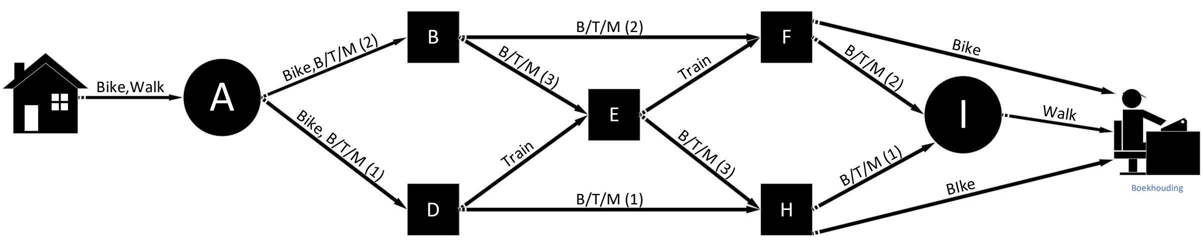


Figure 5.10: Multimodal Public transport network from home A to work or education I

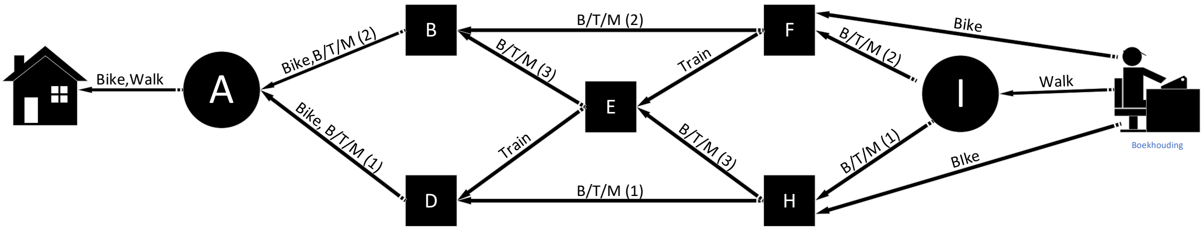


Figure 5.11: Multimodal Public transport network from work or education I to home A

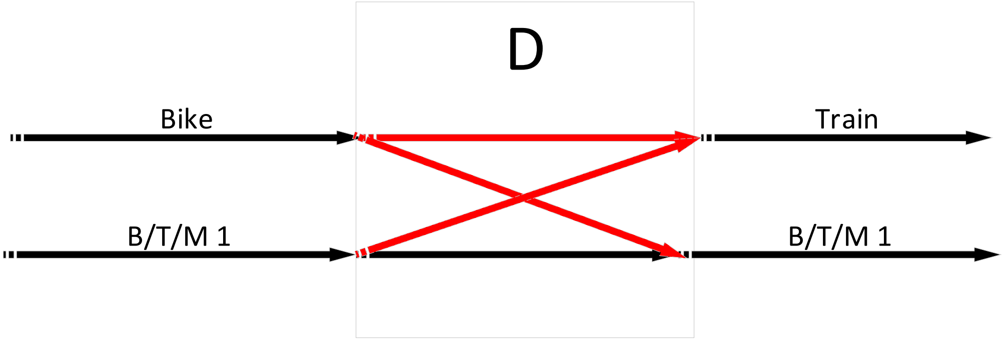


Figure 5.12: Detailed look at transfer zone D, red lines indicate transfers

ROUTE-SET GENERATION ALGORITHM

Given the Public transport network, the next step is to model route-choice behaviour. The first step of modelling route choices is to generate the set of routes from which travellers choose their preferred option. There is chosen to use a stochastic-shortest route method to generate routes. This method is chosen because it is easier applicable in Excel and is expected to be sufficient to consider all relevant path alternatives.

Using a stochastic shortest path generation is based on the assumption that travellers have not full information about path costs. Therefore path costs are perceived differently by different travellers. This is expressed by a random term for the generalized cost function on link level (Prato, 2009). The random term can be extracted from different probability distributions such as the normal distribution and the truncated normal distribution (Tan, 2016). Within each random draw a shortest path method is used to find a new alternative. This is done until the choice set is considered large enough for model estimation.

The links in the Public transport network contain the minimal travel times. The random term is assumed to have a normal distribution with only positive values (absolute normal distribution). This means that the travel links need to contain information about the standard deviation. To model multimodality, the stochasticity in this study is only included for all access and egress links and links that contain a transfer between different modes (Public transport and walk or Public transport and bike). This means that when someone accessed the Public transport network the route-search is deterministic, so travel times between a set of stations does not vary.

There are 40 draws of the normal distribution for all transport links. This means that there are 40 iterations in which the shortest path algorithm is used to obtain shortest paths. When 40 shortest paths are generated, only the unique paths are interesting to include in the choice set. Examples of possible generated routes are visualised in figure 5.13. What a generated set of routes looks like in Excel is presented in Appendices C.

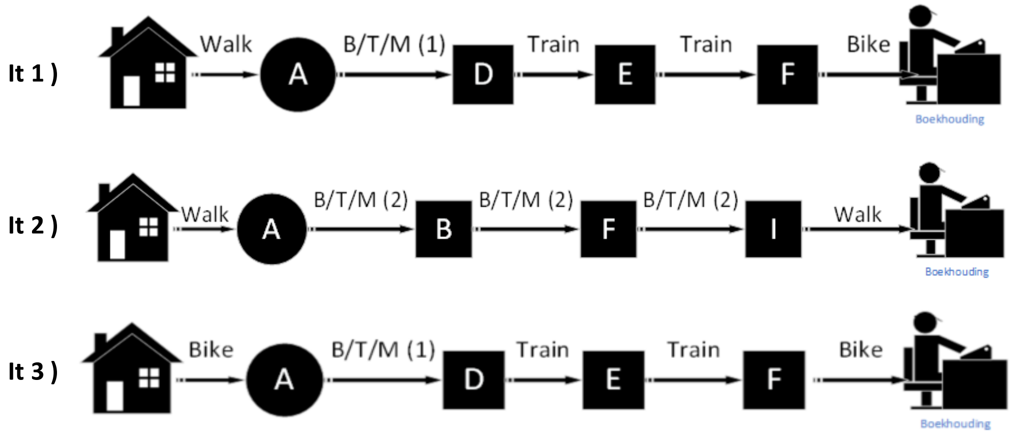


Figure 5.13: Result of the first three iterations of the stochastic shortest path algorithm

DETERMINING THE UTILITY OF THE PATHS

After the route-set generation, the route shares of the different travel paths are calculated. With the route shares, the amount of passengers that bike to and from each station can be derived. To calculate route shares, the utility V_k of each travel path k must be determined first. The formula presented below with the variables and parameters in table 5.4 is used to obtain the utility values.

Compared to the utility functions to calculate the total Public transport demand in paragraph 5.2.3 some factors are added to the function. First the biking time is added. In this study it is assumed that the value of time to access and egress Public transport is similar to the value of time of the regular biking alternative.

Penalties are added to the function to represent the fact that biking in a multimodal trip is valued differently compared to directly biking to a destination. As described earlier, people are willing to bike longer to a station with good facilities. Therefore the penalties for a station “type one” are different from the penalties for a station “type two”.

Besides, penalties for accessing a station will be different compared to penalties for egress legs. As pointed out earlier, in the Netherlands it is more popular to use a bike to access the station than it is to use for egressing the station. Hence, penalties for egress must be higher. The egress trip leg of the outgoing trip is the access trip leg of the incoming trip. For this reason the beta’s of the access and egress penalties for the returning trips I-A are shifted compared to the trip A-I.

It should be noted that all beta’s are different compared to the beta’s used in paragraph 5.2.3 to determine the general mode choice. This is because the beta’s are at this point not person type specific anymore. For this reason general bettas need to be estimated to give an average estimation for the whole population.

$$V_k = \beta12 * Tiv + \beta13 * Ttr + \beta14\,(Twa + Twe) + \beta15 * (Tba + Tbe) + \beta16 * Ct + \beta17 * Ntr + \beta18 * Pba1 + \beta19 * Pbe1 + \beta20 * Pba2 + \beta21 * Pbe2$$

Table 5.4: Variables and parameters for the route choice model

Variables	Parameter
In-vehicle time (Tiv)	β_{12}
Transfer time (T_{tr})	β_{13}
Access time walk (Twa)	β_{14}
Egress time walk(Twe)	β_{14}
Access time Bike (Tba)	β_{15}
Egress time Bike (Tbe)	β_{15}
Travel cost (Ct)	β_{16}
Number of Transfers (Ntr)	β_{17}
Penalty bike access station type one (Pba1)	β_{18}
Penalty bike egress station type one(Pbe1)	β_{19}
Penalty bike access station type two (Pba2)	β_{20}
Penalty bike egress station type two(Pbe2)	β_{21}

PATH SIZE LOGIT TO CALCULATE PATH SHARES

Because different travel paths share some transport links, there is similarity between alternatives. This leads to correlation, which influences the route shares. Complete distinct routes will have relatively higher shares of traffic compared to similar routes.

The Multinomial Logit and Nested logit model as discussed in section 4.1, are not suitable to address the route-choice problem. Multinomial logit does not consider correlation at al. Nested logit assumes that alternatives belong to one certain nest, while in route-choice modelling different routes share links with hundreds of other alternatives (Prato, 2009). However, there exist other modifications of the logit structure that can be used to address this issue.

A relatively straightforward and easy applicable approach is the path size logit model. Moreover this approach is said to outperform other approaches to address path correlations, like C-logit (Prato, 2009). The function for the path-size logit is presented in formulas on the next page. For each route alternative k there is a correction factor that considers the part of a Public transport path that is considered as a complete distinct alternative. This factor is multiplied with a parameter that needs to be estimated. The following set of functions is used to obtain the mode shares. How this process works in Excel is presented in Appendices C.

$$P(k) = \frac{exp\left(V(k) + \beta(ps) * LN\big(PS(k)\big)\right)}{\sum_{l \in C} exp\big(V(l)\big) + \beta(PS) \ * LN(PS(l)))}$$

$$PS(k) \ = \sum\nolimits_{vw \in A} \frac{t(vw)}{t(k)} * \frac{1}{\sum_{l \in L} x(l, vw)}$$

P(k) = Share of passengers that use path k
PS(k) = Factor for Shared path
t(vw) = travel time of link between node v and w
t(k) = travel time of route k
x(l,vw) = binary variable for link between node v and w for path l

ROUTE SHARES AND ADJUSTING MATRICES

In the end, by using the mentioned formulas for all travel paths, it is possible to calculate the mode shares. With the results of all multimodal trips, it can be calculated what percentage of the travellers uses a bike to access or egress each Public transport station. With this information, the aggregated matrices F^{m}_{ij} obtained in paragraph 5.2.4 are adjusted. Modelling multimodality is the step before the assignment, this means that the only objective of modelling multimodality is to adjust the matrices and not to assign the generated routes to the network.

To adjust the matrices, the model must exactly know what part of the transport trip is performed with what transport mode. Therefore, the transport trip of each alternative k is divided into trip legs $Z^{m}_{k..}$ This variable Z^{m}_{k} is a binary variable which tells if a trip leg is used in alternative k.. In the example networks in figures 5.10 in the access leg travellers can Walk or Bike from origin A to zone A, B or D. For the egress leg travellers walk or bike from zone F, H or I to destination I. Lastly the trip leg between the set of stations is travelled by Public transport. The formula below is used to obtain the number of travellers that use each trip leg. The result obtained from this formula are illustrate in Appendices C

$$F(Z, ij) = \sum_{k \in L} Z(k) * P(k) * Q\,(ij)$$

F(Z,ij) = Total number of travellers that use multimodal leg Z to travel between i and j
Z(k) = Binary variable, is one when Public transport leg Z is used for alternative k
P(k) = Path share for alternative k
Q(ij) = number of travellers between i and j

With the number of travellers that use each trip leg the two-step mode-choice model calculated the number of multimodal trips. This information is used to adjust the matrices that are generated for the main transport modes in paragraph 5.2.3.

With the information about the adjusted matrices the traffic can be assigned to the transport networks. Assigning the traffic to the transport network is outside the scope for this study. This means that all steps to model multimodal transport trips in the Visum transport model are performed. The next step is to implement the SB-bike-sharing system to the procedure.

5.3 IMPLEMENTING SB-BIKE-SHARING TO THE TWO-STEP MODE-CHOICE APPROACH

The objective of chapter 5 is to implement SB-bike-sharing to the replicated Visum two-step mode choice approach .So this paragraph will elaborate how the shared bikes are added to the model as discussed in paragraph 5.2. The implementation of SB-bike-sharing results in adjustments of the multimodal transport networks and the utility functions as discussed in paragraph 5.2.5. The new modelling setup is presented in figure 5.14.

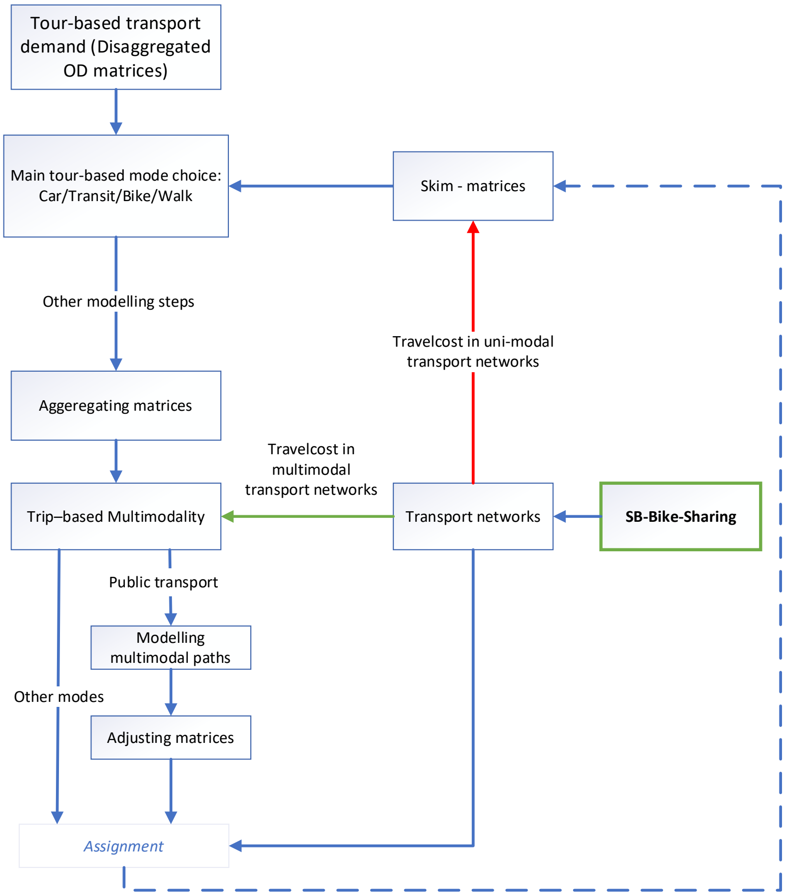


Figure 5.14: Implementing SB-bike-sharing to the replicated Visum two-step mode-choice approach

It is assumed that SB-bike-sharing is only used in combination with Public transport trips. Therefore bike-sharing is not included in modelling mode choice in the tour-based travel demand. Besides, the Visum model only uses unimodal transport networks to calculate the demand for public transport. Accordingly, the model does not consider SB-bike-sharing when calculating skim-matrices for Public transport in the Visum approach. This is indicated by the red line from the transport network to the Skim-matrices. Nevertheless, SB-bike-sharing does play an important role when modelling multimodal trips. Therefore the steps in paragraph 5.2.5 are adjusted for the implementation of SB-bike-sharing.

5.3.1 THE NEW MULTIMODAL PUBLIC TRANSPORT NETWORK

The Public transport network needs to be adjusted at stations where the SB-bike-sharing system is offered. It is assumed that the sharing system is only used at the egress side of transport trips. In the example network this means that station E, F, H and I are modelled such that they can offer the Bike-sharing system. When bike-sharing is available at all mentioned stations, the multimodal Public transport network for trip A-I is obtained as shown in figures 5.15 and 5.16. The same set of criteria is used compared to the multimodal networks in paragraph 5.2.5 This means that it is not possible to use the shared-bike to travel from E in a multimodal trip from A to I.

In figure 5.17 there is given a detailed look of what a transfer zone looks like when the SB-bike-sharing alternative is available. In this case, extra transfer links are added to the shared-bike mode. However, the shared-bike does not have its own network to travel between zones. This is modelled this way because the system has exactly the same characteristics compared to the normal bike. Hence, the SB-bike-sharing system can use the normal bike network. To connect the bike-sharing alternative to the normal bike network an extra transfer link is added. It is modelled as if a person first transfers from the train to the shared-bike and then from the shared-bike to the normal bike. The transfer links contain all information about the transfer time, the cost and the transfer resistance.

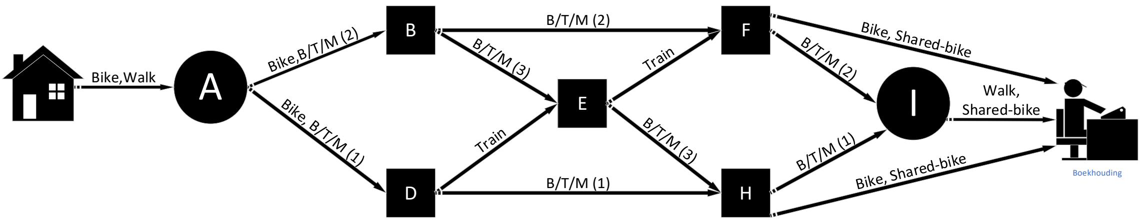


Figure 5.15: Multimodal Public transport network A to I with SB-bike-sharing

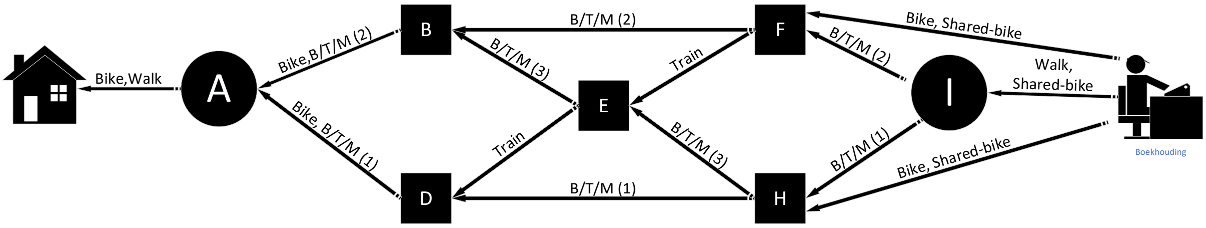


Figure 5.16: Multimodal Public transport network I to A with SB-bike-sharing

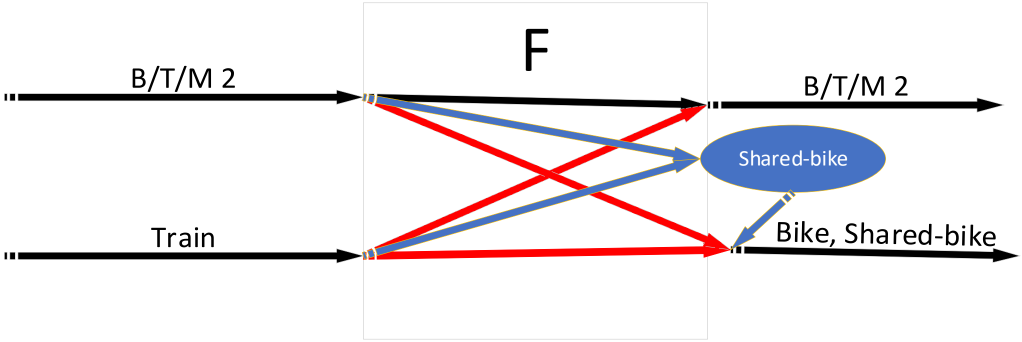


Figure 5.17: Detailed look at transfer zone F, Blue lines indicate SB-bike-sharing transfers

5.3.2 ROUTE-SET GENERATION ALGORITHM

The transfer links have to be added to the optimization problem. The added links are illustrated in Appendices D. In the generation step the cost and resistance are not explicitly considered, therefore they are added to the travel time with a penalty. All transfer links to the SB-bike-sharing have a standard deviation. The transfer links to transfer from the shared-bike alternative to the normal bike have no travel times and standard deviation. By performing the same stochastic shortest path algorithm with 40 iterations, extra alternatives are added to the path alternatives k.

5.3.3 ROUTE CHOICE MODEL

The transfer link to the bike-sharing alternative contains information about the transfer time, the cost and the transfer resistance. The penalty to use bike-sharing for access and egress has to be added to the original utility function. This gives a new utility function for the multimodal Public transport trips as shown in the formula below. In contrast to the bike alternative there is no distinction in preferences between station types. This is chosen because in the case of bike-sharing travellers do not have to bother about parking facilities. Bike-sharing is in reality only used for the egress trip leg in the outgoing trip. For this reason the penalty to access Public transport with bike-sharing is very high. The beta's for the returning trip are again shifted compared to the outgoing trip.

Nothing changed about the path-size logit function to obtain the route-shares. This function automatically considers the fact that the bike-sharing alternatives are relatively similar to the bike alternatives as they share many links. The extra parameters for SB-bike-sharing can be found in Appendix D.

$$V_k = \beta 12 * Tiv + \beta 13 * Ttr + \beta 14\,(Twa + Twe) + \beta 15 * (Tba + Tbe) + \beta 16 * Ct + \beta 17 * Ntr + \beta 18 * Pba1 + \beta 19 * Pbe1 + \beta 20 * Pba2 + \beta 21 * Pbe2 + \beta 22 * Psba + \beta 23 * Psbe$$

Table 5.5: Variables and parameters for the route choice model

Variables	Par.
Penalty shared bike access (Psba)	β_{22}
Penalty Shared bike egress (Psbe)	β_{23}

5.3.4 ROUTE SHARES AND ADJUSTING MATRICES

By adding the SB-bike-sharing links and performing all steps as discussed, extra alternative paths k are added to the route choice model and new mode shares are obtained. The availability of bike-sharing also means that extra legs become available. The same procedure is used as in paragraph 5.3.4 to calculate the number of travellers that use each multimodal Public transport leg.

The last step is to adjust the matrices, given the number of travellers that use the SB-bike-sharing legs. As Bike-sharing has no travel demand from the tour-base mode-choice modelling, a new empty matrix has to be added for this mode. The travellers that use SB-bike-sharing are added to the new empty matrix. In the end, this results to fulfil the objective to implement SB-bike-sharing to the two-step mode-choice approach.

By creating the model and implementing the SB-bike-sharing system, some problems of the current modelling approach became apparent. These problems result in the fact that the current Visum transport modelling software is at this point not regarded as suitable to test some policy scenarios regarding SB-bike-sharing.

5.4 PROBLEM DISCUSSION ABOUT THE VISUM APPROACH

This paragraph discusses problems regarding the two-step mode-choice approach used in the Visum model. There problems are indicated with the red boxes in figure 5.18. The first problem is the consistency problem, this is caused by the fact that multimodality is modelled at trip level. The second problem is the travel demand problem, which is caused by the procedure to obtain skim-matrices. The last problem is the aggregation problem, which is caused by the fact that matrices are aggregated before multimodality is modelled. All problems are further elaborated in the next subparagraphs.

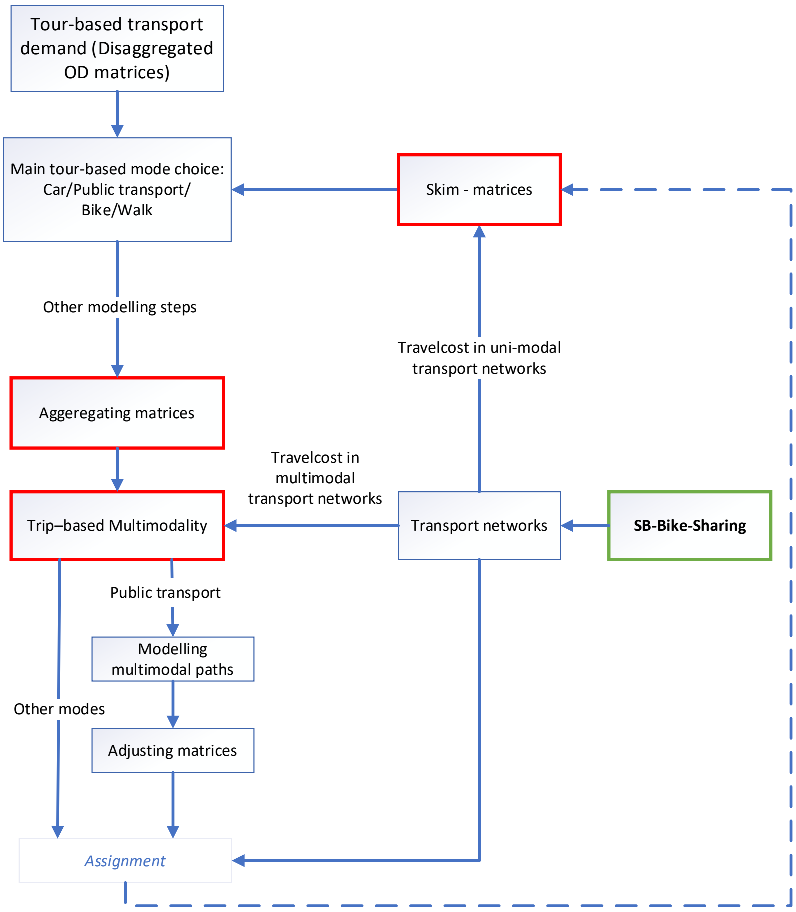


Figure 5.18: Problems of the Visum approach to model SB-bike-sharing indicated with the red boxes

5.4.1 THE CONSISTENCY PROBLEM

The consistency problem means that there is no consistency in the use of SB-bike-sharing. In reality, a person that uses SB-bike-sharing for the egress part of an outgoing trip, has to return the bike later in the trip to the same station. When there is no consistency, the person that used a bike could leave the bike at the activity location or could return the bike to another station.

The problem occurs because multimodality is modelled at trip-level instead of tour-level. The main mode choice is on tour level, this gives consistency in the main mode-choice between multiple trips within a tour. However, the consistency between access and egress modes within a tour is not explicitly modelled. Therefore mode availability constraints are not considered for the access and egress trip legs. The SB-bike-sharing system shows a tangible example of this problem.

Let’s assume that a person uses "public transport" as its main mode. This means that the outgoing trip, as well as the returning trip, will have to use a public transport leg in their travel path. In the morning a person decides to use a combination of the train and SB-bike-sharing. For the returning trip the model knows that the same person has to use the main mode "public transport" again. However, this time it is more efficient to use the bus to return to the train station. Consequently, the person left the bike at the destination although it is obligatory to return the bike to the station. Hence, explicitly considering mode availability of access and egress modes is required to model SB-bike-sharing. The problem is visualized in figure 5.19.

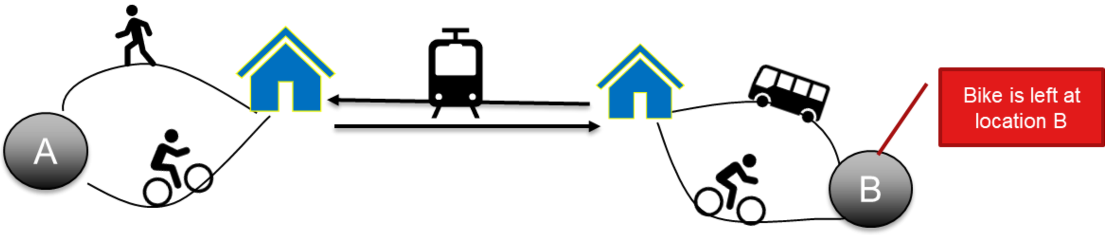


Figure 5.19: Consistency problem that could occur with the Visum modelling approach. The main transport mode is transit. At trip level the model calculates different multimodal trips for the outgoing trip compared to the returning trip. As a result, the bike i s left at destination B.

5.4.3 THE AGGREGATION PROBLEM

The aggregation problem means that the model cannot consider person type specific preferences when modelling the demand for SB-bike-sharing. For this reason the model cannot consider that students are more likely to use the system compared to other person groups.

The aggregation problem occurs because the person specific and activity purpose specific matrices are aggregated (summed) to one matrix before the trip-based multimodality is modelled. When modelling the main-mode choice on tour-level, the model is disaggregated. So at this stage, persontype specific travel behaviour can be taken into account. However, between the main-mode choice step and the multimodal mode-choice step the matrices are aggregated, leading to the aggregation problem.

5.4.2 THE TRAVEL DEMAND PROBLEM

The travel demand problem refers to the fact that the model does not consider the relation between SB-bike-sharing and the demand for public transport. Promoting SB-bike-sharing is an interesting policy measure to increase public transport ridership. Nevertheless, the effect of this kind of policy measures cannot be tested with the current Visum approach due to the travel demand problem.

The travel demand problem exists because of the assumption that is made about the attributes assigned to the skim-matrices to model the main-mode-choice. It is assumed that the value assigned to the skim-matrices is based on the path with the lowest weighted cost that only uses the unimodal public transport network. This means that the path only combines walking and public transport to calculate the share of people that use public transport.

5.5 CONCLUDING REMARKS

SB-bike-sharing is implemented in a created model in Excel, using the modelling procedure used in P.T.V Visum 2021, to illustrate that this modelling approach has some limitations regarding the combination of modelling tour-based mode choice and multimodality.

The model uses a two-step mode-choice approach to combine multimodality and tour-based mode choice. In this approach people first make a choice for a main transport mode that is used for the complete transport tour. Conditioned to this choice people make a choice on trip-level about multimodal trips. So on tour level the model calculates the share of people that choses public transport versus the car. Then for all people that use public transport the model calculates what multimodal trips people make. This means for example that the number of people that use a bike to reach a station is calculated in the second step of the mode-choice approach.

It is assumed that SB-bike-sharing is only used for multimodal transport. This means that SB-bike-sharing is modelled in the second step of the two step-mode choice approach. SB-bike-sharing is implemented by adding new transfer links between public transport and the biking network to the multimodal transport network. The transfer links contain information about the transfer time, the transfer cost and the resistance to transfer between public transport and SB-bike-sharing. The information about the transfer resistance is represented by a penalty for SB-bike-sharing in the utility function of multimodal routes. With the added transfer link the route-set generation will find paths that use SB-bike-sharing. Based on the travel utility of the multimodal paths that use SB-bike-sharing compared to other path alternatives, it can be calculated what share of people uses the system.

By analysing the approach three problems to properly model SB-bike-sharing were found:

The consistency limitation means that there is no consistency in the use of SB-bike-sharing. In reality, a person that uses SB-bike-sharing for the egress part of an outgoing trip, has to return the bike later in the trip to the same station. When there is no consistency, the person that used a bike could leave the bike at the activity location or could return the bike to another station. The problem occurs because multimodality is modelled at trip-level instead of tour-level. The main mode choice is on tour level, this gives consistency for the main-mode. People that go to work by car will also use the car to return from work. However, because multimodality is modelled at trip level, the consistency between access and egress modes within a tour is not explicitly modelled.

The aggregation limitation means that the model cannot consider person type specific preferences when modelling the demand for SB-bike-sharing. For this reason the model cannot consider that students are more likely to use the system compared to other person groups. The aggregation problem occurs because the person specific and activity purpose specific matrices are aggregated (summed) to one matrix before the trip-based multimodality is modelled. When modelling the main-mode choice on tour-level, the model is disaggregated. So at this stage, persontype specific travel behaviour can be taken into account. However, between the main-mode choice step and the multimodal mode-choice step the matrices are aggregated, leading to the aggregation problem.

The travel demand problem refers to the fact that the model does not consider the relation between SB-bike-sharing and the demand for public transport. Promoting SB-bike-sharing is an interesting policy measure to increase public transport ridership. Nevertheless, the effect of this kind of policy measures cannot be tested with the current Visum approach due to the travel demand problem. The travel demand problem exists because of the assumption that is made about the attributes assigned to the skim-matrices to model the main-mode-choice . It is assumed that the value assigned to the skim-matrices is based on the path with the lowest weighted cost that only uses the unimodal public transport network. This means that the path only combines walking and public transport to calculate the share of people that use public transport.

All problems discussed can be generalised to other multimodal transport concepts and policies. The consistency problem is also a problem for park and ride facilities and for normal bikes. The aggregation problem is for all multimodal transport relevant. Some groups use more multimodal transport alternatives compared to others. Therefore socio-demographics can be an important explanatory variable for the amount of multimodal transport that is used in a particular area. Because of the aggregation problem the models miss out on explanatory power regarding multimodality. The travel demand problem is relevant for all promoting policies regarding SB-bike-sharing. Examples of such policies are smooth transfers in park and ride facilities or improved biking lanes towards stations.

NEW METHOD

6. TOUR-BASED MODE-CHAIN AND STATION CHOICE APPROACH

Chapter 5 discussed three problems about the Visum two-step mode choice approach; the consistency problem, the aggregation problem and the travel demand problem. This research wants to create an applicable approach to realistically model SB-bike-sharing. The three problems show that using the current Visum approach does not succeed in fulfilling the research objective. Therefore this chapter will create a new approach to combine multimodality and tour-based mode-choice. The new approach is designed to address all three problems. The main difference is that components that need consistency on tour-level are modelled at tour-level instead of trip-level. The model uses a set of person type and activity purpose specific discrete choices to model multimodal public transport tours. First the structure of the discrete choice model is explained. Afterwards, there is elaborated about the modelling steps. This is first done for a simple tour (home – activity – home). Afterwards the modelling structure is extended to make the approach also applicable to more complicated tours (home – activity – sub activity – home). The chapter ends with an example of an application of the modelling procedure for a practical case. This chapter will contribute to the second research objective:

1. *Create an approach to combine tour-based mode choice and multimodality in order to address the limitations of the current Visum modelling approach.*

And answer the following research question:

> *4. How to create an approach that combines multimodality and tour-based mode choice?*

6.1 THE DISCRETE CHOICE MODELLING STRUCTURE

Figure 6.1 illustrates the discrete choices in the tour-based mode-chain and station choice approach. The discrete choices are based on Random utility maximization principles. The choices upstream are all calculated based on the expected utility of choices downstream (Logsum). The new approach gives a solution for all three problems discussed in chapter 5.

The discrete choices in the figure are all on tour-level. This means that multimodality is modelled at tour level and not at trip level as in the Visum approach. Besides, the discrete choices are all persontype and activity purpose specific to overcome the aggregation problem of the Visum approach. This means that groups of people performing the same activity are the decision making unit in the discrete choice model. Because the utility of public transport is calculated based on the log-sum of the different mode-chain utilities, the approach also considers multimodal transport when calculating the travel demand of public transport. Consequently, the new approach is also a solution for the travel demand problem.

- The first choice is what *pre-specified mode-chain* is used. The concept of pre-specified mode-chains is widely used in literature and practice to model multimodality in trip-based methods. This is discussed in paragraph 4.5. When using this method there is assumed that there is only a limited number of mode combinations available in the tour. Those mode combinations are pre-specified in so-called mode-chains. For each mode-chain there is a certain chance that it is chosen, this is based on the expected utility. As this study only considers multimodal biking-tours there are only four mode-chains available:

        - Walk – Transit – Walk (WTW)
        - Walk – Transit – Bike (WTB)
        - Bike – Transit – Walk (BTW)
        - Bike – Transit – Bike (BTB)

    Note that the first mode-chain is actually a unimodal public transport tour as only one vehicular mode is used. The other chains all use biking at the access or egress side of the transport tour. Using biking at the egress-side of a transport tour means that the bike is used to bike from the station to the activity location and is later returned to the station again. Likewise, biking at the access side means that the bike is used to reach a station and is later picked up to bike home again.

- **The second choice** in the discrete choice model is the **station choice**. This step is only modelled for all mode-chains that contain a biking access or egress trip (or both). This is based on the assumption that people that use a bike have to return to the same station as they used earlier in a tour. If people do not use a bike, they would not necessarily have to return to the same station. Therefore the station choice only has to be modelled for multimodal transport tours. For this reason, there are no conditioned choices to the WTW mode-chain as can be seen in figure 6.1.

  For all other mode-chains the station choice is optimized at tour-level. The station-optimization is based on research of Khani (The reason to optimize the station choice at tour level is visualised in figure 4.16. When optimizing the station choice on trip level, station T2 is the best choice for the morning trip. However, Looking at the complete tour, station T1 is the best choice. When the station choice is optimized at tour-level, the model will consider that passengers are more likely to transfer to the bike at station T1 compared to station T2 in the morning trip.

- **The last choice** is about using a **normal bike or SB-bike-sharing**. This choice is only relevant for the mode-chains that use a bike at the egress-side of the transport tours.. Moreover, the station that is used must have shared-bikes available. The choice to use a shared-bike instead of a normal bike, is based on different characteristics. The shared bike has different transfer resistance, different transfer time and different cost compared to the normal bike.

To obtain utility values for all discrete choices, the model needs data about attributes of the different choice alternatives. These attributes can be obtained from the transport network. This is based on shortest path algorithms. Those shortest path algorithms will optimize complete tours, instead of separate trips. How the complete modelling setup works, is explained based on a few modelling steps in the next paragraph. To get a better understanding of the approach a practical example is given in paragraph 6.4.

After the set of discrete choices is performed, the obtained distribution of multimodal and unimodal public transport tours have to be added to unimodal origin and destination matrices. All unimodal transport tours (W-T-W) are directly added to the public transport matrices. All multimodal mode-chains that contain a biking access or egress trip leg, will add the biking leg to the bike-matrices and the rest of the tour performed by public transport to the unimodal public transport matrices. For example the bike-public transport-walk mode-chain, gives a biking tour from the origin to the station and a unimodal public transport tour from the station to the destination.

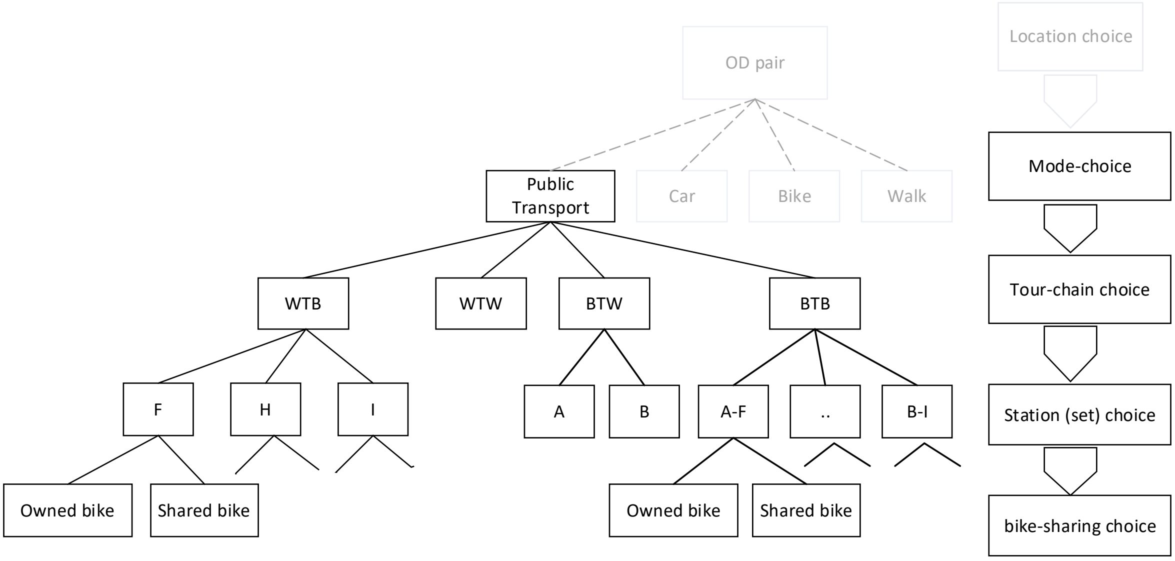


Figure 6.1: The discrete choice model of the tour-based mode-chain and station choice approach including the choice for SB-bike-sharing.

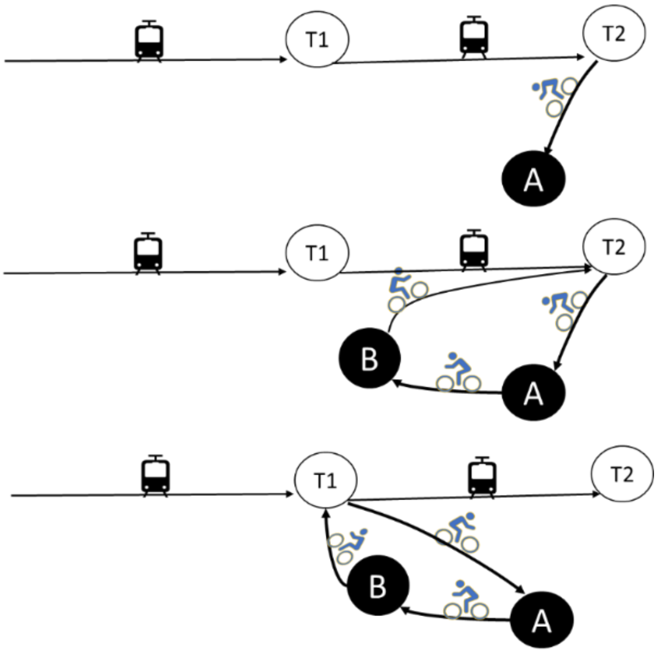


Figure 6.2: The reason to optimize station choice at tour level. The station that is for the morning trip the most efficient option (first illustration) is not always the most efficient option when considering the complete tour (second and last illustration)

6.2 THE TOUR-BASED MODE-CHAIN AND STATION CHOICE MODELLING STEPS FOR A SIMPLE TOUR

The tour-based mode-chain and station choice modelling approach is summarized in 10 steps, as presented below. The coming sections will elaborate how the individual steps work. The approach is first presented for the simple type of tours. This refers to tours that perform one activity and then directly return home (home-work-home).

The tour-based mode-chain and station choice modelling approach:

Set tour-based mode-chain specific transport networks.

1. Setting origins and destinations in the transport network, copy the network as many times as there are activities and add artificial links that represent whether an activity is performed.

Set constraints for the multimodal station optimization.
(Only for mode-chains B-T-W, W-T-B and B-T-B)

2. Search for stations that are in the combined travel time radius from the origin and the destinations in the tour.
3. Setting consistency constraints for transfers from bike access legs or to bike egress legs for each station. (Consistency constraints)

Optimize tours to find input attributes for the RUM-models.

4. Search for the unimodal mode-chain with a shortest path algorithm to the travel alternative with the lowest utility in the tour-based transport network.
   (Only for mode-chain W-T-W)
5. Search for the multi-modal mode-chains for each station with a constrained shortest path algorithm to the travel alternative with the lowest utility in the tour-based transport network.
   (Only for mode-chains B-T-W, W-T-B and B-T-B)

Preparation process before calculating the RUM-models.

6. Add SB-bike-sharing to the choice model, when available given the mode-chain and station-choice
   (Only for mode-chains W-T-B and B-T-B).
7. Using dominance criteria to only use alternatives that are relevant.

Calculating the mode-chain, the station choice and the bike-sharing choice based on RUM-models

8. Calculate person type specific and activity purpose specific utility values.
9. Calculate the shares of persons using a normal bike and a shared bike.
   (Only for mode-chains W-T-B and B-T-B).
10. Calculate the station choice distribution for the multi-modal transport tours.
    (Only for mode-chains B-T-W, W-T-B and B-T-B).
11. Calculate the mode-chain distribution of all public transport tours.

6.2.1 SET TOUR-BASED MODE-CHAIN SPECIFIC TRANSPORT NETWORKS

The first step generates the transport networks that are used to find tour-based shortest paths. The transport networks are mode-chain specific. How this works is elaborated in this sub-paragraph.

Step 1: Setting origins and destinations in the transport network, copy the network as many times as there are activities and add artificial links that represent whether an activity is performed.

The network used for the optimization problem is a tour-based network. This means that the outgoing transport trip and the returning transport trip are connected with an “activity state” link. Figure 6.3 shows the transport network that is used for the new optimization problem. Instead of optimizing multimodal trips from home to work, as done in the two-step mode-choice approach of Visum (Figure 5.10), the optimization is for the complete tour.

The network state is “one” when the activity is not performed, and becomes “two” when the activity is performed. The green home and red home in state 1 and 2, represent the fact that the new optimization problem is a tour-based approach that optimizes the tour from home to home. The only difference is that, before returning home the activity state must be two instead of one.

The pre-defined mode-chains determine the exact network that is available. In the example, the mode-chain walk-transit-bike is used. For this reason the network has only walking links available at the home-side of the trip and only bike links at the egress side.

The stations that are used, is the last determinant for the optimization problem. In step 1, possible station sets are defined. In the case of the Walk- Public transport – Bike trip, the station-sets were A-F, A-H and A-I. This means that the model will have to optimize a tour for each mentioned station set.

What the new network setup looks like in Excel is illustrated in Appendices E.

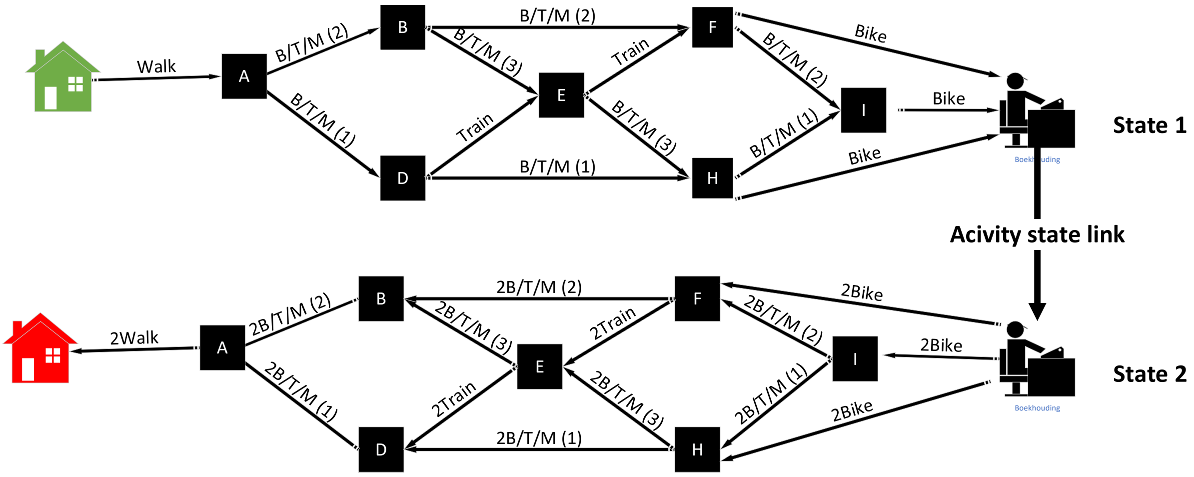


Figure 6.3: The pre-defined multi-state network for the mode-chain: Walk-Pubic transport-Bike

6.2.2 SET CONSTRAINTS FOR THE MULTIMODAL STATION OPTIMIZATION

The second and the third step prepare the transport networks that are used to find shortest paths for all multimodal mode-chains. In step 2 there is a search for the set of stations that can be used for each multimodal mode-chain. In step 3 the model sets consistency constraints to make sure that people that bike to or from a station return to the same station later in the tour. The following steps are only performed for the multimodal mode-chains: B-T-W, W-T-B and B-T-B.

Step 2 : Search for stations that are in the combined travel time radius from the origin and the destinations in the tour.

It is assumed that the input for the tour-based mode-chain and station choice approach are origin and destination pairs. Given the origin and destination, the first step is to find the set of stations that can be used to access or egress by bike. This means that there are two criteria:

- The station must have bike-parking facilities or shared-bike availability.
- The station must be within a certain threshold value for the maximum distance or travel time that people are willing to bike to access or egress a station. A visualisation of this process is shown in figure 6.4. The travel time between the stations and origins and destinations is found with a shortest path algorithm.

The travel time that persons are willing to bike to a station also depends on characteristics of the station. Some stations are more attractive compared to other stations to board or alight public transport. Station type 1 (Stations d and f) is in this study regarded as more attractive compared to station type 2 (all other stations). This is for example caused by better bike-parking facilities.

Note that it depends on the mode-chain that is used, what stations have to be considered for the station choice. For the walk – public transport – bike mode-chain, stations I, F and H are available. To calculate the chance that each station is used, a shortest path must be generated for each of the stations. For the bike-public transport-bike mode-chain there are three access stations and also three egress stations available. This means that an optimal tour must be found for each combination of stations. Hence, for all 9 sets of stations a shortest path is generated.

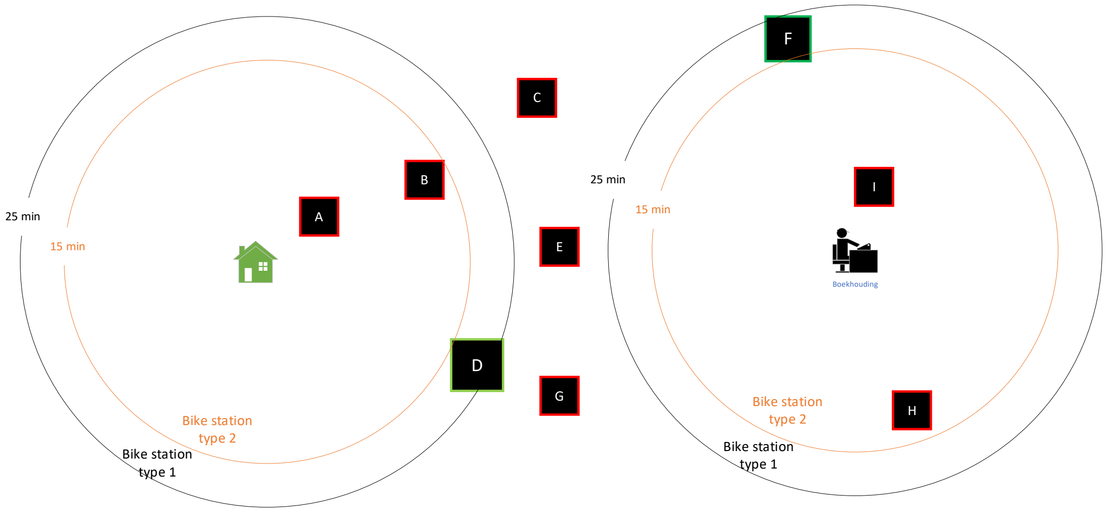


Figure 6.4: Searching for stations within travel time threshold values from home (left) and the activity (right). People are prepared to bike longer to stations of type 1 (Green) compared to stations of type 2 (Red).

Step 3: Setting consistency constraints for transfers to bike access legs and transfers from bike egress legs for each station

The consistency constraints limit the degrees of freedom in network state 2, given the station choice in network state 1. This constraint is needed to represent the fact that (shared) bikes have to be returned from the station where they are rented. The example in figure 6.5, visualises a situation where station F is chosen for the first trip. For the returning trip this means that there is only one access station left, which is biking to station F again.

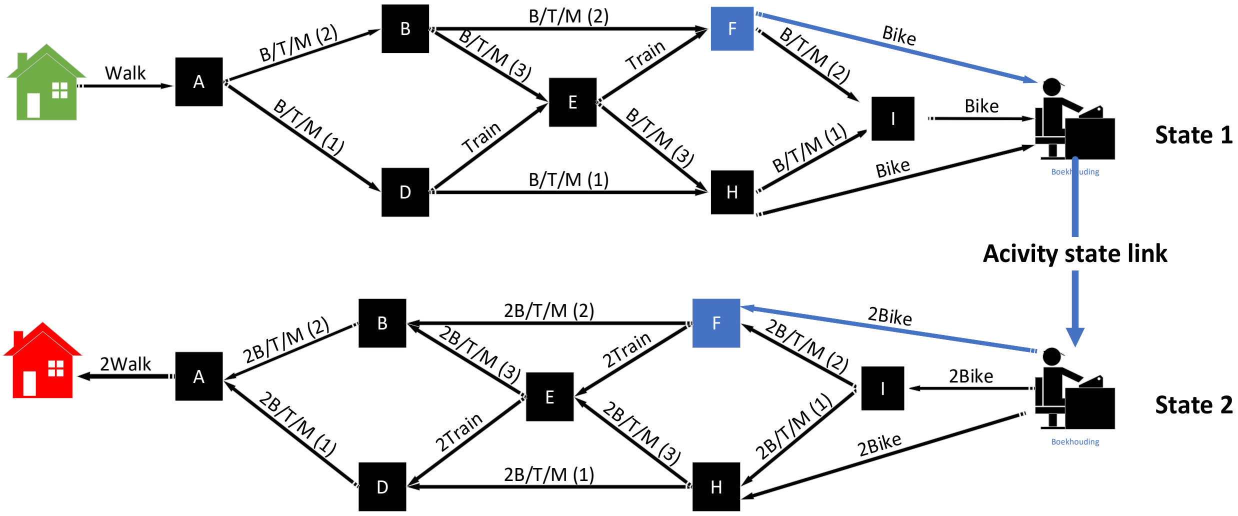


Figure 6.5: Constraint to return to the station used in state 1

6.2.3 OPTIMIZE TOURS TO FIND INPUT ATTRIBUTES FOR THE RUM-MODELS

The next steps want to find shortest paths for each mode-chain in the tour-based networks. The shortest paths for all multi-modal mode-chains (B-T-W, W-T-B and B-T-B) are constrained to use specific stations for the outgoing and returning trip. This constraint is not used for the unimodal mode-chain (W-T-W). Therefore, the shortest-path algorithm for the unimodal mode-chain is different compared to the multimodal mode-chains. The unimodal shortest path is obtained in step 4, the multimodal shortest paths are obtained in step 5.

Step 4: Search for the unimodal mode-chain with a shortest path algorithm to the travel alternative with the lowest utility in the tour-based transport network.

The algorithm searches for a path with the lowest utility in the tour-based network for the uni-modal mode-chain. This means that the transport network only contains walking links and public transport links. Because the path searches for the minimal utility, the betas of the utility functions are already considered in the shortest path algorithm. The same utility function and betas are used as in the Visum approach, the formula can be found on page 55. The optimization problem starts from home i_1 in state one, and goes to home i_2 in state two. The shortest path algorithm is changed accordingly. This gives the optimization problem as presented in formula 6.1. An example of a possible shortest unimodal-path K in the tour-based transport network is presented in figure 6.6. All attributes C_k of the obtained path K for the mode-chain W-T-W are stored in skim-matrices. This is done in order to calculate the person and activity specific utility for the RUM-models.

$$\mathrm{k(M)} = \min -\beta(C) * \sum_{(v,w)\in \mathrm{A}} C\,(vw)X(vw)$$

$Subject\ to$:

$$1)\ \sum_{w|(\mathrm{i(1),w})\in \mathrm{A}} X(i(1)w) = 1$$

$$2)\ \sum_{v|(\mathrm{v,i(2)})\in \mathrm{A}} X\big(vi(2)\big) = 1$$

$$3)\ \sum_{w|(\mathrm{v,w})\in \mathrm{A}} X(vw) - \sum_{v|(\mathrm{u,v})\in \mathrm{A}} X(uv) = 0\ \forall\ v\ \in \mathrm{V} \setminus \{i(1), i(2)\}$$

$$4)\ X(vw) \in \{0{,}1\} \qquad\qquad \forall\ (\mathrm{v,w})\ \in \mathrm{A}$$

Formula 6.1: The shortest path algorithm to optimize the tours from i in state 1 to i in state 2

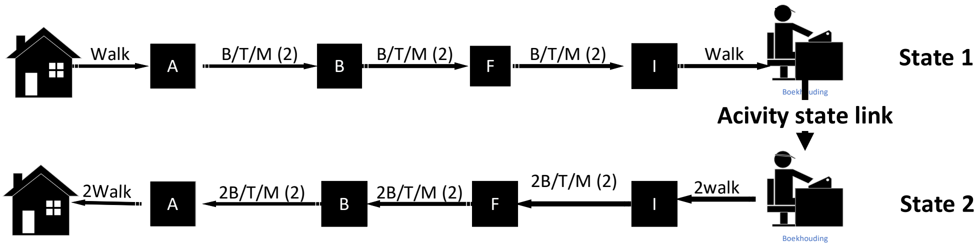


Figure 6.6: Example of an optimal unimodal tour

Step 5: Search for the multimodal mode-chains per available station with a constrained shortest path algorithm to the travel alternative with the lowest utility in the tour-based transport network.

The optimization problem for alle multimodal mode-chains M is constrained based on the stations found in step 2. The model wants to calculate the chance for each station, that people access the specific station or egress from the specific station with the bike. For this reason, for each station that is potentially used, a separate shortest path algorithm is performed. This results for each station to a path $K_{s.}$ So in the case of the walk-public transport-bike chain, the algorithm searches for shortest paths in the tour-based network for station F, H and I. Because of the constraints formulated in step 3, travellers always have to return to the station used in the outgoing trip. While considering the constraints the shortest path K^{M}_{s} (specific for each mode-chain M and station s) in the tour-based transport network is found with the shortest path algorithm in formula 6.1 and the utility function as discussed in the Visum approach on page 55. The attributes C^{M}_{ks} of each path k_s and mode-chain M are stored in skim-matrices An example of a possible result of the optimization problem when optimizing the tour for station F and the mode-chain walk – public transport – walk is presented in figure 6.7.

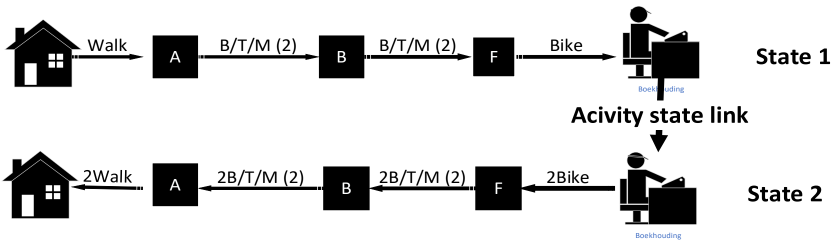


Figure 6.7: Example of a Path generated for station combination A - F

6.2.4 PREPARATION STEPS BEFORE PERFORMING THE RUM-MODELS

Before calculating the station choice and mode-chain choice with the RUM-models, two preparation steps are performed. First SB-bike-sharing has to be added to the choice model. SB-bike-sharing is only for a limited set of alternatives available. Furthermore, not all stations will be relevant alternatives. For this reason dominance criteria are used to filter the possible station-choice set.

Step 6: Adding SB-bike-sharing to the choice model when available given the mode-chain and station-choice

The Bike-sharing alternative is only available for mode-chains that use a bike at the egress-side of the transport tour. So these are the mode-chains: walk – public transport – bike and bike – public transport – bike. Moreover, the shared-bikes must be available at the station that is used. When both criteria are met, an extra conditioned choice is added to the choice models. This is the choice between using an owned bike or the shared bike for the egress trip leg. The choice to use a shared-bike instead of a normal bike, is based on a different transfer link between public transport and the biking leg. The shared bike has different transfer resistance, different transfer time and different cost compared to the normal bike.

Step 7: Using dominance criteria to only use paths that are relevant

When the method is used on a real network, there could exist many feasible stations to use for the multimodal mode-chains. Therefore, first all paths are filtered with dominance criteria before the utilities are calculated. For this study an alternative path is considered to be dominated if it scores similar or worse compared to another alternative for every attribute saved in the skim-matrices. When this is the case for an alternative, it is assumed that there is no reason for a traveller to choose the specific alternative. This is visualised in table 6.1 (for the mode-chain B-T-B). The name of the variables can be found in table 6.1. Alternative A – H, scores in none of the attributes better compared to alternative B – I, therefore this alternative is considered dominated and is not considered when calculating the utilities in the next step. Note, that the alternative D-I, seems an unattractive alternative as well. However, there is no alternative in the choice set that scores better or equal in every path attribute. Hence, the station set D-I is not dominated and still considered when calculating path shares. When there is for example a person group that wants to minimize the biking time, alternative D – I could be an interesting alternative for this group of people (Tba/Tbe are within this set of alternatives lowest for D-I). Also the fact that a station has bike-sharing available is considered when testing for dominance. The value assigned to the table is 0 when there is a shared bike available and 1 when there is no shared bike available. This is chosen because in this way it is consistent with the other variables, where a lower value is better.

Table 6.1: Example of a dominated alternative for the mode-chain Bike - Transit - Bike

Station set s	A - H	B - I	D - F	D - I
Tiv	116	102	33	147
Ttr	16	16	16	16
Ntr	0	0	0	0
Ct	3,2	3	4,8	3,2
Twa/Twe	0	0	0	0
Tba/Tbe	38	24	47	23
Pba2	1	1	0	0
Pba2	1	1	0	1
Pba1	0	0	1	1
Pba1	0	0	1	0
shared-bike available 1= no/ 0=yes	1	0	1	0
Total Tt	**170**	**142**	**96**	**186**

6.2.5 CALCULATING THE MODE-CHAIN, THE STATION CHOICE AND THE BIKE-SHARING CHOICE BASED ON RUM-MODELS.

Given the values for the attributes for all paths K_s that are found with the shortest path algorithms, the utilities for each travel path can be calculated for each persontype and activity purpose. Based on the utility values the choice probabilities for all discrete choices in the RUM-models can be calculated. The choice structure of the RUM-models is already discussed in paragraph 6.1.

Step 8: Calculate person type specific and activity purpose specific utility values.

The function as presented in the formula below and table 6.2, is used to obtain the persontype and activity specific utility values V^{M}_{Ks}. The utility values are obtained for all paths k^{M}_{s} that use a specific station s and mode-chain M. Because the formula is activity purpose specific, the betas in the function will vary for the different activity purposes. Moreover the formula uses dummy variables to represent user specific preferences of different person types. Compared to the utility function used in the Visum model for the mode choice an extra dummy variable is added to the function. For each person type there must be determined what the penalty is to transfer from the bike to public transport and from public transport to the bike. In reality there is a clear difference between person groups in their attitude towards multimodal transport, this will be represented by the Dummy variable D_{mm}. For instance, students that travel for education purposes are more likely to use multimodal mode-chains compared to a family that goes shopping. With the new modelling setup, the parameters can be changed accordingly, to take this kind of relations into account.

$$V^{k}_{Ms} = \beta_3 * Tiv + \beta_5 * Ttr + \beta_4 (Twa + Twe) + \beta_8 * (Tba + Tbe) + \beta_6 * D_{tc} * Ct + \beta_7 * Ntr + D_{mm} * \beta 18 * Pba1 + D_{mm} * \beta 19 * Pbe1 + D_{mm} * \beta 20 * Pba2 + D_{mm} * \beta 21 * Pbe2 + D_{mm} * \beta 21 * Psb$$

Table 6.2: Variables in the tour-based mode-chain utility function

Formula	Variables
Tiv	In-vehicle time
T_t	Transfer time
Twa	Walk access time
Twe	Walk Egress time
Tba	Bike access time
Tbe	Bike egress time
Ct	Travel cost
Ntr	Number of Transfers
Pba1	Penalty access station type 1
Pbe1	Penalty egress station type 1
Pba2	Penalty access station type 2
Pbe2	Penalty egress station type 2
PSb	Penalty shared bike
D_{nca}	Dummy - no car available
D_{st}	Dummy – student
D_t	Dummy – Public transport cost
D_{mm}	Dummy – Multimodal transport

Step 9: Calculate the choice distribution for the normal bike versus the shared bike

Because the utilities of choices downstream in the discrete choice models influence the choices upstream. The RUM-models are performed from bottom up. Therefore the first choice is between using the shared bike and the normal bike. The choice for a shared-bike is only available when using the W-T-B or B-T-B mode-chain and when the specific station s has shared bikes available. The shared-bike penalty is included in the choice model. The utility of the normal bike alternative and the shared bike alternative can be different because of three reasons:

- The transfer time T_t can be different, transfers to the bike-parking can be longer or shorter compared to transferring to the rental service of the shared bikes.
- The cost Ct will be different, the shared bike costs money each time that it is used, the normal bike is free of charge once someone parked a bike at the parking facility (assuming there are no parking costs).
- The penalty Pbe1 and Pbe2 for the normal bike are changed to the penalty Psb when using the shared bike.

The choice distribution for each path K^M_s to use a shared bike compared to the normal bike is calculated with the Nested logit model. As the alternatives probably share many unobserved factors, the dispersion factor θ has to be relatively low. The total utility for path K^M_s is calculated with the log sum. The formulas are presented on the next page.

$$P(Ksb) = \frac{exp(V(ksb)/\theta)}{exp(V(ksb)/\theta) + exp(V(kb)/\theta)}$$

$$V(kMs) = \theta(sb) * \ ln\ ((exp(V(ksb)/\ \theta) + \ (exp(V(kb)/\theta))$$

P (ksb) = Probability to use path k with a shared bike
V (ksb) = Utility of using path k with the shared bike
V(kb) = Utility of using path k with the normal bike
V(kMs)= Utility of path k, using mode-chain M and station s.

Step 10: Calculate the station choice distribution for the multi-modal transport tours.

With the determined utilities V^M_{Ks} the number of people using each station specific path K_s can be calculated. In the distribution of paths K_s, it is considered that paths share transport links and are therefore correlated. Hence, the path-size logit is used to calculate the distribution over all paths K_s within a mode-chain M. The number of persons using a specific path K_s is the number of persons that use a multimodal tour with station s.

$$P(KsM) = \frac{exp\left(V(k) + \beta(ps) * LN\big(PS(kM)\big)\right)}{\sum_{l\in C} exp\big(V(l)\big) + \beta(PS)\ * LN(PS(l)))}$$

$$PS(ksM) \ = \sum\nolimits_{vw\in A} \frac{t(vw)}{t(k)} * \frac{1}{\sum_{l\in L} x(vw)}$$

P(KsM) = *Share of passengers that use path Ks within mode chain M*
PS(ksM) = *Factor for Shared paths*
t(vw) = *travel time of link vw*
t(k) = *travel time of route k*

$\sum\nolimits_{l\in L} x(vw)$ $= number\ of\ paths\ l\ that\ use\ link\ X(vw)$

Given the utilities V^M_{Ks} the total utility of the mode chain M can be derived by taking the log sum over all feasible paths for the specific mode-chain. The dispersion parameter θ to consider similarity between alternatives is set to 1. This is done because correlation between the station sets is already considered by the paths size logit.

$$V(M) = \theta(k) * \ \ln\left(\sum_{k\in M} \exp\ (V\ (k|M)/\theta(k))\right)$$

V(M) = *Utility of mode chain M*
V(ksM) = *Utility of path ks in mode chain M*

Step 11: Calculate the mode-chain distribution of all public transport tours

With the utility V_M of each mode-chain M the distribution P(M) between the different mode-chains can be calculated. Note that the utility of the uni-modal mode-chain W-T-W is only based on one path K. The total utility of public transport can be calculated by using exactly the same formulas. How the choice models are calculated in Excel is explained in Appendix X.

$$P(M) = \frac{\exp(V(M))}{\sum_{T\in R} \exp(V(T))}$$

$P(M)$ = Share of passengers that use mode chain M
$V(M)$ = Utility of mode chain M

$$P(pt) = \frac{\exp(V(pt))}{\sum_{m\in R} \exp(V(m))}$$

$$V(pt) = \theta(M) * \ln\left(\sum_{M\in pt} \exp\ (V\ (M|pt)/\theta(M))\right)$$

$P(pt)$ = Share of passengers that use mode Public transport
$V(pt)$ = Utility of public transport

6.3 THE TOUR-BASED MODE-CHAIN AND STATION CHOICE APPROACH FOR MORE COMPLEX TOURS

As the proposed method is designed for tour-based models it must also be able to deal with more complex tours. More complex tours are tours that contain one or multiple sub-activities in the tour chain. This paragraph will give an example of tours with one extra sub-activity. So the new tour is of the type: Home - Main-Activity - Sub-activity - Home. The same modelling steps are used as for the simple tour. Only step 1, step 2 and step 3 slightly change because of the more complex tours. The changes of the three steps are explained in this paragraph.

Step 1: Setting origins and destinations in the transport network, copy the network as many times as there are activities and add artificial links that represent whether an activity is performed.

It is assumed that the sub-activity takes place in zone H. An extra activity also means that an extra "State" has to be modelled. The transport network with a sub-activity in H (Shopping), for the activity chain Walk-Transit-Bike is presented in figure 6.8. As can be seen, the optimization problem is again from home to home. The only difference is that the person returns home in state 3 instead of state 2. To reach state 3, the person has to perform the sub-activity in zone H. What the net

What the new network setup looks like in Excel is illustrated in Appendices F.

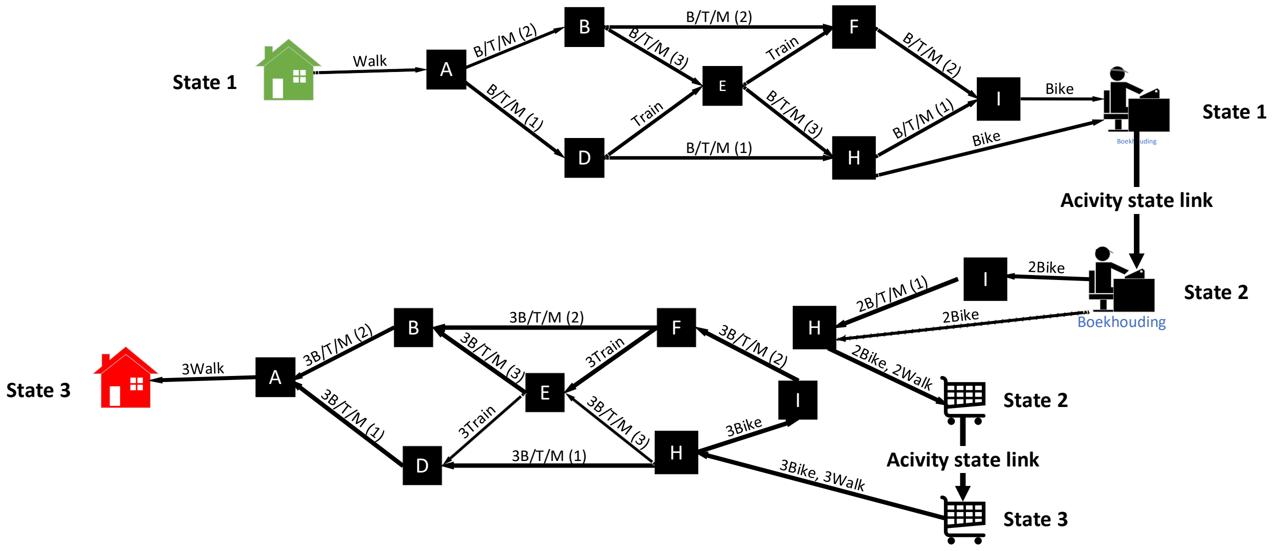


Figure 6.8: Pre-defined multi-state network for a tour that contains a sub-activity

Step 2 : Search for stations that are in the combined travel time radius from the origin and the destinations in the tour.

There is one important assumption in the proposed modelling setup for more complex tours. A person that uses a bike in a tour-chain always tries to choose the stations such that it is possible to combine multiple activities with the bike, before returning to the station. The person can also search for a station to perform the activity on the home-side of the tour.

When the travel times by bike get too high to combine multiple activities, it is assumed that travellers use a bike to reach the main activity. For the remaining part of the transport tour the specific traveller has no bike available anymore. This is chosen because it is not likely that a person will use a bike from two different stations. This means that the activities need to have an hierarchical order to depict what activity is the main activity in a tour. Most likely activities such as working and education are prioritized to activities such as shopping and visiting friends.

An example of the station choice procedure is presented in figure 6.9. When multiple activities are performed at the activity-side of a transport tour, a person will search for a station that is efficiently located compared to both activities. Therefore the stations have to be located within a certain radius from both activity locations. Considering the tour Home – Work – Shopping – Home, the model looks for stations that are within a certain radius of both activities. The work radius is presented in orange and the shopping radius is presented in green. As can be seen there are two stations that are within both boundary conditions. Assuming a Walk-Transit-Bike tour, the available stations in the station choice model are station I and station H.

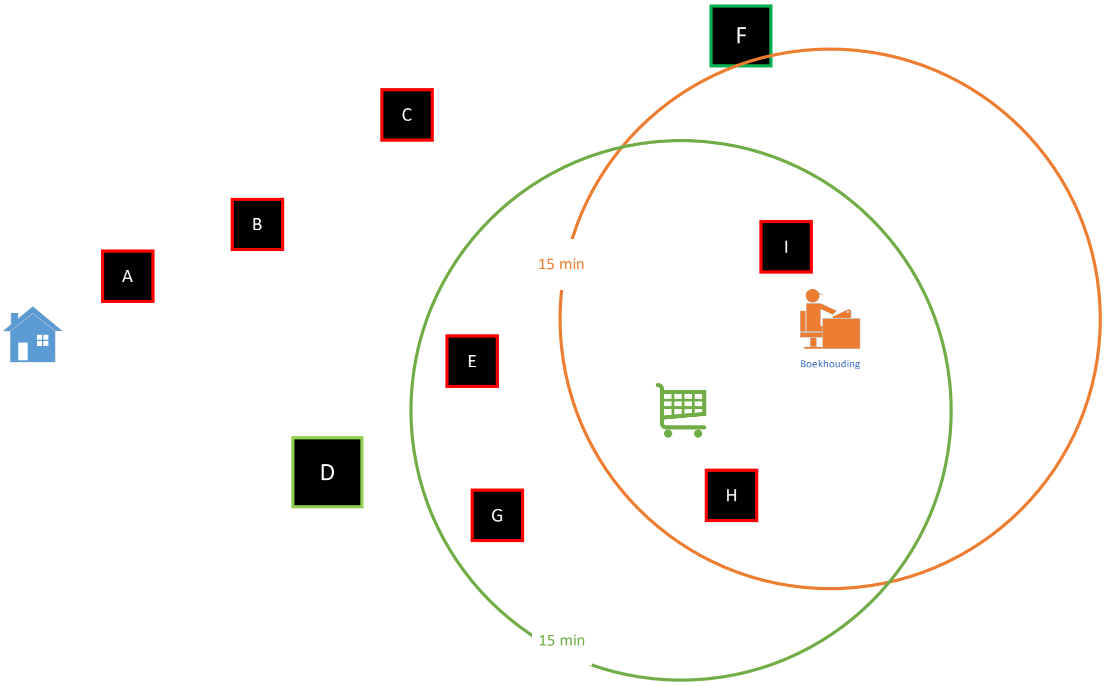


Figure 6.9: Finding the station availability for tours with multiple activities (activity chain Walk-Transit-Bike)

Step 3: Setting consistency constraints for transfers to bike access legs and transfers from bike egress legs for each station

The consistency constraint makes sure that a person returns to a station where he or she came from. For the simple tour this means that a person always has to return the bike in state 2. In case of a more complex tour, there are multiple options for the traveller. Looking at figure 6.8 a person can already return the bike in state 2, but can also choose to return the bike in state 3. Therefore the consistency constraint is formulated such that when a station is used in state X, that it is possible to return the bike in all states that follow.

The remaining modelling steps for the more complex tours are similar to the simple tours discussed in paragraph 6.2. To further clarify the complete tour-based mode-chain and station choice approach the next paragraph will give a practical example of the approach.

6.4 PRACTICAL EXAMPLE OF THE MODELLING APPROACH

To clarify the pre-specified mode-chain and station choice approach, this paragraph will give a brief example of how the approach can be used to determine multimodal transport tours in reality. There is a high number of students that study at the Delft university of technology (TU Delft) and live in the region Rotterdam-west (Heemraadsplein) . Because most students have no car available, they rely on public transport. There are many uni-modal as well as multi-modal public transport options to travel between Rotterdam-west and the TU Delft. Therefore it is interesting to see what share of students uses what multimodal or unimodal transport option.

Step 1: Setting an origin and a destination in the transport network, copy the network and add an artificial link that represents whether an activity is performed.

The origin is Rotterdam West, to be more specific the “Heemraadsplein”, the destination is the TU Delft and the students will use the public transport network in combination with the biking network. The optimization will be from the Heemraadsplein in state 1 to the Heemraadsplein in state 2. To reach state 2, the person has to perform an activity at the TU Delft.

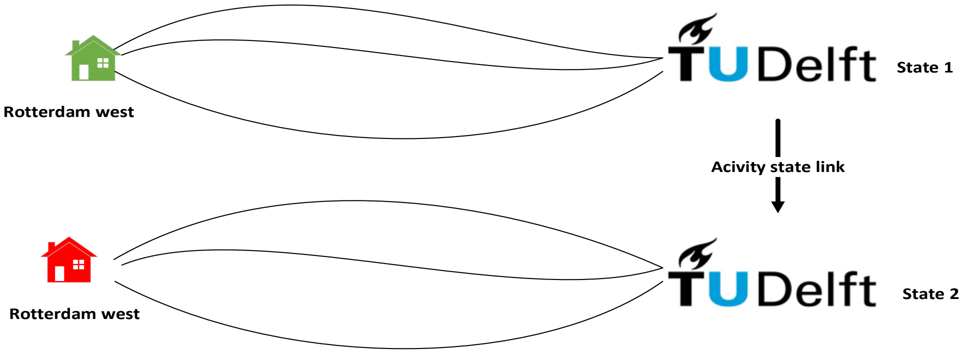


Figure 6.10: The optimization problem, the black lines represent the multimodal bike and public transport network

Step 2: Search for stations within a certain travel time to access or egress by bike.

Search for available station choices given the mode-chain and the maximum travel time radius with the bike. Only public transport stations are considered that have considerable bike-parking facilities available. The orange circle shows the 15 minutes radius that people are willing to bike towards a type 2 station. The blue circle shows the travel radius that people are willing to bike to a type 1 station. For the home-side of the trip there can be seen that station Schiedam and station Blaak are just within the orange circle. This means that Rotterdam Central, station Schiedam and station Blaak are all part of the station choice set for tours that use biking at the access-side of the trip. For the activity-side it can be seen that station Delft and station Campus are both easily within the biking radius from the TU Delft. For biking at the egress-side station Delft and station Campus are part of the station choice set. For each tour-chain, in table 6.3 is indicated what part of the tour is travelled with the unimodal public transport network. This means for example that for the B-T-W tour chain, people use public transport from Rotterdam central to TU Delft. The remaining part of the trip from home to Rotterdam central is performed with the bike. The B-T-B transport chain will optimize a tour for each set of stations.

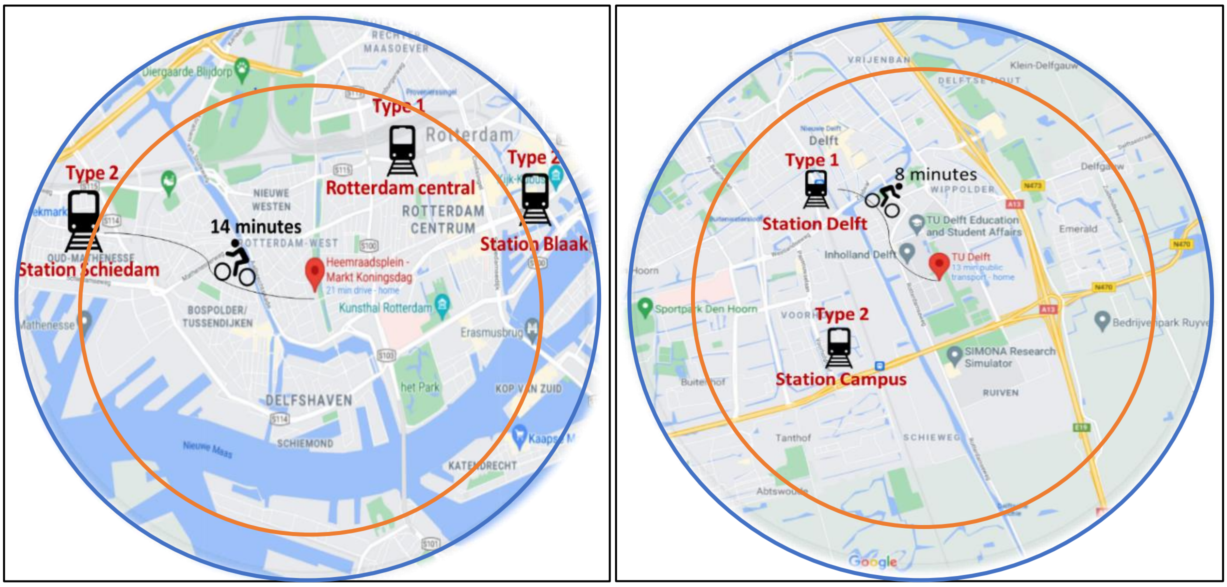


Figure 6.11: Searching for available stations from the origin and destination to access or egress by bike. The orange indicates 15 minutes bike-time the blue circle indicates 20 minutes

Table 6.3: The Uni-modal part of the multimodal transport tour, the remaining part is performed with the bike

W-T-W		B-T-W		W-T-B		B-T-B	
From	To	From (station)	To	From	To (Station)	From (station)	To (Station)
Heemraadsplein	TU Delft	Rotterdam central	Tu Delft	Heemraadsplein	Station Campus	Rotterdam central	Station Campus
		Station Schiedam	TU Delft	Heemraadsplein	Station Delft	Rotterdam central	Station Delft
		Station Blaak	TU Delft			Station Schiedam	Station Campus
						Station Schiedam	Station Delft
						Station Blaak	Station Campus
						Station Blaak	Station Delft

Step 3: Setting consistency constraints for transfers to bike access legs and transfers from bike egress legs for each station

For each station that is used as a transfer station from access and egress biking legs, constraints are set to make sure that people return to the station that they used in the outgoing trip.

Table 6.4: The constrained stations in the shortest path algorithm, each person that uses this set of stations have to return later in the tour to the same station

W-T-W		B-T-W		W-T-B		B-T-B	
From	**To**	**From (Station)**	**To**	**From**	**To (Station)**	**From (Station)**	**To (Station)**
Heemraadsplein	TU Delft	**Rotterdam central**	Tu Delft	Heemraadsplein	**Station Campus**	**Rotterdam central**	**Station Campus**
		Station Schiedam	TU Delft	Heemraadsplein	**Station Delft**	**Rotterdam central**	**Station Delft**
		Station Blaak	TU Delft			**Station Schiedam**	**Station Campus**
						Station Schiedam	**Station Delft**
						Station Blaak	**Station Campus**
						Station Blaak	**Station Delft**

Step 4: Search for the unimodal mode-chain with a shortest path algorithm to the travel alternative with the lowest utility in the tour-based transport network

To perform the shortest path algorithm, beta's have to be assumed for all variables within the multimodal-function. This paragraph only functions as a practical clarification of the modelling steps, so the same set of parameters is used as in the case study in the next chapter. In the next chapter there is briefly explained how the values for the different parameters are obtained. To generate possible routes google maps is used for a morning trip from Heemraadsplein to TU Delft and an evening trip from TU Delft to Heemraadsplein. Normally the shortest path algorithm would generate the path with the lowest utility. For this example there is manually calculated what the alternative in google maps was with the lowest utility. The best alternative is in this case an alternative that is 12 minutes walking from Heemraadsplein to a bus station at Beukelsdijk. From Beukelsdijk there is a direct bus connection to TU Delft.

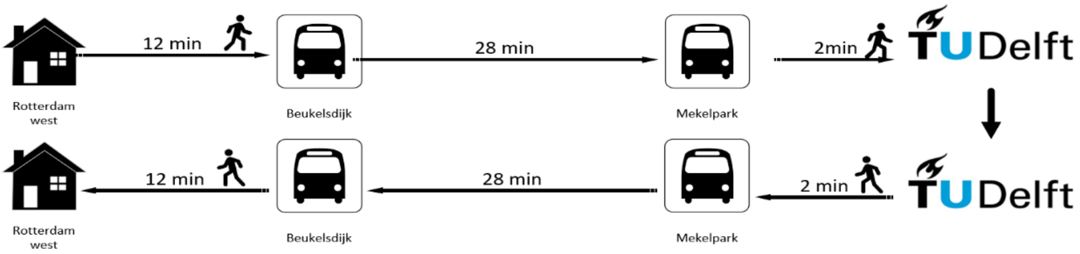


Figure 6.12: Transport tour optimized for the unimodal mode-chain W-T-W

Step 5: Search for the multimodal mode-chains per available station with a constrained shortest path algorithm to the travel alternative with the lowest utility in the tour-based transport network.

For all multimodal mode-chains, the same concept is used as in step 4. There is a search for the best uni-modal public transport path for each set of origin (stations) and destination (stations) in table 6.4. For each station that is accessed or egress by bike, the biking time from the origin (Heemraadsplein) or destination (TU Delft) to the station is also obtained from google maps. An example for an optimal tour found for the mode-chain W-T-B and the station Campus is shown in figure 6.13. Station campus is a type 2 station. So note that the egress penalty is of the type “Penalty bike egress station type 2”(Pbe 2). For each station in each mode-chain the shortest path algorithm is performed to obtain the attributes for each travel alternative. This set of attributes can be seen in table 6.5. These attributes are used to obtain utility values.

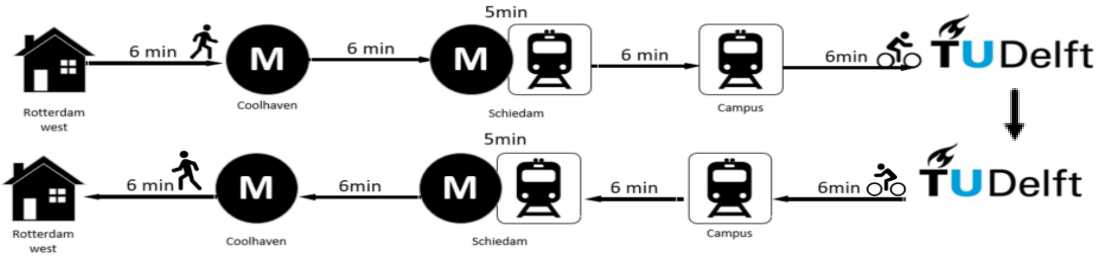


Figure 6.13: Transport tour optimized for station Campus and the W-T-B mode-chain

Step 6: Adding SB-bike-sharing to the choice model when available given the mode-chain and station-choice

SB-bike-sharing is only added to alternatives of the mode-chains W-T-B and B-T-B for the biking trip on the egress-side. The available stations on the egress-side are Delft central and Delft Campus. Delft central has SB-bike-sharing available and Delft campus has not. This means that only for Delft central the distribution between normal bikes and shared-bikes has to be calculated. The utility for the Delft central alternatives is then calculated based on the logsum of the normal bike alternative and the shared-bike alternative.

Step 7: Using dominance criteria to only use paths that are relevant

In the specific example none of the alternatives was found to be dominated. So all alternatives are considered relevant alternatives.

Step 8: Calculate person type specific and activity purpose specific utility values.

The next step is to calculate the utilities for every generated path. This is done in table 6.5 for all relevant alternatives of the mode-chain W-T-W, B-T-W and W-T-B. The B-T-B mode-chain is calculated in the same manner but not illustrated in the table. As can be noted the prices are rounded. This means for the shared bike that there is assumed that the price is 4 euros.

Table 6.5: Calculating utilities for different travel alternatives with the tour-based mode-chain and station choice approach.

			W-T-W	B-T-W			W-T-B		
Formula	**Variables**	β		**Rot.**	**Schie**	**Blk.**	**Camp.**	**Delft Normal bike**	**Delft Shared-bike**
Tiv	*In-vehicle time*	**-0,04**	54	22	12	32	24	28	28
T_t	*Transfer time*	**-0,3**	0	0	0	0	10	10	10
Twa	*Walk access time*	**-0,035**	24	0	0	0	12	12	12
Twe	*Walk Egress time*	**-0,5**	4	40	40	40	0	0	0
Tba	*Bike access time*	**-0,05**	0	20	28	20	0	0	0
Tbe	*Bike egress time*	**-0,05**	0	0	0	0	12	16	16
Ct	*Travel cost*	**-0,5**	6	6	6	8	8	8	14
Ntr	*Number of Transfers*	**-0,3**	0	0	0	0	2	2	2
Pba1	*Penalty access station type 1*	**-0,3**	0	1	0	0	0	0	0
Pbe1	*Penalty egress station type 1*	**-1,2**	0	0	0	0	0	1	0
Pba2	*Penalty access station type 2*	**-1,2**	0	0	1	1	0	0	0
Pbe2	*Penalty egress station type 2*	**-1,8**	0	0	0	0	1	0	0
PSb	*Penalty shared bike*	**-0,5**	0	0	0	0	0	0	1
	Total Utility		**-6,6**	**-7,6**	**-8,6**	**-9,9**	**-9,2**	**-9,0**	**-9,8**

Step 9: Calculate the choice distribution for the normal bike versus the shared bike

Step 10: Calculate the station choice distribution for the multi-modal transport tours.

Step 11: Calculate the mode-chain distribution of all public transport tours

The last three steps are all regarding calculating the discrete choice models. The result of performing the calculations with the utility values as obtained in table 6.5 are shown in figure 6.14. The nesting parameter for the choice between bike-sharing and the normal bike was set to 0,3. The nesting parameter for the station choice was set to 0,6 and the nesting parameter for the mode-chain was set to 1. The nesting parameters were estimated to get plausible results. However, a nesting parameter of 1 for the mode-chain choice is not realistic. There is definitely some unobserved correlation between the mode-chain alternatives.

Note that this paragraph functioned as a clarification of the method based on a practical example. The percentages found do not provide a good representation of the situation in reality. This is because the parameters are not specifically estimated for this case study. Instead they are directly copied from the theoretical case-study performed in the next paragraph. When performing a real-case study it is important to calibrate the parameter estimation. Based on real-data, the parameters can be estimated such that they represent the real situation.

The percentages indicate that 56% of the tours from Rotterdam West to TU Delft are performed with unimodal public transport. 22% of the people would bike to a station at the home-side of the trip. This is a relatively low percentage, this is probably because the train stations at the activity-side are not efficiently located to travel the last-mile by walking. In general people prefer to bike to Rotterdam central compared to other train stations. The W-T-B tour is the least popular transport option with only 7% of the travellers, this is in reality also the case. B-T-B is used by around 15% of the travellers. The most popular option is to bike towards Rotterdam Central station and bike from the Delft campus station. This is in reality not the case, probably because there are less frequent trains towards Delft campus compared to Delft central which is in this example not considered. Lastly, only 1% of the egress biking trips uses the shared-bike. This is a logical number with the current price of the system. When the price drops the model indicates a massive increase of the use of shared-bikes versus owned bikes.

The results of the model would be used to adjust OD-matrices. All uni-modal tours are added to the public transport matrix with an origin Rotterdam-West (Heemraadsplein) and Destination TU Delft. All other tours are partly added to the bike matrices (from station to origin or destination) and the public transport matrices (from station to origin or destination).

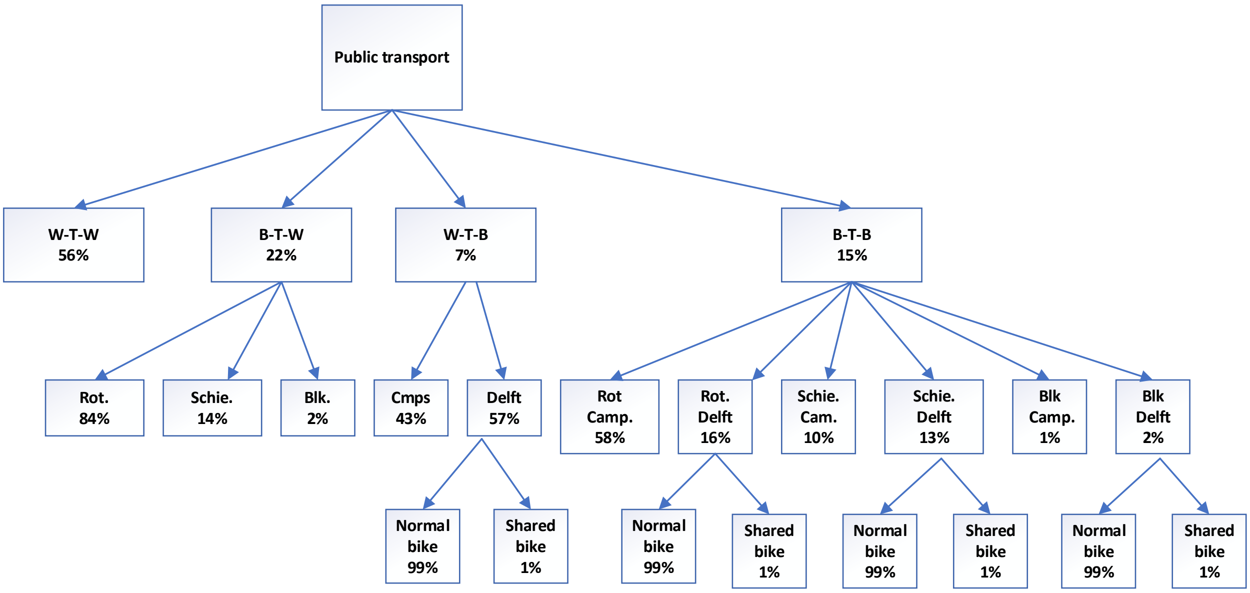


Figure 6.14: Distribution of multimodal tours from Rotterdam west to the TU Delft

6.5 CONCLUDING REMARKS

Chapter 5 discussed three problems about the Visum two-step mode choice approach; the consistency problem, the aggregation problem and the travel demand problem. For this reason, this study proposes “the tour-based mode-chain and station choice approach”. The main difference compared to the Visum approach is that components that need consistency on tour-level are modelled at tour-level instead of trip-level. The model uses a set of discrete choices. The discrete choices are based on Random utility maximization principles. The choices upstream are all calculated based on the expected utility of choices downstream (Logsum). The decision making unit for the discrete choices are groups of people with the same characteristics (each person type). There is a set of three discrete choices:

- **The first choice** is what **pre-specified mode-chain** is used. It is assumed that there is only a limited number of multimodal mode combinations available. For this study the mode combinations used are: walk/public transport/walk, bike/public transport/walk, walk/public transport/bike and bike/public transport /walk. This means that the set of pre-specified modes is used in a tour. The walk/public transport/bike chain refers to a tour that uses walking at the access-side of a tour, public transport as its main transport mode and biking at the activity-side of a tour.
- **The second choice** is the **station choice**. People that use a (shared) bike to reach a station have to return to the same station as they used earlier in a tour. Consequently, the station choice has to be optimized at tour level in order to find the most efficient station considering the complete tour.
- **The last choice** is about using a **normal bike or SB-bike-sharing**.

The model performs the discrete choice models for complete tours. The input is derived from a shortest path algorithm through a constrained tour-based transport network. The optimization process is constrained per station and mode-chain. In the end this leads to attributes for each combination of stations and mode-chain that is available in the choice-set. To find the available stations, the model looks at a maximal travel-time radius with the bike and what stations are available for each origin and destination. When the optimal path is found for each station, the method reviews if an alternative is dominated by another alternative. In this way, only relevant stations are considered in the choice model.

THE RESULTS

7. THEORETICAL CASE STUDY

This chapter has as its main objective to give quantitative evidence about limitations of the "two-step mode choice approach" as used in Visum. On the other hand the chapter wants to show that the "Tour-based mode-chain and station choice approach" can address these limitations. Three relevant scenarios regarding the mentioned problems in chapter 5 are tested on a small-scale theoretical transport network. The first scenario tests if SB-bike-sharing is modelled in relation to the demand for public transport (the travel demand problem). The second scenario tests if socio-demographics are considered when calculating the demand for SB-bike-sharing. The last scenario tests if mode-choice consistency regarding SB-bike-sharing can be modelled. The chapter starts with elaborating what input is used for the case study in the base situation (before making adjustments to test the scenarios). Then, the mentioned scenarios are first tested for the two-step mode-choice approach. Afterwards the same scenarios are tested for the tour-based mode-chain and station choice approach. The chapter will end with some concluding remarks.

This chapter contributes to answer the following sub-questions:

> *3. What are the limitations of the Visum modelling approach looking at the requirements to model SB-bike-sharing?*
> *5. Is the created modelling approach able to address the limitation of the current Visum approach to model SB-bike-sharing?*

7.1 INPUT FOR THE CASE-STUDY

The input consists of two elements. First, the attributes used in the transport network. Second, the parameters that are used in the utility functions. First the input attributes are discussed. Then the parameters used for the study are discussed. Note that parameter estimation is not an objective of this research or this case study. For this reason the parameters are chosen such that they give feasible results.

7.1.1 MODEL ATTRIBUTES OF THE COMPLETE TRANSPORT NETWORK

For this case study a transport network is used with nine nodes N and four different transport modes m available. The network is illustrated in figure 7.1. Each transport mode has links L available to travel between the nodes. Each link has a certain travel time t_L and a monetary cost c_L. The travel time for each link is presented in table 7.1. The travel times are obtained by assuming an average speed for a transport mode and the distance between a set of nodes. Some travel times are longer for cars and buses because the specific links are assumed to face congestion during the morning and evening peak. The network is chosen in order to have:

- Enough explanative power to indicate the limitations of the Visum approach.
- Enough multimodal transport options from the origin to the destination.
- A feasible network size for shortest path algorithms in Excel.

As can be seen the home location and the working location are already visualised in the network. This is because it is assumed that all people live in zone A and perform activities in zone I. These two nodes are chosen as the home and activity location because there are many travel alternatives to travel between them. The transport links between the nodes and the home address and the working address indicate the interzonal travel-time for node A and node I. The intrazonal travel time can only be travelled with the private transport modes (Walk, Bike and Car). The intrazonal travel times are presented in table 7.2.

There are three different person types considered in the model and three different activity purposes. The first type are working people without a car available. The second person types are working people with a car available and the last person types are students without a car available. The activity purposes are work, education and shopping. The input is chosen such that the effect of disaggregated modelling can be illustrated. More person groups and activity purposes would make the model unnecessarily complicated for the purpose of this case-study (quantitatively illustrating the limitations of the Visum modelling approach). In total there live 9800 people in zone A, they are divided over the person groups and activity purposes as shown in table 7.3.

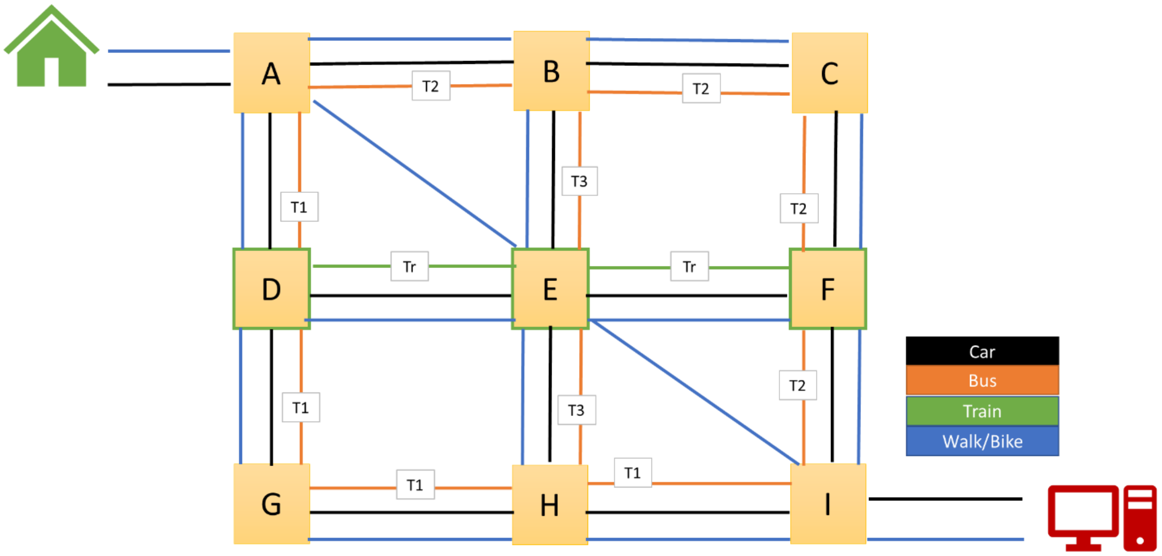


Figure 7.1: The transport network used for the case-study for tours between origin A and destination I

Table 7.1: Travel time of each transport link between each set of nodes

Link/Mode	Car	Train	Bus Line 1	Bus Line 2	Bus Line 3	Bike	Walk
AB	9			12		12	36
AD	3		7			10	30
BC	7			16		24	72
BE	5				10	16	48
CF	6			14		20	60
DE	6	5				20	60
EF	15	5				20	60
DG	10		23			32	96
EH	12				16	16	48
FI	11			14		14	42
GH	21		28			28	84
HI	11		14			14	42
AE						30	90
EI						30	90

Table 7.2: The intrazonal travel times of zone A and I

Node/Mode	Walk	Bike	Car
A	7	3	3
I	12	5	5

Table 7.3: Number of traveller that make a tour A-I-A of each persontype

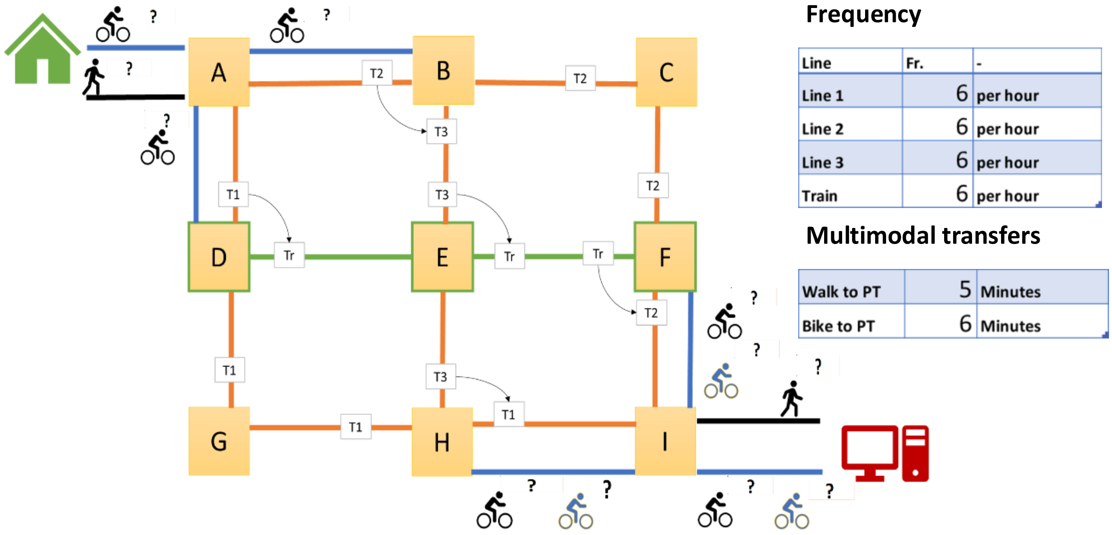
Persontype	Name in the model	Activity	#Persons A-I-A
Work NCA	Type 1	Work	1400
Student NCA	Type 1	Education	400
Student NCA	Type 1	Shopping	0
Work CA	Type 2	Work	4800
Work CA	Type 2	Education	1200
Work CA	Type 2	Shopping	0
Student NCA	Type 3	Work	700
Student NCA	Type 3	Education	1300
Student NCA	Type 3	Shopping	0
		Total	9800

7.1.2 THE MULTIMODAL PUBLIC TRANSPORT NETWORK

Figure 7.2 represents the multimodal transport network. As can be noted there are three public transport lines and a train line. The model handles the discontinuity of the public transport network based on a frequency based assignment procedure. Frequency-based assignment is only realistic when transport lines have a relative high frequency. Therefore all public transport lines have a frequency of 6, resulting in a waiting time of 5 minutes to transfer between service lines. The frequencies are similar for all transit lines to make sure that the time for the outgoing and returning trip are similar for the base scenario.

Next to the public transport lines there are also biking and walking links included in the network. It is assumed that station A, B, D, E, F and H all have bike-parking facilities available. Station D, E and F are type 1 stations (indicated with the green box) and the other stations are type 2 stations. It is assumed that people that walk to the public transport network have a transfer time of 5 minutes. People that bike towards the stations have a transfer time of 6 minutes, because they also have to park the bike.

Also bike-sharing is added to the multimodal transport network later in the scenario analyses. Transferring to the shared-bike is possible at station F, H and I. The objective of the case-study is to fill in the question marks in the multimodal network. This means that the model needs to find out how all multimodal tours are distributed across the multimodal transport network. The question marks will represent accumulated numbers. Note that there is one transport network for the outgoing trip, and one transport network for the returning trip.



Frequency

Line	Fr.	-
Line 1	6	per hour
Line 2	6	per hour
Line 3	6	per hour
Train	6	per hour

Multimodal transfers

Walk to PT	5	Minutes
Bike to PT	6	Minutes

Figure 7.2: The multimodal transport network for the outgoing trip with frequencies and transfer times. The goal of the case-study is to fill in all questions mark to show how the multimodal tours are distributed over the multimodal transport network

7.1.2 SETTING THE PARAMETERS FOR THE CASE STUDY

The parameters used to calculate the utility values for each transport mode are shown in table 7.4 on the next page. The parameters are chosen such that it gives a reasonable indication of travel behaviour in reality. The value of time for travelling by car and public transport for commuting is approximately 10 euros according to the Dutch mobility penal (Warffemius, 2013).

Estimating the value of time for public transport is more complicated, as it contains multiple components in the utility function. The estimated parameters for all components are based on research into relations between factors which influence the combined bike and transit trip (van Mil et al., 2020). The value of the fare parameter is the starting point for the parameter estimation. The fare parameter is set to -0,5. The value of time for a car trip with the purpose of work is 10 euros per hour, this leads to a parameter of -0,05 (-0,5/12=-0,04) .

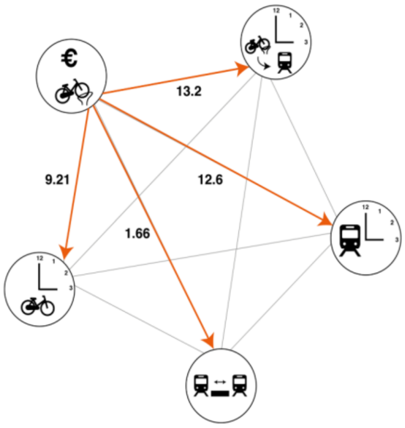


Figure 7.3: Interrelation between factors that influence the utility of the transit trip (van Mil et al., 2020)

After setting the mentioned parameters the remaining parameters are estimated based on calibration. In the end the model should give likely results in comparison with the situation on the Dutch market in reality. Research of Shelat et al. (2018) indicates for each travel distance the mode-shares of the most important transport modes. The transport tour from A to I is between 15 and 20 Kilometres. In this distance class around 55 % of the tours is in reality travelled by car, around 20% by public transport and around 10% by bike (there is no indication how the remaining 15% is travelled). In the case study for this research, the number of public transport trips are assumed to be around 35%. This is chosen because there are relatively a lot of students and working people without a car in the population.

Table 7.4: Parameters used in the case study to calculate the utilities of the different transport modes

	Car		Public transport		Bike		Walk	
Variables	**Par.**	**value**	**Par.**	**Value**	**Par.**	**Value**	**Par.**	**Value**
Alternative specific constant (ASC)	Asc_{car}	-2	$Asc_{transit}$	0	Asc_{bike}	-1	Asc_{walk}	0
Travel time (Tt)	β_1	-0,05			β_8	-0,07	β_{10}	-0,05
Travel cost (Ct)	β_2	-0,5	β_6	-0,5	β_2	-0,5		
In-vehicle time (Tiv)			β_3	-0,04				
Access time (Ta) / Egress time (Te)			B_{10}	-0,05				
Transfer time (T_{tr})			β_5	-0,035				
Number of Transfers (Ntr)			β_7	-0,3				
Dummy - no car available (D_{nca})	$ASC_{nca,car}$	-3	D_{ncs}					
Dummy – student (D_{st})			D_{st}	0				
Dummy – transit cost (D_{tc})			D_{tc}	0,25				

As discussed for multimodal transport another function is used. This function also contains penalties to indicate the resistance to travel between a set of transport modes. In reality the most common trip combination is the bike-transit-walk chain, with 56 % of the long distance multimodal trips. The bike-transit-bike chain has 15 % of the multimodal trips and the walk-transit-bike chain only 3% percent. The penalties are estimated such that these mode shares were approximately obtained. This resulted in different penalties for both modelling setups. This is shown in table 7.5. As both modelling approaches have a completely different way of modelling multimodality it is not surprising that the parameter estimates have to be different.

There are also some dummy variables included in the model to indicate differences in preferences between different person types. For the base scenario there is assumed that the only differences are caused by the fact that person types 1 and 3 have no car available and that person type 3 has a discount for public transport fare. The dummy variable representing different preferences regarding multimodal transport is in the base scenario set to 1 for all person groups.

Table 7.4: Penalties used to calculate utilities of multimodal travel alternatives.

	Visum two-step mode choice approach		**Tour-based mode-chain and station choice approach**	
Penalties	Parameter	Value	Parameter	Value
Acces bike type 2 (Pba2)	β20	-1,2	β20	-1,2
Egress bike type 2 (Pbe2)	β21	-1,8	β21	-2,5
Acces bike type 1 (Pba1)	β18	-0,3	β18	-0,3
Egress bike type 1 (Pba1)	β19	-1,2	β19	-2

Table 7.5: Dummy variables used for the case study

	Type 1	Type 2	Type 3
Dummy variable Student	0	0	1
Dummy variable Transit fare	1	1	0,25
Dummy variable NCA	0	1	0
Dummy variable multimodal transport	1	1	1

7.2 SCENARIO ANALYSES FOR THE TWO-STEP MODE-CHOICE APPROACH IN VISUM

This paragraph will give quantitative evidence for the demand problem, the aggregation problem and the consistency problem as discussed in chapter 5. First, this paragraph will present the results as obtained based on the input presented in paragraph 7.1. Then, the input is changed per scenario to illustrate how the modelling results change based on changed input data.

7.2.1 SCENARIO 0 – THE BASE SCENARIO USED AS REFERENCE

Note that the results for the base-scenario are not of key-interest for this study, it is mainly used to see how the modelling result changes by the implementation of the SB-bike-sharing system.

The two-step mode choice approach calculates for the base-scenario the mode shares as shown in table 7.6. As can be seen, the mode-shares strongly depend on the person type. Person type 2 mainly uses the car, as this person group has a car available. Person type 3 mainly uses public transport, because this group has a student discount. Person type 1 has no discount and no car available, so relatively uses the bike more often. In the end, given the number of people in the population, the number of car trips, public transport trips and biking trips are obtained as shown in figure 7.4. The car is responsible for 54% percent of the tours, public transport for 34% and biking for 13%. In reality these mode shares are around 55% for cars, 20% for public transport and 10% for bikes (Shelat, 2018). This means public transport has a relatively high mode-share in this study.

Table 7.6: The mode shares the base scenario with the Visum approach, the results show that the model considers the fact that person type 2 has a car available and person type 3 has a student discount

Persontype	Activity	Car	Public Transport	Bike	Walk
Type 1	Work	17%	52%	31%	0%
Type 1	Education	17%	52%	31%	0%
Type 1	Shopping	17%	52%	31%	0%
Type 2	Work	80%	12%	7%	0%
Type 2	Education	80%	12%	7%	0%
Type 2	Shopping	80%	12%	7%	0%
Type 3	Work	7%	81%	12%	0%
Type 3	Education	7%	81%	12%	0%
Type 3	Shopping	7%	81%	12%	0%

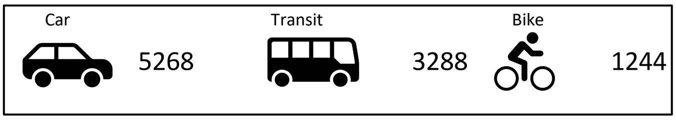


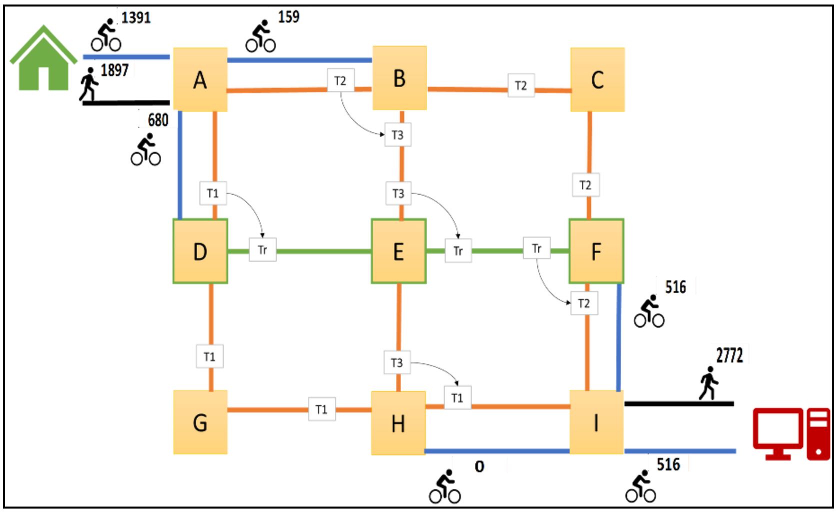
Figure 7.4: The number of passengers using each mode in the Visum approach

The number of public transport trips is divided across the multimodal transport networks as shown in figure 7.5 and 7.6 on the next page. Note, that all values in the transport network are accumulated values. As an example, the 1391 persons on the link between home and station A are the sum of the people that bike from A (home) to A (station), from A (home) to B and from A (home) to D (552+159+680=1391). The values in the table next to the visualisation of the transport network are not accumulated.

The results obtained are feasible. First of all, it is important to notice that the evening trip and the morning trip are consistent with each other. Each bike that is left or picked up at a station in the morning trip is returned during the evening trip. Besides, the number of multimodal trips show realistic results. From all public transport trips (3288) 43% use a bike at the access side of the public transport trips. This number is 16% at the egress side of the trip. In reality these shares are around 35% and 10% (Shelat et al., 2017).

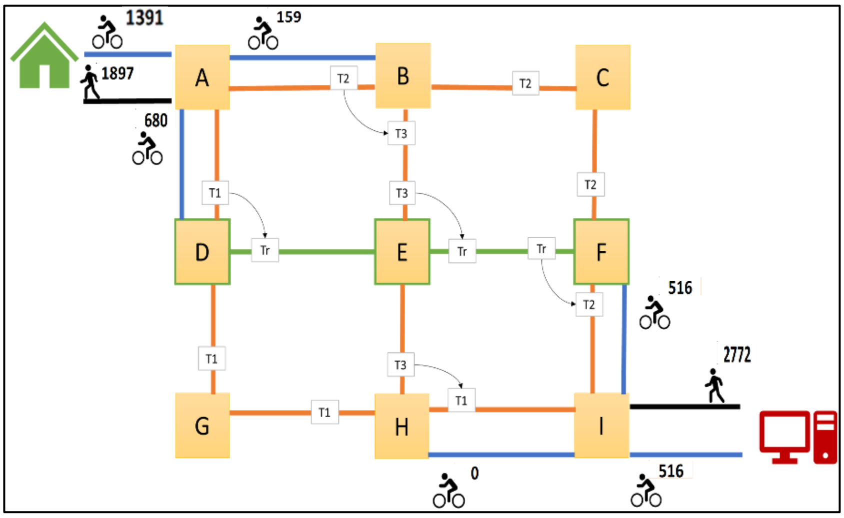
Most of the multimodal trips board the public transport network at station D. This is expected as station D is a type 1 station and has a relatively fast connection toward station F with the train network. Likewise, all egress trips with the bike are from station F. This is also caused by the fact that station I has no bike-parking facility.

According to the model, using station H to transfer to the bike is not an interesting alternative. That literally nobody uses station H is the result of the stochastic route-set generation used in the development of the Visum model. The algorithm did not generate any routes coming from station H. This shows a risk for stochastic shortest path algorithms. The algorithm could always miss out on a feasible alternative. The real Visum approach does not use a stochastic shortest path algorithm. This means that problems caused by this algorithm cannot be generalised to the Visum modelling approach.



A-A	Walk	1897
I-I	Walk	2772
A-A	Bike	552
A-B	Bike	159
A-D	Bike	680
F-I	BIke	516
H-I	Bike	0
A-F	Transit	255
A-H	Transit	0
A-I	Transit	2194
B-F	Transit	0
B-H	Transit	0
B-I	Transit	159
D-F	Transit	261
D-H	Transit	0
D-I	Transit	419

Figure 7.5: Distribution of multimodal transport trips in the morning with the Visum approach



I-I	Walk	2772
A-A	Walk	1897
I-H	Bike	0
I-F	Bike	516
B-A	BIke	159
D-A	Bike	680
A-A	BIke	552
I-A	Transit	2194
H-A	Transit	0
F-A	Transit	255
I - B	Transit	159
H -B	Transit	0
F -B	Transit	0
I - D	Transit	419
H-D	Transit	0
F-D	Transit	261

Figure 7.6: Distribution of multimodal transport trips in the evening with the Visum approach

7.2.2 SCENARIO 1 - THE TRAVEL DEMAND PROBLEM - IMPLEMENTING SB-BIKE-SHARING AND REDUCING THE PRICE

This sub-paragraph studies what the impact is of implementing SB-bike-sharing to the model results. Also the price of the system is adjusted. The problem that is illustrated is that the public transport demand does not change based on the policy measures to promote SB-bike-sharing.

CHANGED INPUT

As already mentioned in the input paragraph, the shared bikes are distributed at station F, H and I. The shared-bikes have the supply characteristics as shown in table 7.7. Furthermore, there is also a penalty for the use of shared-bikes. This penalty is significantly lower compared to the penalty of using a normal bike. It is assumed that when the shared-bikes are free of charge, travellers are more likely to use a shared bike compared to parking an owned bike at a station.

Table 7.7: Input characteristics of SB-bike-sharing

Speed	15	**KM/H**
Price	3,8	**Euro**
Transfer time	6	**Minutes**

Table 7.8: Parameter estimation for SB-bike-sharing

Variable	Parameter	Visum approach	Tour-based mode-chain approach
Penalty shared-bike (Psb)	$\beta 21$	-1,5	-0,5

RESULTS WITH THE IMPLEMENTATION OF SB-BIKE-SHARING

First of all there can be concluded that SB-bike-sharing was successfully implemented in the Visum model. However, the total number of public transport users did not change compared to the base scenario as can be seen by comparing figure 7.4 and figure 7.6. This is because the mode shares in table 7.6 did not change. As elaborated in the demand-problem in chapter 5.4, this is caused by the fact that the demand for the main-modes is only calculated based on uni-modal travel paths. This means also that when decreasing the price of SB-bike-sharing it will not have any effect on the public transport demand, this is shown in table 7.10 (later elaborated).

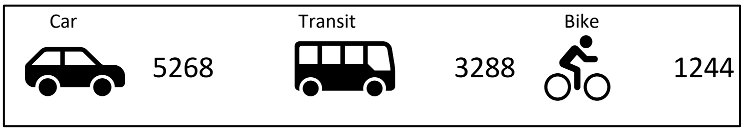


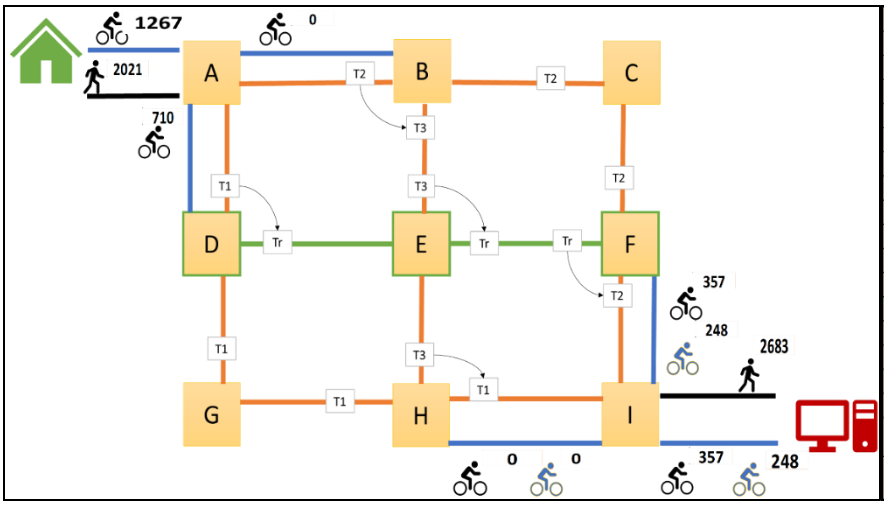
Figure 7.6: The number of people using each transport mode after the implementation of SB-bike-sharing. There is no change compared to the situation in figure 7.4.

The distribution of multimodal transport trips did change as a result of the implementation of SB-bike-sharing. The results are presented in figure 7.7 and figure 7.8 on the next page. Again there can be seen that the results of the evening and morning trip are consistent with each other.

The limiting factor of the stochasticity of the model also becomes evident. The availability of shared-bikes at station I results in interesting new travel alternatives. However, because the proposed method does not generate any routes from this station, the model does not calculate any travellers using station I. Another surprising result is that because of the implementation of SB-bike-sharing nobody bikes towards station A and station B anymore. This is caused by the fact that there are new routes generated with the shared-bikes. For this reason routes that bike towards station A and station B are not part of the choice-set anymore.

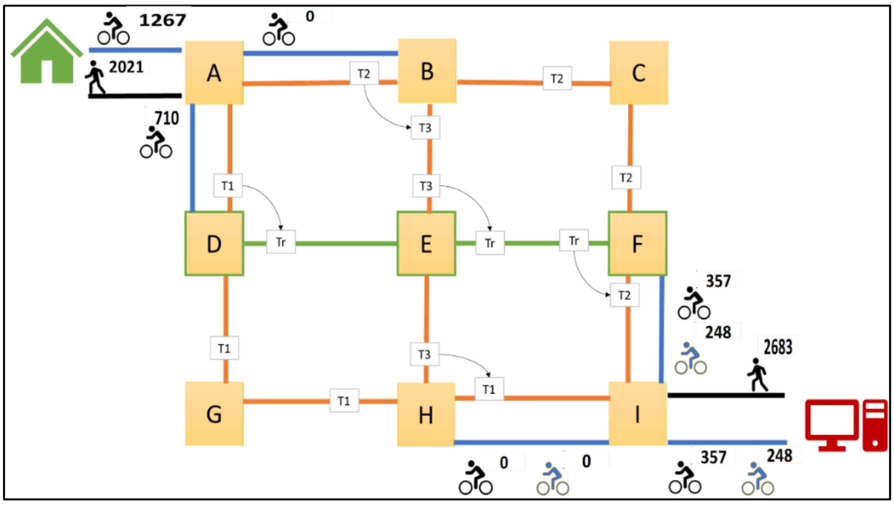
Looking at the remaining results there can be seen that all shared-bike and bike users still use station F on the egress-side of the transport trips. The total (summing shared-bikes and normal bikes) **number of bike users from station F, raised from 517 to 605**. It is an intuitive result that the total number of people that use a bike on the egress-side increased. Nevertheless, given the input attributes of SB-bike-sharing, the number of SB-bike-sharing users compared to normal bike users is not realistic. This means that for real application the penalty for SB-bike-sharing must be significantly lower than the parameter used in this study. To clearly see other theoretical effects of the implementation of SB-bike-sharing, it is chosen for this study to keep the penalty for SB-bike-sharing as it is.

The number of bikes towards D at the access-side increased. This is also a logical result, as station F is made more attractive by the implementation of SB-bike-sharing. As station D has a fast connection to station F, station B becomes also more attractive and attracts more travellers.



A-A	Walk	2021
I-I	Walk	2683
A-A	Bike	557
A-B	Bike	0
A-D	Bike	710
F-I	BIke	357
H-I	Bike	0
A-F	Transit	277
A-H	Transit	0
A-I	Transit	2302
B-F	Transit	0
B-H	Transit	0
B-I	Transit	0
D-F	Transit	207
D-H	Transit	0
D-I	Transit	381
F-I	S-B	248
H-I	S-B	0
I-I	S-B	0

Figure 7.7: Distribution of multimodal transport trip in the morning in the Visum modelling approach with the implementation of SB-bike-sharing



I-I	Walk	2683
A-A	Walk	2021
I-H	Bike	0
I-F	Bike	357
B-A	BIke	0
D-A	Bike	710
A-A	BIke	557
I-A	Transit	2302
H-A	Transit	0
F-A	Transit	277
I - B	Transit	0
H -B	Transit	0
F -B	Transit	0
I - D	Transit	381
H-D	Transit	0
F-D	Transit	329
I-I	S-B	0
I-H	S-B	0
I-F	S-B	248

Figure 7.8: Distribution of multimodal transport trips in the evening in the Visum modelling approach with the implementation of SB-bike-sharing

THE EFFECT OF DECREASING THE PRICE OF SB-BIKE-SHARING

In table 7.10 the price of SB-bike-sharing is decreased until it is free of charge. This is done to clearly demonstrate that the Visum two-step mode choice approach does not model any relation between promoting policies regarding SB-bike-sharing and the demand for public transport. As expected the *total public transport demand keeps constant despite the price for SB-bike-sharing decreased.* At the same time, lowering the price of SB-bike-sharing does increase the number of SB-bike-sharing users. The increase of SB-bike-sharing is mainly caused by a decrease of people that use a normal bike and also to some extent by people that first used the bus to reach zone I.

Also another scenario is analysed to demonstrate that policy measures to the public transport network do influence the shares of people that use public transport. The policy measure tested is to decrease the time of link F to I in the public transport network. For the use of SB-bike-sharing it is an interesting scenario. This is because on one hand, these policy measures stimulate the use of public transport (which has a positive effect on bike-sharing usage) . On the other hand it makes multimodal transport trips from station F less interesting (because another transport alternative gets more attractive). As can be seen in table 7.11, the model does indeed show a significant increase in public transport ridership. As a result the number of SB-bike-sharing users from F to I also increases. This seems not intuitive, as a competing travel alternative for SB-bike-sharing is made more attractive.

Table 7.10: The effect of pricing on the total public transport (total P-T) and bike-sharing (total S-B) users in the Visum approach

Price (Euros)	Total P-T	Total S-B	F	H	I
3,85	3288	248	248	0	0
3,35	3288	278	278	0	0
2,85	3288	312	312	0	0
2,35	3288	349	349	0	0
1,85	3288	390	390	0	0
1,35	3288	435	435	0	0
0,85	3288	484	484	0	0
0,35	3288	538	538	0	0
0	3288	579	579	0	0

Table 7.11: The effect of travel times for public transport link F-I on the public transport (total P-T) and bike-sharing (total S-B) users in the Visum approach

Traveltimes link F-I	Total P-T	Total S-B	F	H	I
14	3288	248	248	0	0
12	3517	247	247	0	0
10	3752	279	279	0	0
8	3996	276	276	0	0
6	4246	334	334	0	0
4	4504	326	326	0	0

7.2.3 SCENARIO 2 - THE AGGREGATION PROBLEM - CONSIDERING SOCIO-DEMOGRAPHIC IN THE DEMAND FOR SB-BIKE-SHARING

This scenario demonstrates the limitation that the Visum approach cannot consider socio-demographic when calculating the demand for SB-bike-sharing. To test this scenario parameters of different person types are changed and the number of inhabitants of the different person types are varied.

CHANGED INPUT

In order to make this comparison, first the parameters and dummies are adjusted to consider heterogeneity. There are currently two activities considered in the model. There is a transport chain of the type “home-work-home” and a chain of the type “home-education-home”. The value of time for working purposes is higher compared to educational purposes. The model assumes for this reason that all working parameters are 0,005 lower compared to the base scenario and the parameters for education purposes are 0,005 higher compared to the base scenario. Further, it is assumed that travellers are willing to pay more for working trips compared to education trips. For this reason the parameter for education is 0,2 lower compared to the base scenario. The adjusted set of parameters is shown in table 7.12.

To consider the fact that students are more willing to use multimodal transport, this dummy variable is also changed for different person groups as shown in table 7.13. However, the Visum model does not consider different person groups when modelling multimodality. This means that the changed dummy variables will not influence the results.

Table 7.12: Activity specific parameters to test the effect of socio-demographics on the model results

Mode	Activity purpose	Travel time (Tt and Tiv)	Travel cost (Ct)
Car	**Work**	β -0,055	β -0,7
	Education	β -0,045	β -0,7
Public transport (Tiv)	**Work**	β -0,045	β -0,7
	Education	β -0,035	β -0,7
Bike	**Work**	β -0,075	β -0,7
	Education	β -0,065	β -0,7
Walk	**Work**	β -0,055	β -0,7
	Education	β -0,045	β -0,7

Table 7.13: Values of the Multimodal dummy variables to test effect of socio-demographics on the model results

	Type 1		Type 2		Type 3	
Multimodal transport dummy	D_{mm}	0,9	D_{mm}	1,2	D_{mm}	0,7

RESULTS WITH THE CHANGED SOCIO DEMOGRAPHICS

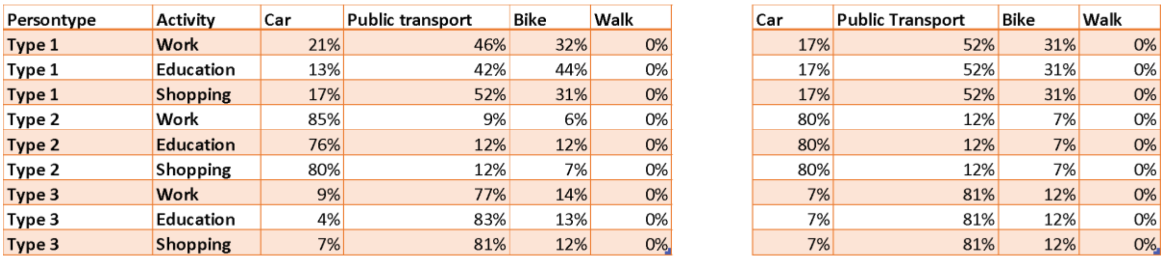
Given the changed set of parameters, new results for both modelling setups are obtained. In the base scenario and scenario one there were 6000 people of type 2, 1800 persons of type 1, and 2000 of type 3. The results before changing the parameters are illustrated in table 7.15. As can be seen in the first row of table 7.16, the total number of public transport users decreased from 3288 to 3015. The new results can be mainly attributed to the fact that the value of time for the working population decreased. Public transport is a relatively slow alternative compared to the car, for this reason the lower parameter has more effect on the utility of public transport. As can be seen in table 7.14, for type 2, the number of public transport users decreased by 3%. As type 2 accounts for 6000 people in the total population, this influences the total number of public transport users considerably.

Because of the high differences in travel preferences it is interesting to see how the results of the model would change when socio demographics in the population change. Person type 2 relatively uses the car a lot and has a negative attitude towards multimodal transport. On the other hand, person type 3 (students) mostly uses public transport and is willing to use multimodal transport trips (dummy variable multimodality). In table 7.16 the effect of increasing the number of persons of type 3 and decreasing the number of persons of type 2 is illustrated.

The results show what the problem is of aggregating the matrices before modelling multimodal transport in the Visum model. This illustrates the aggregation problem as discussed in chapter 5. In the first place, by increasing the number of students there is expected that the number of public transport usage increases. This effect can be seen clearly. However, the second expected effect is that within the population which uses public transport, the number of multimodal trips increases as well. *This means that SB-bike-sharing usage is expected to increase relatively more compared to the usage of public transport.*

In the Visum model this is not the case. The number of SB-bike-sharing users increases proportional to the number of public transport users. This is calculated in table 7.17, which shows the relative increase in public transport users and bike-sharing users for each row in table 7.16. As an example, in the situation with 2500 students, the public transport usage is 3370. When there are 2000 students, the public transport usage is 3015. This means that the number of public transport users increased 12% (3370/3015=112%). By increasing the number of students from 2000 to 2500, the number of bike-sharing users also increased with 12%.

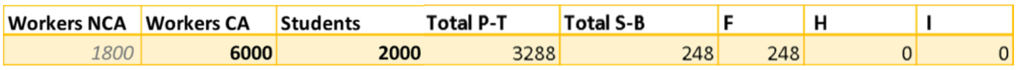
Table 7.14: The distribution of transport modes for the Visum modelling approach. The results with the changed parameters on the left and the results for the base scenario as a reference on the right



Persontype	Activity	Car	Public transport	Bike	Walk
Type 1	**Work**	21%	46%	32%	0%
Type 1	**Education**	13%	42%	44%	0%
Type 1	**Shopping**	17%	52%	31%	0%
Type 2	**Work**	85%	9%	6%	0%
Type 2	**Education**	76%	12%	12%	0%
Type 2	**Shopping**	80%	12%	7%	0%
Type 3	**Work**	9%	77%	14%	0%
Type 3	**Education**	4%	83%	13%	0%
Type 3	**Shopping**	7%	81%	12%	0%

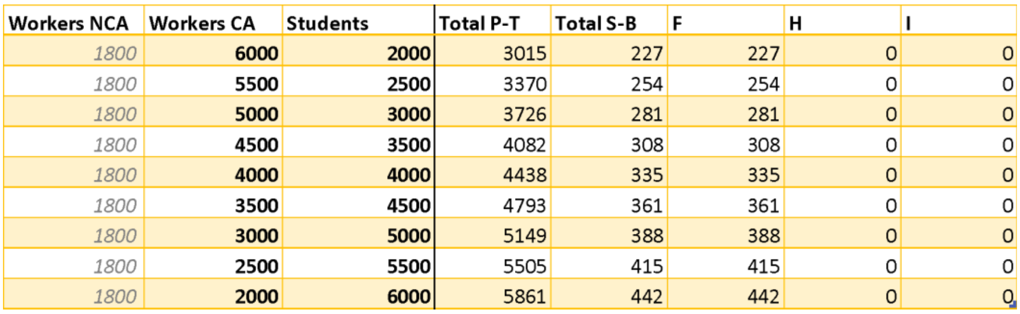
Car	Public Transport	Bike	Walk
17%	52%	31%	0%
17%	52%	31%	0%
17%	52%	31%	0%
80%	12%	7%	0%
80%	12%	7%	0%
80%	12%	7%	0%
7%	81%	12%	0%
7%	81%	12%	0%
7%	81%	12%	0%

Table 7.15: The results before changing the parameters in the Visum modelling approach



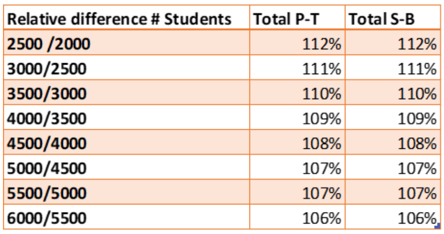
Workers NCA	Workers CA	Students	Total P-T	Total S-B	F	H	I
1800	**6000**	**2000**	3288	248	248	0	0

Table 7.16: The effect of changing the social demographics on public transport usage and SB-bike-sharing usage in the Visum modelling approach



Workers NCA	Workers CA	Students	Total P-T	Total S-B	F	H	I
1800	**6000**	**2000**	3015	227	227	0	0
1800	**5500**	**2500**	3370	254	254	0	0
1800	**5000**	**3000**	3726	281	281	0	0
1800	**4500**	**3500**	4082	308	308	0	0
1800	**4000**	**4000**	4438	335	335	0	0
1800	**3500**	**4500**	4793	361	361	0	0
1800	**3000**	**5000**	5149	388	388	0	0
1800	**2500**	**5500**	5505	415	415	0	0
1800	**2000**	**6000**	5861	442	442	0	0

Table 7.17: Relative increase of public transport usage and SB-bike-sharing usage when increasing the number of students in the Visum modelling approach. The number of S-B bike-sharing users increasing proportionally



Relative difference # Students	Total P-T	Total S-B
2500 /2000	112%	112%
3000/2500	111%	111%
3500/3000	110%	110%
4000/3500	109%	109%
4500/4000	108%	108%
5000/4500	107%	107%
5500/5000	107%	107%
6000/5500	106%	106%

7.2.4 SCENARIO 3 - THE CONSISTENCY PROBLEM – CHANGING ATTRIBUTES OF THE EVENING TRIP COMPARED TO THE MORNING TRIP

This scenario illustrates that the Visum approach has consistency problems when the attributes for the evening trip change compared to the morning trip. In the scenarios so far travel times for the returning trip were similar to the outgoing trip.

CHANGED INPUT

To start off, the socio demographic in the last paragraph are changed back to the original values (1800, 6000 and 2000 of each person type respectively). The parameters are kept the same as in scenario 2.

Furthermore, the frequency is changed on the different service lines. Varying with the frequency can already result in different travel times for the outgoing trip compared to the returning trip. The frequencies are changed to the values as shown in table 7.18.

Table 7.18: Frequency of the different public transport lines

	Train	**Line 1**	**Line 2**	**Line 3**
Frequency	8	4	6	4

The changed frequencies only have a small effect on the travel times (changing the frequency from 6 to 4 changes the travel times within 2,5 minutes). To make it more challenging to model consistency between the morning and evening trip there is assumed that public transport link I-F has significantly higher travel times during the evening peak compared to the morning peak. The travel time is changed from 14 minutes to 25 minutes during the evening peak.

RESULTS

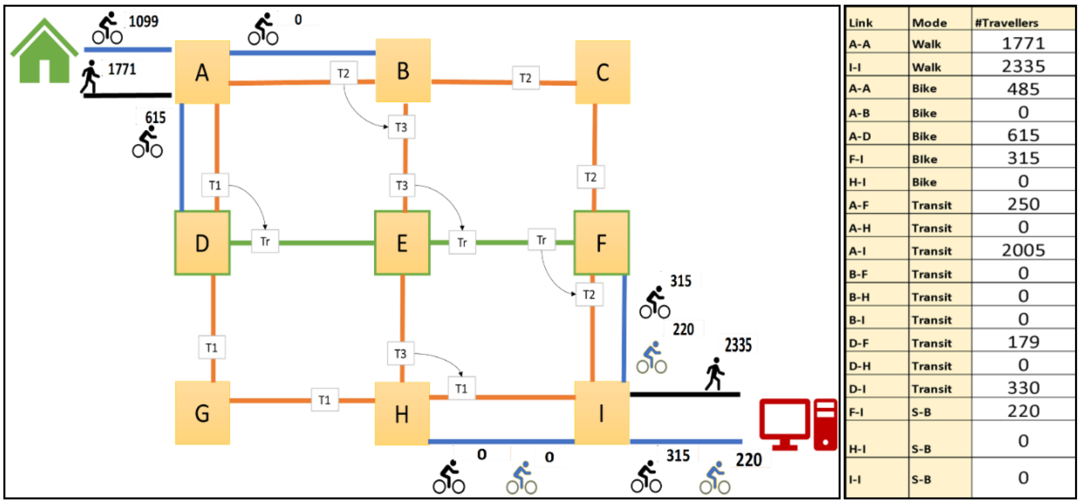
First of all by increasing the travel time of link I-F the total demand for public transport decreased from 3015 to 2870. The result for the multimodal trips are shown for the Visum model in figures 7.9 and 7.10. The mode choice consistency problem is directly noticeable. Because the travel times for public transport increased for the evening trip the model estimates substantial higher shares of multimodal transport**.** *All red numbers in the evening trip indicate mode shares which are not consistent with the morning trip*. As an example 220 people used a shared bike to reach the destination in the morning. In the evening the model assumes that 584 people use a shared bike for the returning trip. This is not realistic, as there are only 220 shared bikes available.

The changes for the evening trip are logical considering the fact that the public transport line I to F is made less attractive. For this reason the shares of people performing a multimodal trip in the evening increase. Because multimodality is handled at trip level and not a tour level, the effect of the changed travel time of line I to F is not noticeable during the morning trip. Hence, the multimodal distribution during the morning trip and evening trip are different.

When comparing the morning and evening trip there can be seen that the extra shared bikes are mainly cause by people that decide to use a shared bike to reach station F. The extra number of people that bike towards station F also results in more biking trips from D to A. Another remarkable difference is that for the returning trip people also bike towards station H. The same amount of people use a bike from station B towards home.

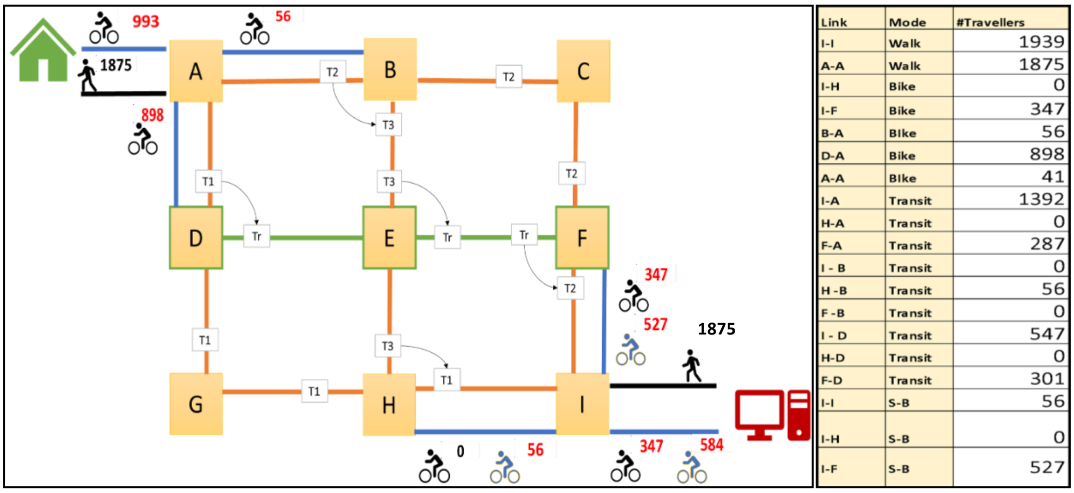
In the model used by Visum in reality there is a solution for the consistency problem. This is that the results for the multimodal morning trips are copied to the evening trip. However, there are two problems of this solution:

- The model does not consider the evening trips when calculating the multimodal mode shares in the morning trip. In case of the situation with the increased link travel time for the evening trip, this can be a reason to use bike-sharing in the morning; people already consider in the morning that the travel-times with public transport for the returning trip are longer. Hence, people already consider the evening trip when making a decision about their multimodal mode-choice in their morning trip.
- When there are more complex tours it is not possible to copy the results anymore. This is illustrated in the next section.



Link	Mode	#Travellers
A-A	Walk	1771
I-I	Walk	2335
A-A	Bike	485
A-B	Bike	0
A-D	Bike	615
F-I	Bike	315
H-I	Bike	0
A-F	Transit	250
A-H	Transit	0
A-I	Transit	2005
B-F	Transit	0
B-H	Transit	0
B-I	Transit	0
D-F	Transit	179
D-H	Transit	0
D-I	Transit	330
F-I	S-B	220
H-I	S-B	0
I-I	S-B	0

Figure 7.9: Multimodal mode-choice distribution in the morning for the Visum model



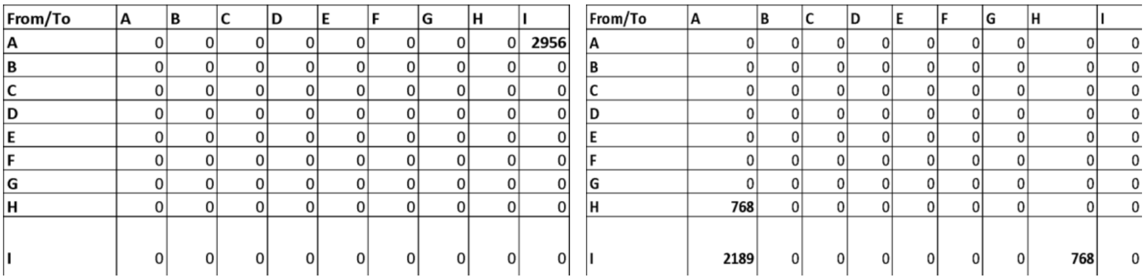
Link	Mode	#Travellers
I-I	Walk	1939
A-A	Walk	1875
I-H	Bike	0
I-F	Bike	347
B-A	Bike	56
D-A	Bike	898
A-A	Bike	41
I-A	Transit	1392
H-A	Transit	0
F-A	Transit	287
I - B	Transit	0
H -B	Transit	56
F -B	Transit	0
I - D	Transit	547
H-D	Transit	0
F-D	Transit	301
I-I	S-B	56
I-H	S-B	0
I-F	S-B	527

Figure 7.10: Multimodal mode-choice distribution in the evening for the Visum model. The red number indicate all number that are not consistent with the morning trip

CONSIDERING TOURS THAT CONTAIN A SUB-ACTIVITY

This section will consider tours that also contain a sub-activity before returning home. This means that the public transport trips are divided into a share of people that directly returns home and a share of people that first performs a sub-activity before returning home. The sub-activity performed in this case is shopping.

The travel time for link I-F is set to the original value of 14 minutes. Based on changed activity schedules from the total demand for public transport of 2956, 2189 people still perform the simple tour A-I-A. At the same time 768 perform a complex tour, where they first go shopping in H before returning home again. It is assumed that all subtour takes place in the evening. In the Visum modelling procedure this would result in the following morning and evening matrices (figure 7.11).



From/To	A	B	C	D	E	F	G	H	I
A	0	0	0	0	0	0	0	0	2956
B	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0

From/To	A	B	C	D	E	F	G	H	I
A	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0	0
H	768	0	0	0	0	0	0	0	0
I	2189	0	0	0	0	0	0	768	0

Figure 7.11: The new origin destination matrices when complex tours are considered, all sub-activities are performed in the evening leading to 768 trips from I to H and from H to A

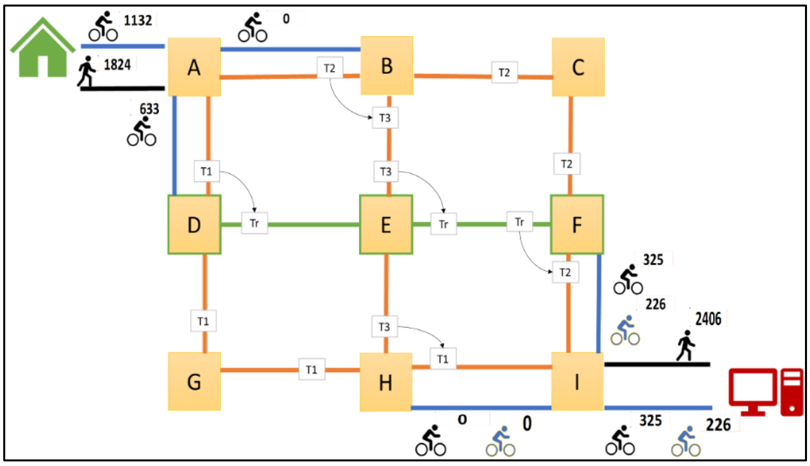
Running the Visum model with the adjusted demand to consider the sub-tours results in multimodal network distribution as shown in figure 7.12 and figure 7.13. As can be seen, for the evening trip, new links are added to the transport network. First of all, there are biking and walking links added to reach the shopping location. Secondly, there is an opportunity to bike from station H to station E and from station H to station I.

The opportunity to bike to station E becomes available because this station is within the threshold value from station H. The extra travel possibility to bike to I is added because people can in theory bike back to I or F to return the bike to the station where they rented it in the morning. The values in the visualisation of the transport network are still accumulated values. The number of bikes that are returned to a station is the sum of all bikes towards the station minus all bikes leaving the station. For station H there are zero shared bikes coming from station I, there are 448 shared bikes coming from shopping location H. At the same time there are zero bikes leaving from station H to station I and shopping location H and there are 265 shared bikes leaving towards station E. This means that there are 448+0-(0+0+265)=183 people returning a bike at station H. There are three problems looking at the results of the Visum model.

- First of all, *there is no consistency* in the multimodal mode-choice distribution. 183 people return a bike to station H in the evening. As can be seen in figure 7.12, there are no travellers who rented a bike from this station in the morning. The same phenomena can be seen for all other stations. The reason follows from the fact that the number of people directly travelling from A to I and returning from I to A varies within this modelling scenario. People performing a sub-activity and coming from station H and returning to station A have another station choice distribution compared to people coming from station I. For example, biking towards station E also becomes an interesting alternative from shopping location H. This shows clearly what the problem is of a lack in mode-choice consistency when modelling SB-bike-sharing.

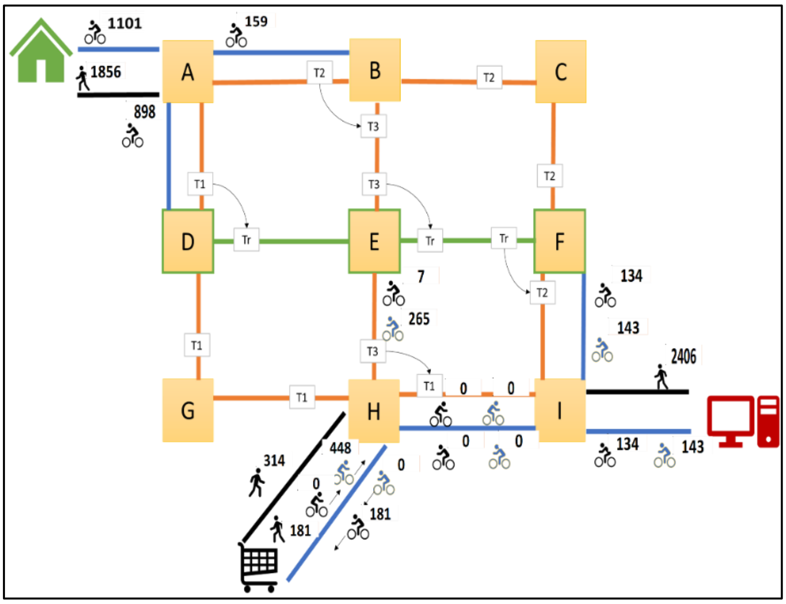
- Secondly, there is *no demand for biking from station I to shopping location H*. In reality, the bike is an attractive travel mode because of its flexibility. It is easy to go to multiple activity locations before returning home again. In spite of this, the Visum model expects that the trips from I to H are all performed by transit line 1. The reason for this follows from the modelling setup. The trip from I to H is modelled as it is a complete distinct trip with the mode public transport, as can be seen in the matrices in figure 7.11. As it is a transit trip, the trip has to contain at least one transit leg. This means that the model urges travellers to use line 1 to travel between I and H.

- Lastly, it is remarkable that there are 448 people coming from the shopping location which use shared-bikes and there are no people using a normal bike. *This is a result of the problem that the model does not consider trip dependent leg properties.* This problem is discussed in chapter 4.4 about multimodal modelling challenges. Trip dependent leg properties mean for example that travellers are more likely to use a bike at the home-side of a trip compared to the activity-side of a trip. When trips are modelled for the evening, the model most likely assumes that it is a trip coming from the activity location and returning home. This means that the trip from I to H is assumed to be a trip from work to home. At the activity side of a trip the penalties for using an owned bike are higher compared to the home-side of the trip. For this reason the model expects that 181 travellers use a bike to reach destination H. Destination H is then modelled as the home-side of the trip. At the same time the model expects that nobody uses the normal bike to return from the shopping location to station H. Station H is then modelled as the activity side of the trip, resulting in high penalties for the use of an owned bike. Because of the high penalties to use the owned bike there is a high share of people that use the shared bike for the returning trip.



Link	Mode	#Travellers
A-A	Walk	1824
I-I	Walk	2406
A-A	Bike	499
A-B	Bike	0
A-D	Bike	633
F-I	BIke	325
H-I	Bike	0
A-F	Transit	258
A-H	Transit	0
A-I	Transit	2066
B-F	Transit	0
B-H	Transit	0
B-I	Transit	0
D-F	Transit	185
D-H	Transit	0
D-I	Transit	340
F-I	S-B	226
H-I	S-B	0
I-I	S-B	0

Figure 7.12: The multimodal mode choice distribution for the morning trip in the Visum modelling approach



Link	Mode	#Travellers
A-A	Walk	1856
I-I	Walk	2680
H-H egress	Walk	587
H-H access	Walk	314
I-I	Bike	0
I-H (station)	Bike	0
I-H (shopping)	Bike	0
I-F	Bike	134
H- H egress	Bike	181
H -H access	Bike	0
H-E	Bike	7
H-I	Bike	0
H-F	Bike	0
B-A	Bike	159
D-A	Bike	898
A-A	Bike	22
I-A	Transit	79
H-A	Transit	218
F-A	Transit	79
I - B	Transit	0
H -B	Transit	159
F -B	Transit	0
I - D	Transit	348
H-D	Transit	0
F-D	Transit	198
I-I	S-B	0
I-H (station)	S-B	0
I-H (shopping)	S-B	0
I-F	S-B	143
H-H	S-B	0
H-H (Access	S-B	182
H-E	S-B	265
H -I	S-B	0
H-F	S-B	0

Figure 7.13: The multi-modal mode choice distribution for the evening trip including a sub-trip with the Visum model

7.3 SCENARIO ANALYSES FOR THE TOUR-BASED MODE-CHAIN AND STATION CHOICE APPROACH

This paragraph will perform the same scenario analyses as performed with the Visum two-step mode choice approach. This is done to illustrate that the tour-based mode-chain and station choice approach is able to address the limitations of the two-step mode choice approach. Because in paragraph 7.2 there is elaborated about all input this is not done in this paragraph. The tour-based mode-chain approach always has a consistent morning and evening trip. For this reason only the morning trips are illustrated in scenario 0 to 2. In scenario 3, when the consistency is tested the model results for the morning trip as well as the evening trip are shown to illustrate that the tour-based mode-chain and station choice approach always gives consistent results.

7.3.1 SCENARIO 0 - THE BASE SCENARIO USED AS REFERENCE

Note that the results for the base-scenario are not of key-interest for this study, it is mainly used to see how the modelling result changes by the implementation of the SB-bike-sharing system.

RESULTS

The tour-based mode-chain and station choice approach calculates for the base-scenario the mode shares as shown in table 7.18. Also the tour-based mode-chain model can consider the person type specific characteristics (Type 2 has a car and Type 3 has student discount). In the end, given the number of people in the population, the number of car trips, public transport trips and biking trips are obtained as shown in figure 7.14. The car is responsible for 52% percent of the tours, public transport for 37% and biking for 11%. Compared to the Visum method, public transport has an even higher share of the modal split. This is caused by the fact that the tour-based mode-chain method considers multimodal transport when calculating the public transport demand (this is further elaborated in scenario 1).

Table 7.18: Mode shares obtained with the tour-based mode-chain approach

Persontype	Activity	Car	PT	Bike	Walk
Type 1	Work	15%	57%	27%	0%
Type 1	Education	15%	57%	27%	0%
Type 1	Shopping	15%	57%	27%	0%
Type 2	Work	78%	15%	7%	0%
Type 2	Education	78%	15%	7%	0%
Type 2	Shopping	78%	15%	7%	0%
Type 3	Work	5%	86%	9%	0%
Type 3	Education	5%	86%	9%	0%
Type 3	Shopping	5%	86%	9%	0%

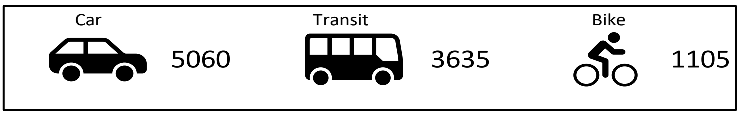


Figure 7.14: Number of users per transport mode with the tour-based mode-chain approach

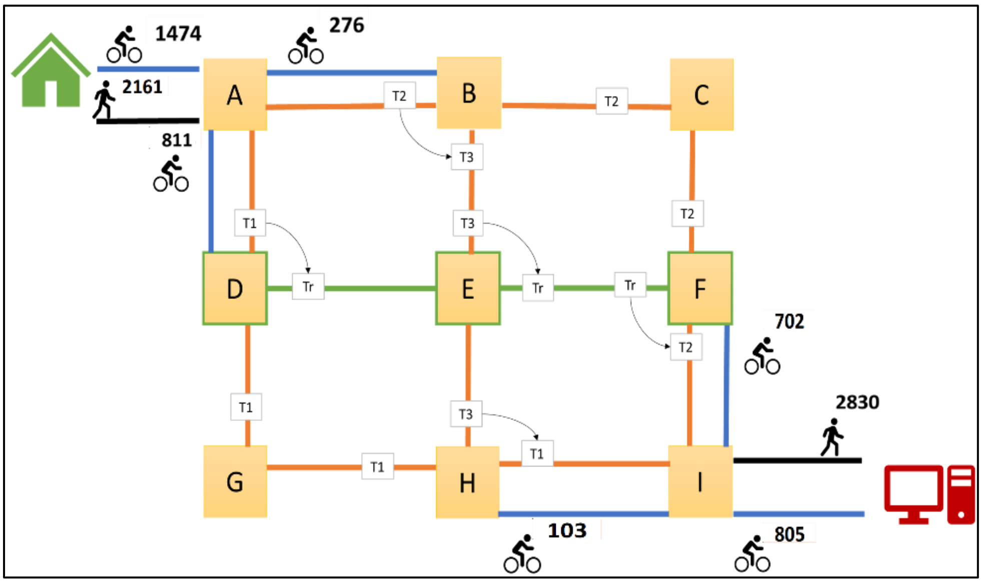
The tour-based mode-chain and station choice approach explicitly models the demand for each mode-chain. The results obtained are illustrated in table 7.19. Approximately half of the public transport trips are unimodal (walk-public transport-walk), this is consistent with research from the Dutch mobility penal (Hamersma, 2020). Within the multimodal trips, the trip chain B-T-W is the most attractive travel alternative**.** This is consistent with the study of Shelat et al. (2018), which indicated that this mode-chain is used for around 50 percent of the multimodal transport trips by bike. Also the fact that the bike-transit-bike chain is more popular than walk-transit-bike is consistent with the literature (Shelat et al.,2018).

The Multimodal tours are distributed over the multimodal transport network as shown in figure 7.15 (the evening trip is consistent with this morning trip). The results show the same pattern compared to the Visum approach.

Station D and Station F are the most popular multimodal transport options. In contrast to the Visum approach also station H has some demand to use the bike on the egress side.

Table 7.19: Multimodal mode shares for the tour-based mode-chain approach

Persontype	Activity	W-T-W	B-T-W	W-T-B	B-T-B
Type 1	Work	65%	22%	3%	10%
Type 1	Education	65%	22%	3%	10%
Type 1	Shopping	65%	22%	3%	10%
Type 2	Work	65%	22%	3%	10%
Type 2	Education	65%	22%	3%	10%
Type 2	Shopping	65%	22%	3%	10%
Type 3	Work	49%	42%	1%	8%
Type 3	Education	49%	42%	1%	8%
Type 3	Shopping	49%	42%	1%	8%



A-A	Walk	2161
I-I	Walk	2830
A-A	Bike	388
A-B	Bike	276
A-D	Bike	811
F-I	BIke	702
H-I	Bike	103
A-F	Transit	117
A-H	Transit	41
A-I	Transit	2622
B-F	Transit	42
B-H	Transit	37
B-I	Transit	360
D-F	Transit	543
D-H	Transit	25
D-I	Transit	727

Figure 7.15: Distribution of multimodal transport trips in the morning with the tour-based mode-chain approach. The evening trip is consistent with the morning trip, the demand is completely similar only in the reversed direction

7.3.2 SCENARIO 1 - THE TRAVEL DEMAND PROBLEM - IMPLEMENTING SB-BIKE-SHARING AND REDUCING THE PRICE

This sub-paragraph studies what the impact is of implementing SB-bike-sharing to the model results. Also the price of the system is adjusted. The objective is to demonstrate that the tour-based mode-chain approach can model the relation between promoting policies regarding SB-bike-sharing and the demand for public transport. The input is changed exactly the same as for the Visum approach is scenario 1.

INPUT

Table 7.20: Input characteristics of SB-bike-sharing

Speed	15	**KM/H**
Price	3,8	**Euro**
Transfer time	6	**Minutes**

Table 7.21: Parameter estimation for SB-bike-sharing

Variable	Parameter	Visum approach	Tour-based mode-chain approach
Penalty shared-bike (Psb)	$\beta 21$	-1,5	-0,5

RESULTS

Also for the tour-based mode-chain approach SB-bike-sharing was successfully implemented. In contrast to the Visum approach the implementation affected the number of public transport users as can be seen in figure 7.16. *The number of public transport users increased from 3635 to 3713*, indicating an *increase of around one to two percent.* Table 7.22 approves this; the public transport shares increased by around one to two percent in the tour-based mode-chain model for person type 1 and type 3. This is caused by the fact that SB-bike-sharing makes public transport in general more attractive by promoting multimodal transport tours. Therefore the utility of public transport increased while the utility of other modes kept constant. This results in higher mode shares for public transport and a lower share for other modes. The reason that this is only the case for persontype 3, has to do with the fact that this group has a discount for public transport. As SB-bike-sharing is modelled like it is part of the multimodal public transport trip there is assumed that students also have a discount for SB-bike-sharing. For this reason the impact of implementing SB-bike-sharing is bigger compared to the other person types.

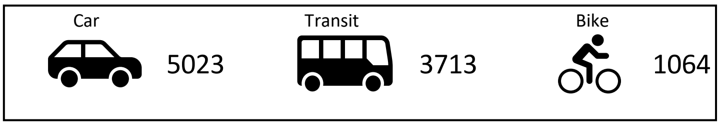
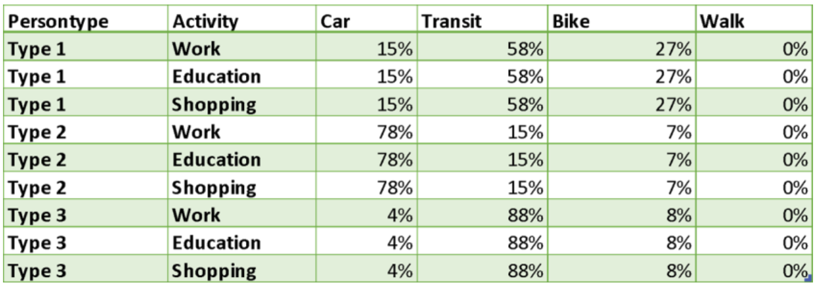
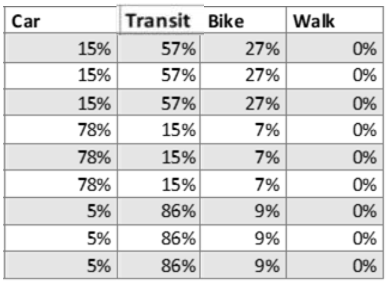


Figure 7.16: Number of travellers using each transport mode tour-based mode-chain model

Table 7.22: Mode shares with the implementation of SB-bike-sharing on the left compared to the situation before implementing SB-bike-sharing on the rights



Persontype	Activity	Car	Transit	Bike	Walk
Type 1	Work	15%	58%	27%	0%
Type 1	Education	15%	58%	27%	0%
Type 1	Shopping	15%	58%	27%	0%
Type 2	Work	78%	15%	7%	0%
Type 2	Education	78%	15%	7%	0%
Type 2	Shopping	78%	15%	7%	0%
Type 3	Work	4%	88%	8%	0%
Type 3	Education	4%	88%	8%	0%
Type 3	Shopping	4%	88%	8%	0%



Car	Transit	Bike	Walk
15%	57%	27%	0%
15%	57%	27%	0%
15%	57%	27%	0%
78%	15%	7%	0%
78%	15%	7%	0%
78%	15%	7%	0%
5%	86%	9%	0%
5%	86%	9%	0%
5%	86%	9%	0%

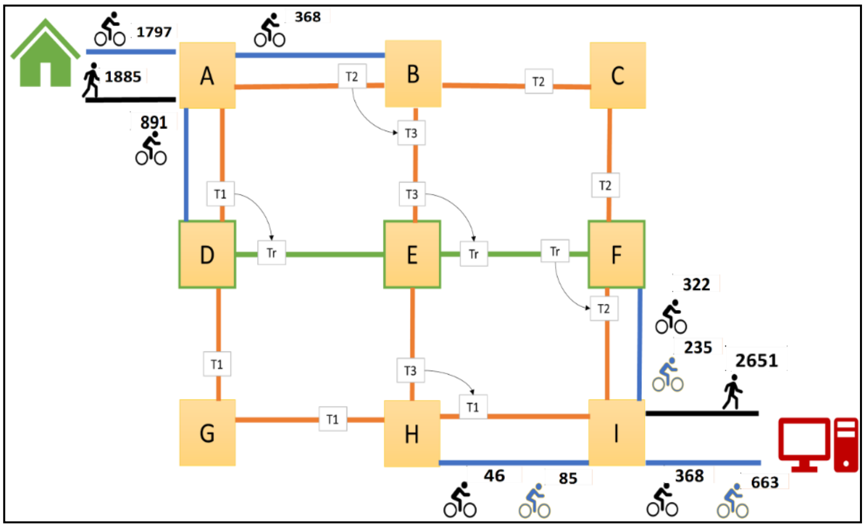
The multimodal mode shares also show the effect of implementing SB-bike-sharing. *The mode-chains W-T-B and B-T-B increased.* For this reason the shares of the *mode-chains W-T-W and B-T-W decreased***.** The old and the new multimodal mode shares can be seen in table 7.23. Again, the effect is most noticeable for person type 3.

Table 7.23: Multimodal mode shares with the implementation of SB-bike-sharing on the left compared to the situation before implementing SB-bike-sharing on the right

Persontype	Activity	W-T-W	B-T-W	W-T-B	B-T-B	W-T-W	B-T-W	W-T-B	B-T-B
Type 1	Work	61%	21%	7%	12%	65%	22%	3%	10%
Type 1	Education	61%	21%	7%	12%	65%	22%	3%	10%
Type 1	Shopping	61%	21%	7%	12%	65%	22%	3%	10%
Type 2	Work	62%	21%	7%	10%	65%	22%	3%	10%
Type 2	Education	62%	21%	7%	10%	65%	22%	3%	10%
Type 2	Shopping	62%	21%	7%	10%	65%	22%	3%	10%
Type 3	Work	33%	28%	15%	25%	49%	42%	1%	8%
Type 3	Education	33%	28%	15%	25%	49%	42%	1%	8%
Type 3	Shopping	33%	28%	15%	25%	49%	42%	1%	8%

The multimodal mode shares are distributed across the multimodal transport network as visualised in figure 7.17. As can be seen, there are *significantly more multimodal trips as a result of the implementation of SB-bike-sharing.* The tour-based mode-chain model seems to give reasonable results in the station choice distribution. *Station I is the most popular station to transfer to shared-bikes.* This is logical, considering that there is no possibility of using the normal bike from this station. Moreover, people prefer long in-vehicle times compared to long access and egress biking trips. For this reason, using line 2 from station A or B to station I is a popular travel alternative. It is interesting to notice that the number of access trips by bike also increased compared to the base-scenario. This is explained by the fact that the mode shares of the B-T-B chain increased substantially.

In the tour-based mode-chain approach the *bike-sharing shares are relatively high compared to the normal bike shares.* This is mainly caused by the assumption that students have a discount for the use of bike-sharing. When bike-sharing is only 25 percent of the normal price, the students in general prefer the shared bike compared to parking an owned bike at the station. Students account for a high share of the use of public transport. Therefore, there are relatively many travellers who use public transport that prefer the shared bike compared to the normal bike. Consequently the number of bike-sharing users is relatively high compared to the use of normal bikes.



A-A	Walk	1885
I-I	Walk	2651
A-A	Bike	537
A-B	Bike	368
A-D	Bike	891
F-I	BIke	322
H-I	Bike	46
A-F	Transit	112
A-H	Transit	28
A-I	Transit	2282
B-F	Transit	16
B-H	Transit	11
B-I	Transit	342
D-F	Transit	195
D-H	Transit	7
D-I	Transit	689
F-I	S-B	235
H-I	S-B	85
I-I	S-B	342

Figure 7.17: Distribution of multimodal transport trip in the morning with the implementation of SB-bike-sharing in the tour-based mode-chain approach. Again the results for the evening trips are similar to the morning results (only revered)

THE EFFECT OF DECREASING THE PRICE OF SB-BIKE-SHARING

In this section there is analysed what the effect is of decreasing the price of SB-bike-sharing. This is done to clearly illustrate that the tour-based mode-chain approach considers the relation between policies to promote multimodal transport and the demand for public transport. As can be seen in table 7.24 in contrast to the result in the Visum approach there is a substantial increase of public transport use in the tour-based mode-chain model. This illustrates that the tour-based mode-chain approach could address the travel demand limitation of the Visum-approach.

When SB-bike-sharing is free of charge, public transport ridership increased 16% compared to the situation with the normal price (€3,85). At the same time, free SB-bike-sharing results in *63% of the travellers that would use the shared-bike for their egress trip leg.* The model results are hard to review quantitatively as there is no hard data available on this regard. However, it seems feasible. Lowering the price of bike-sharing would attract many public transport travellers which currently find bike-sharing too expensive. A research on the relation of pricing and the demand of SB-bike-sharing indicates that from a crowded public transport line in Utrecht 60% is willing to make a switch to SB-bike-sharing when SB-bike-sharing is free of charge (Steegman, 2016).

There would also be some people that switch from the car or bike to public transport because of the policy measure. However, there is little known about the elasticity between access and egress trip legs and the demand for road traffic. An increase of 16% seems too high, as it is hard to change travel habits of people that use a car for commuting.

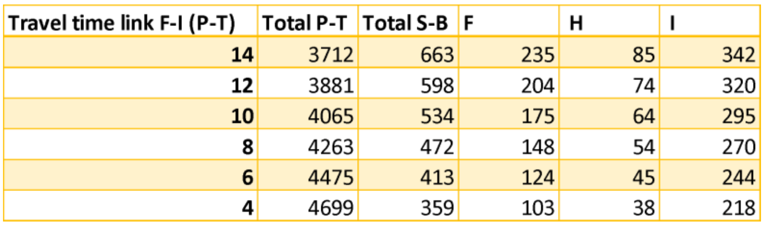
The tour-based mode-chain approach shows another interesting effect considering the pricing policies. As discussed, when the price is €3,85, station I is the most popular station for SB-bike-sharing users. However, in the case that the price drops, station F becomes relatively more popular. This is because station F is a station “type 1”, which has good bike-parking facilities. Consequently, people using station F are not as eager to switch to the shared bike compared to the other stations. However, when the price drops to a certain point, also for travellers using station F, the shared-bike is more interesting compared to parking an owned bike at the station.

The other scenario tested is the effect of lowering the travel-time for the public transport link F-I. This is shown in table 7.25. As can be seen, this policy measure has more effect on public transport ridership compared to the SB-bike-sharing pricing policy. This is because for most travellers uni-modal transport options without transfers are intrinsically preferred to multimodal trips. This means that when the uni-modal transport alternative becomes more attractive, it also stimulates more people to use public transport. The tour-based mode-chain approach expects that the number of SB-bike-sharing users decreases because of these policy measures. This seems a feasible result, as the unimodal transport trip becomes faster, the competing alternatives for SB-bike-sharing become more attractive. This mainly influences the number of people that bike from station F and H.

Table 7.24: The effect of pricing on the total public transport (total P-T) and bike-sharing (total S-B) users in the tour-based mode-chain model

Price (Euros)	Total P-T	Total S-B	F	H	I
3,85	3712	663	235	85	342
3,35	3726	749	269	97	383
2,85	3744	856	307	117	432
2,35	3772	997	356	148	493
1,85	3815	1199	440	188	572
1,35	3885	1500	590	235	674
0,85	3995	1899	801	293	805
0,35	4155	2358	1034	362	963
0	4298	2700	1199	416	1084

Table 7.25: The effect of travel times for public transport link F-I on the total public transport (total P-T) and bike-sharing (total S-B) users in the tour-based mode-chain model



Travel time link F-I (P-T)	Total P-T	Total S-B	F	H	I
14	3712	663	235	85	342
12	3881	598	204	74	320
10	4065	534	175	64	295
8	4263	472	148	54	270
6	4475	413	124	45	244
4	4699	359	103	38	218

7.3.3 SCENARIO 2 - THE AGGREGATION PROBLEM - CONSIDERING SOCIO-DEMOGRAPHIC IN THE DEMAND FOR SB-BIKE-SHARING

This scenario demonstrates the tour-based mode-chain approach can consider socio-demographic when calculating the demand for SB-bike-sharing. To test this scenario parameters of different person types are changed and the number of inhabitants of the different person types are varied. The changed parameters are already discussed in paragraph 7.2.3.

INPUT

Table 7.26: Activity specific parameters to test the effect of socio-demographics on the model results

Mode	Activity purpose	Travel time (Tt and Tiv)	Travel cost (Ct)
Car	**Work**	β	β
		-0,055	-0,7
	Education	β	β
		-0,045	-0,7
Public transport (Tiv)	**Work**	β	β
		-0,045	-0,7
	Education	β	β
		-0,035	-0,7
Bike	**Work**	β	β
		-0,075	-0,7
	Education	β	β
		-0,065	-0,7
Walk	**Work**	β	β
		-0,055	-0,7
	Education	β	β
		-0,045	-0,7

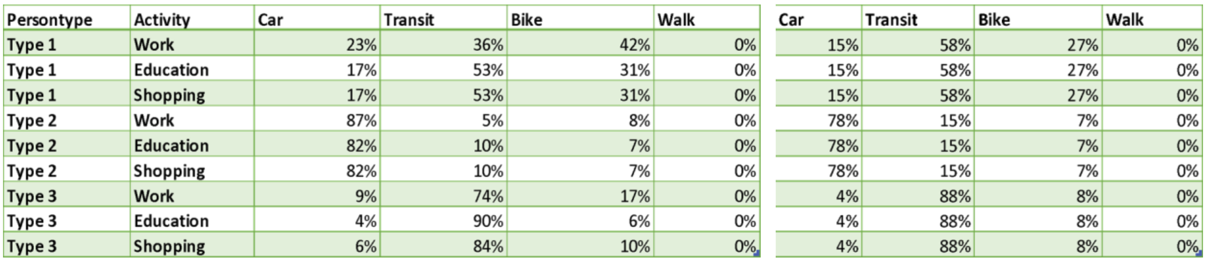
Table 7.27: Values of the Multimodal dummy variables to test effect of socio-demographics on the model results

	Type 1		**Type 2**		**Type 3**	
Multimodal transport dummy	D_{mm}	0,9	D_{mm}	1,2	D_{mm}	0,7

RESULTS

As can be seen in table 7.30 and table 7.31, in the tour-based mode-chain model *the number of public transport users decreased from 3712 to 3114.* The new results, similar to the Visum approach, contributed to the fact that the *value of time for the working population decreased.* This makes the car relatively more attractive. When looking at table 7.28, one can see that the car usage for the purpose work increased with 7% for person type 1 and person type 2. Public transport shares decreased for the purpose work with more than 10% for the purpose work for all person types. In general all person types have more heterogeneity in their travel preferences.

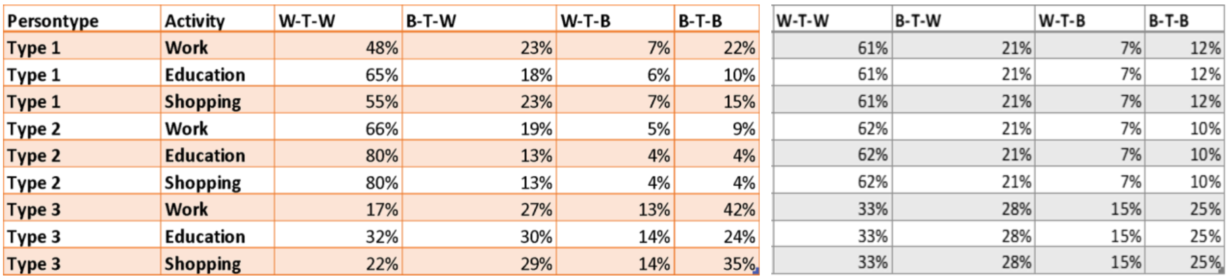
Table 7.28: The distribution of transport modes. The results with the changed parameters on the left and the results from scenario 1 on the right



Persontype	Activity	Car	Transit	Bike	Walk	Car	Transit	Bike	Walk
Type 1	Work	23%	36%	42%	0%	15%	58%	27%	0%
Type 1	Education	17%	53%	31%	0%	15%	58%	27%	0%
Type 1	Shopping	17%	53%	31%	0%	15%	58%	27%	0%
Type 2	Work	87%	5%	8%	0%	78%	15%	7%	0%
Type 2	Education	82%	10%	7%	0%	78%	15%	7%	0%
Type 2	Shopping	82%	10%	7%	0%	78%	15%	7%	0%
Type 3	Work	9%	74%	17%	0%	4%	88%	8%	0%
Type 3	Education	4%	90%	6%	0%	4%	88%	8%	0%
Type 3	Shopping	6%	84%	10%	0%	4%	88%	8%	0%

Looking at the multimodal mode shares in table 7.29 there can be noticed what the effect is of the multimodal dummy variable. For person type 3 and person type 1 the number of multimodal transport tours increased. For type 2 the number of multimodal transport tours decreased. For the activity purpose, multimodal trips are more popular compared to education. This is again because of the higher value of time. In general the multimodal transport options are faster travel alternatives.

Table 7.29: Multimodal mode shares in the tour-based mode-chain modelling setup. The result with the changed parameters on the left and the result from scenario 1 on the right.



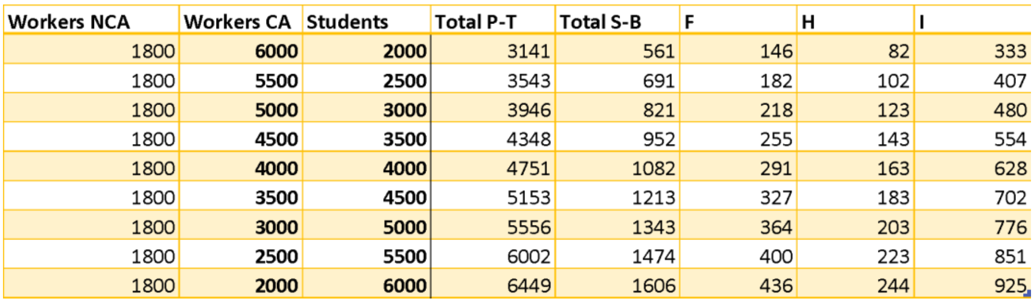
Persontype	Activity	W-T-W	B-T-W	W-T-B	B-T-B	W-T-W	B-T-W	W-T-B	B-T-B
Type 1	Work	48%	23%	7%	22%	61%	21%	7%	12%
Type 1	Education	65%	18%	6%	10%	61%	21%	7%	12%
Type 1	Shopping	55%	23%	7%	15%	61%	21%	7%	12%
Type 2	Work	66%	19%	5%	9%	62%	21%	7%	10%
Type 2	Education	80%	13%	4%	4%	62%	21%	7%	10%
Type 2	Shopping	80%	13%	4%	4%	62%	21%	7%	10%
Type 3	Work	17%	27%	13%	42%	33%	28%	15%	25%
Type 3	Education	32%	30%	14%	24%	33%	28%	15%	25%
Type 3	Shopping	22%	29%	14%	35%	33%	28%	15%	25%

To test the effect of changing socio-demographics, the population is changed in table 7.31. The number of students (type 3) is increased and the number of person types 2 is decreased. In the first place, by increasing the number of students there is expected that the number of public transport usage increases. The second expected effect is that within the population which uses public transport, the number of multimodal trips increases as well. This means that SB-bike-sharing usage is expected to increase relatively more compared to the usage of public transport. Table 7.31 and table 7.32 show that the tour-based mode-chain modelling setup does model both expected effects. By increasing the number of students from 2000 to 2500 the number of public transport users increased with 13% and the number of bike-sharing users increased with 23%. This indicates that the model considers the fact that by increasing the number of *students the number of SB-bike-sharing increases more compared to the total public transport trips.*

Table 7.30: The results before changing the parameters in the tour-based mode-chain approach

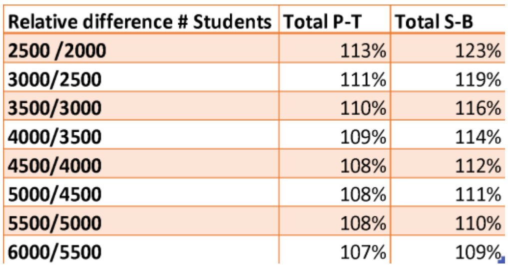
Workers NCA	Workers CA	Students	Total PT	Total SB	F	H	I
1800	**6000**	**2000**	3712	663	235	85	342

Table 7.31: The effect of changing the social demographics on public transport usage and SB-bike-sharing usage in the tour-based mode-chain model



Workers NCA	Workers CA	Students	Total P-T	Total S-B	F	H	I
1800	**6000**	**2000**	3141	561	146	82	333
1800	**5500**	**2500**	3543	691	182	102	407
1800	**5000**	**3000**	3946	821	218	123	480
1800	**4500**	**3500**	4348	952	255	143	554
1800	**4000**	**4000**	4751	1082	291	163	628
1800	**3500**	**4500**	5153	1213	327	183	702
1800	**3000**	**5000**	5556	1343	364	203	776
1800	**2500**	**5500**	6002	1474	400	223	851
1800	**2000**	**6000**	6449	1606	436	244	925

Table 7.32: Relative increase of public transport usage and SB-bike-sharing usage when increasing the number of students in the tour-based mode-chain model



Relative difference # Students	Total P-T	Total S-B
2500 /2000	113%	123%
3000/2500	111%	119%
3500/3000	110%	116%
4000/3500	109%	114%
4500/4000	108%	112%
5000/4500	108%	111%
5500/5000	108%	110%
6000/5500	107%	109%

7.3.4 SCENARIO 3 - THE CONSISTENCY PROBLEM – CHANGING ATTRIBUTES OF THE EVENING TRIP COMPARED TO THE MORNING TRIP

This scenario illustrates that the tour-based mode-chain approach has consistency when the attributes for the evening trip change compared to the morning trip. In the scenarios so far travel times for the returning trip were similar to the outgoing trip. The input is changed similarly to paragraph 7.2.4.

INPUT

The frequencies of the different service lines are changed and the travel time of link F-I is changed (from 14 minutes to 25 minutes) and there is a tour that contains a sub-activity.

Table 7.33: Frequency of the different public transport lines

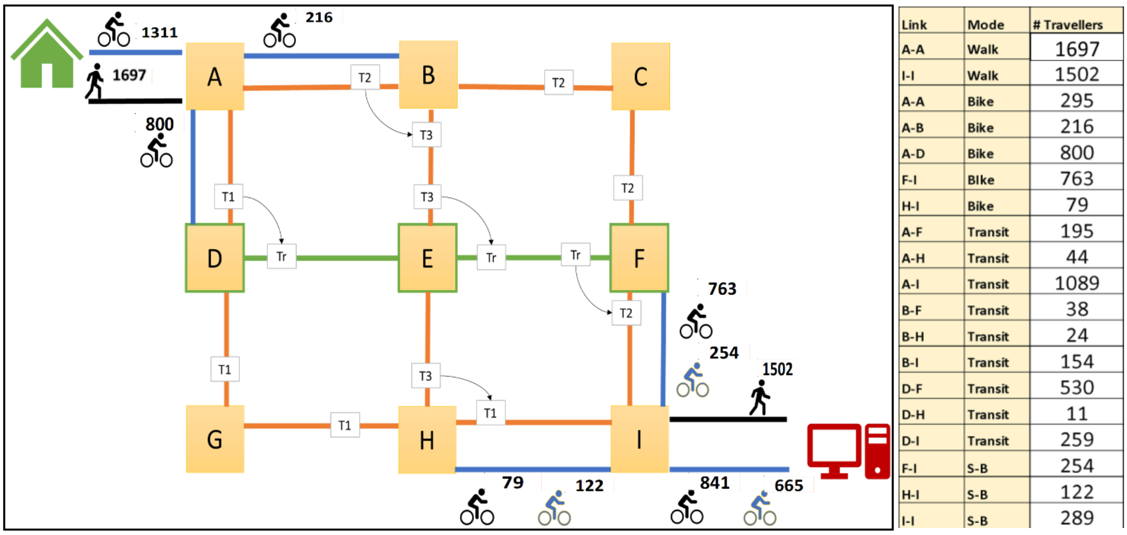
	Train	**Line 1**	**Line 2**	**Line 3**
Frequency	8	4	6	4

RESULTS

In figure 7.18 and figure 7.19 there can be seen that the tour-based mode-chain approach gives *consistent results even with changed travel times for the afternoon trip.* All bikes rented in the morning are returned in the evening trip. The changing travel-times for the returning trip do have influence on the results of the model.

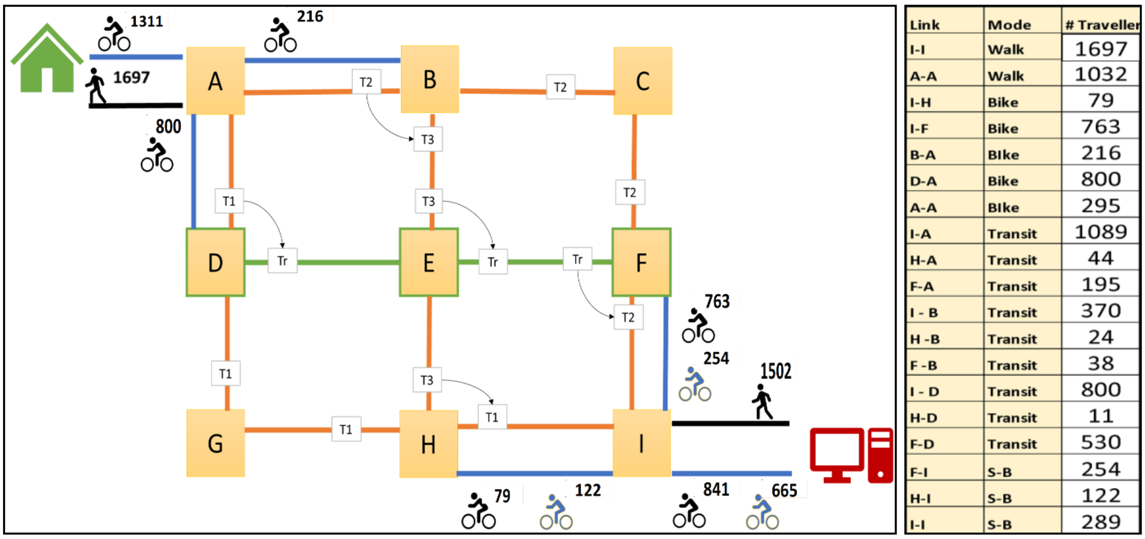
First of all the total number of public transport trips decreased from 3141 to 3008. This is because the total travel-time for the uni-modal alternative was raised as a result of the changed travel time of link F-I.

Furthermore, because the travel times for the returning trip are higher, travellers already consider during the morning trip that it might be better to use a bike or shared bike. Therefore there are many extra multimodal transport tours as a result of the increased travel time of the public transport link. The fact that travellers consider travel times of the complete transport tour means that they assumed that they have full information about the complete transport tour when making a mode choice during the morning trip.



Link	Mode	# Travellers
A-A	Walk	1697
I-I	Walk	1502
A-A	Bike	295
A-B	Bike	216
A-D	Bike	800
F-I	BIke	763
H-I	Bike	79
A-F	Transit	195
A-H	Transit	44
A-I	Transit	1089
B-F	Transit	38
B-H	Transit	24
B-I	Transit	154
D-F	Transit	530
D-H	Transit	11
D-I	Transit	259
F-I	S-B	254
H-I	S-B	122
I-I	S-B	289

Figure 7.18: Multimodal mode-choice distribution in the morning for the tour-based mode-chain approach



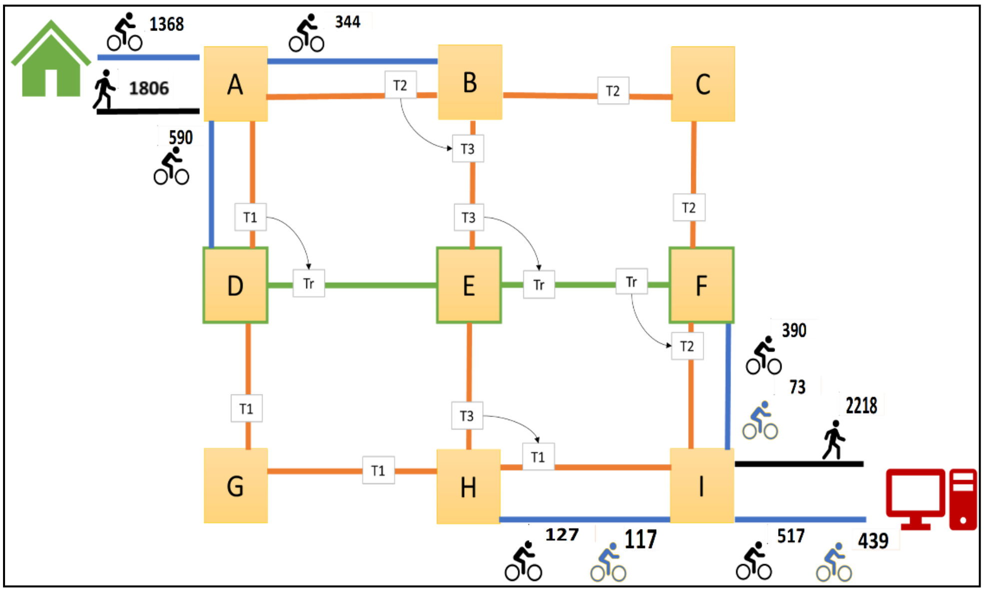
Link	Mode	# Traveller
I-I	Walk	1697
A-A	Walk	1032
I-H	Bike	79
I-F	Bike	763
B-A	BIke	216
D-A	Bike	800
A-A	BIke	295
I-A	Transit	1089
H-A	Transit	44
F-A	Transit	195
I - B	Transit	370
H -B	Transit	24
F -B	Transit	38
I - D	Transit	800
H-D	Transit	11
F-D	Transit	530
F-I	S-B	254
H-I	S-B	122
I-I	S-B	289

Figure 7.19: Multimodal mode-choice distribution in the evening for the tour-based mode-chain approach (with changed travel times compared to the morning trip)

CONSIDERING TOURS THAT CONTAIN A SUB-ACTIVITY

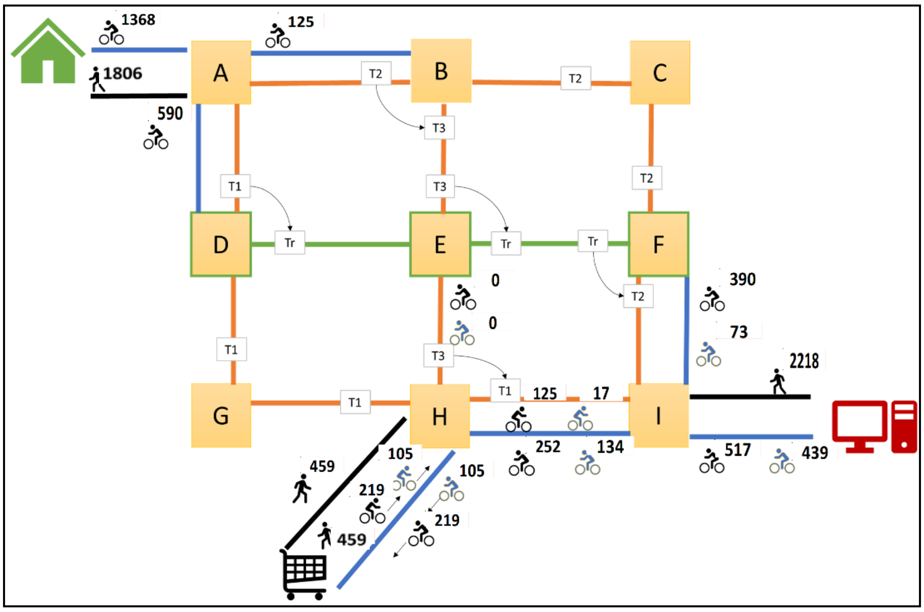
The travel time of link I to F is set back to 14 minutes and an activity chain with a sub-tour is implemented. In total the demand for public transport is 3174. From those 3174, 783 people performed a complex tour and 2391 people performed a simple tour. The results of the mode-choice distribution are shown in figures 7.20 and 7.21.

The tour-based mode-chain model shows promising results as it is able to tackle all mentioned problems. *There is consistency in the number of people renting a bike in the morning and returning the bike in the afternoon.* As an example , the number of people returning the bike in station H is obtained by (134+105)-(105+17+0)=117. There is a significant share of the people that perform a sub trip which bike from destination I to shopping location H. Also the trip-dependent leg properties are considered in a consistent way.



Link	Mode	#Travellers
A-A	Walk	1806
I-I	Walk	2218
A-A	Bike	434
A-B	Bike	344
A-D	Bike	590
F-I	BIke	390
H-I	Bike	127
A-F	Transit	162
A-H	Transit	59
A-I	Transit	1581
B-F	Transit	21
B-H	Transit	59
B-I	Transit	264
D-F	Transit	208
D-H	Transit	9
D-I	Transit	373
F-I	S-B	73
H-I	S-B	117
I-I	S-B	250

Figure 7.20: Multimodal mode choice distribution for the morning trip in the tour-based mode-chain approach



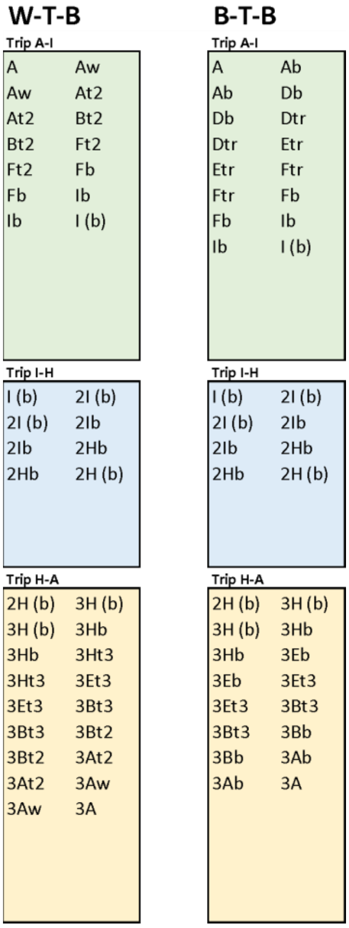
Link	Mode	#Travellers
A-A	Walk	1806
I-I	Walk	2218
H-H egress	Walk	459
H-H access	Walk	459
I-I	Bike	0
I-H (station)	Bike	33
I-H (shopping)	Bike	219
I-F	Bike	266
H- H egress	Bike	0
H -H access	Bike	94
H-E	Bike	0
H-I	Bike	0
H-F	Bike	125
B-A	Bike	344
D-A	Bike	590
A-A	Bike	434
I-A	Transit	1252
H-A	Transit	134
F-A	Transit	162
I - B	Transit	402
H -B	Transit	135
F -B	Transit	21
I - D	Transit	508
H-D	Transit	64
F-D	Transit	186
I-I	S-B	250
I-H (station)	S-B	29
I-H (shopping)	S-B	105
I-F	S-B	55
H-H	S-B	0
H-H (Access	S-B	88
H-E	S-B	0
H -I	S-B	0
H-F	S-B	17

Figure 7.21: Multimodal mode choice distribution for the evening trips, including a sub-trip, with the tour-based mode-chain approach

LEAVING THE ROUND-TRIP CONSTRAINT

The round-trip constraint of the SB-bike-sharing system is extensively discussed in this research. It is one of the most important characteristics of the system. However, the round-trip constraint is a choice from the providers (the Dutch railway company in this case) of the system. Therefore they could consider leaving this constraint to attract more travellers to the sharing system. This is also an interesting selling point compared to the normal bike. Hence, studying what the effect is of leaving the round-trip constraint is an interesting scenario.

As the Visum approach cannot consider round-trip constraints at all, it does not make sense to test this scenario with the approach. For the tour-based mode-chain model, the optimization problem is adjusted so that each tour that bikes at the egress-side of the transport tour have no constraints anymore to return to the station used in the morning. Leaving this constraint gave the two travel alternatives as presented in figure 7.22. The W-T-B alternative uses line 2 from station A and departs at station F to bike from F to I. Then it uses the bike to reach destination H and eventually bikes to station H to use line 3 and line 2 to return to station A again. The B-T-B alternative bikes to station D and picks the train to station F, bikes from F to I and from I to H, and eventually bikes to station E to return with the train to station D again where the bike was left in the morning trip.



W-T-B

Trip A-I

A	Aw
Aw	At2
At2	Bt2
Bt2	Ft2
Ft2	Fb
Fb	Ib
Ib	I (b)

Trip I-H

I (b)	2I (b)
2I (b)	2Ib
2Ib	2Hb
2Hb	2H (b)

Trip H-A

2H (b)	3H (b)
3H (b)	3Hb
3Hb	3Ht3
3Ht3	3Et3
3Et3	3Bt3
3Bt3	3Bt2
3Bt2	3At2
3At2	3Aw
3Aw	3A

B-T-B

Trip A-I

A	Ab
Ab	Db
Db	Dtr
Dtr	Etr
Etr	Ftr
Ftr	Fb
Fb	Ib
Ib	I (b)

Trip I-H

I (b)	2I (b)
2I (b)	2Ib
2Ib	2Hb
2Hb	2H (b)

Trip H-A

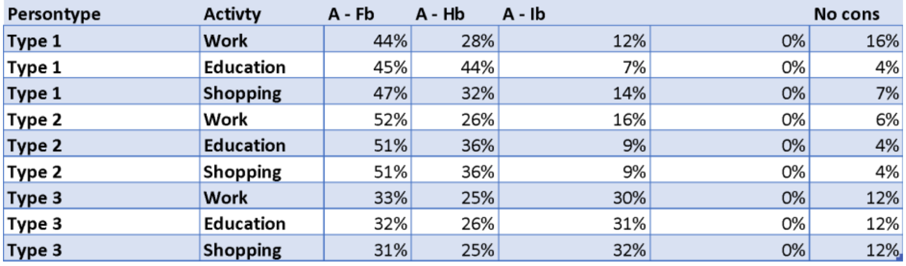
2H (b)	3H (b)
3H (b)	3Hb
3Hb	3Eb
3Eb	3Et3
3Et3	3Bt3
3Bt3	3Bb
3Bb	3Ab
3Ab	3A

Figure 7.22: Generated alternatives without the round-trip constraint

For both alternatives the utility is calculated and compared with the alternatives that do have a round-trip constraint to calculate a new mode-choice and station distribution. Table 7.33 shows the share of people that use the alternative without constraint (No cons) for the W-T-B tour. Table 7.34 shows the same results for the B-T-B tour. The table calculates the shares of the total number of people using a bike for each set of stations. This is the sum of the people using a shared-bike and the normal bike. For the no constraint alternative there is only a shared-bike available, which results in the fact that the utility in contrast with the other alternatives only consist of the utility for using a shared bike. This results in lower total utility values and lower mode shares. However, of the percentage that used the no constraint alternative, 100% used the shared bike.

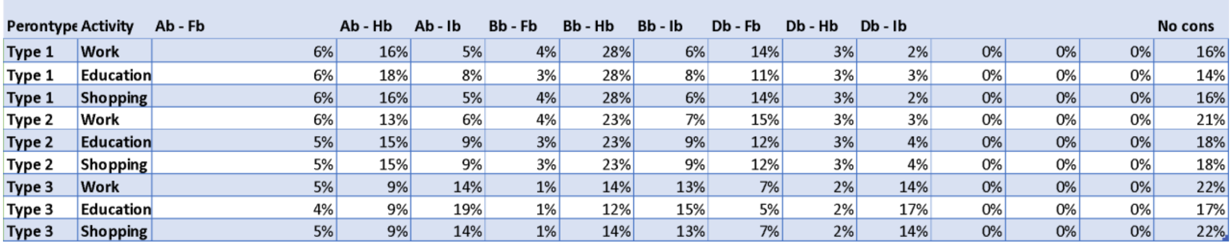
Given the result in the tables, the multimodal mode-choice distribution as shown in figure 7.23 and figure 7.24 is obtained. The effects are clearly noticeable. *The number of people returning the shared bike to station F decreased with 69. Of those travellers 39 people return the bike at station E and 30 people return the bike at station H.* The effect of leaving the round-trip constraint on the number of bike-sharing users is at this point limited. Only 15 extra travellers use the shared-bikes compared to the situation with the round-trip constraint in figure 7.20.

Table 7.33: Station choice distribution for the transport chain W-T-B including the no-constraint option

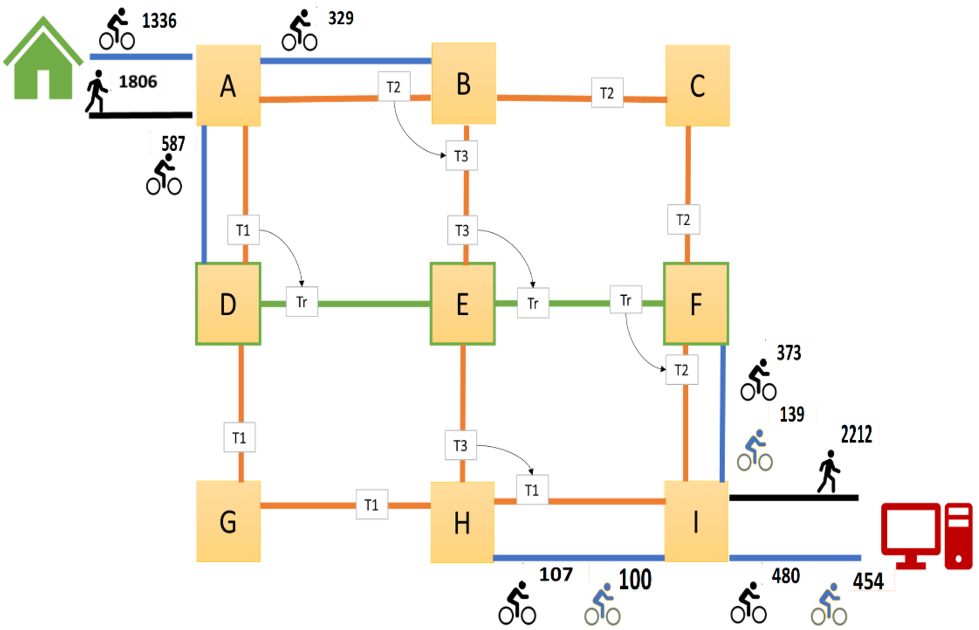


Persontype	Activty	A - Fb	A - Hb	A - Ib		No cons
Type 1	**Work**	44%	28%	12%	0%	16%
Type 1	**Education**	45%	44%	7%	0%	4%
Type 1	**Shopping**	47%	32%	14%	0%	7%
Type 2	**Work**	52%	26%	16%	0%	6%
Type 2	**Education**	51%	36%	9%	0%	4%
Type 2	**Shopping**	51%	36%	9%	0%	4%
Type 3	**Work**	33%	25%	30%	0%	12%
Type 3	**Education**	32%	26%	31%	0%	12%
Type 3	**Shopping**	31%	25%	32%	0%	12%

Table 7.34: Station choice distribution for the transport chain B-T-B including the no-constraint option

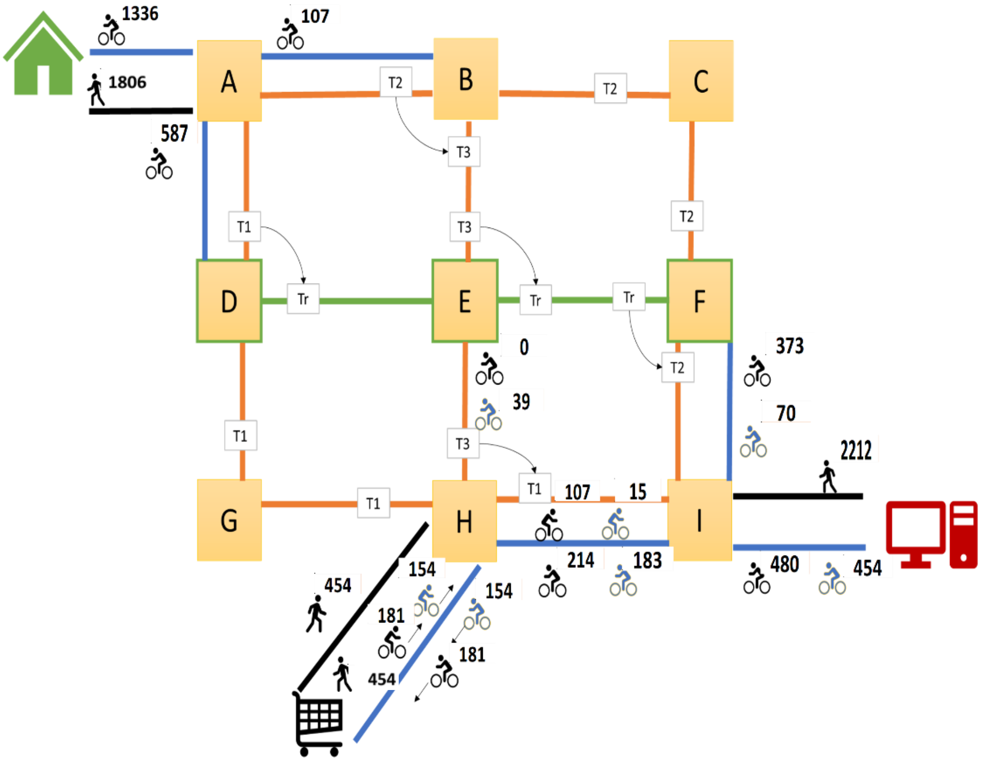


Perontype	Activity	Ab - Fb	Ab - Hb	Ab - Ib	Bb - Fb	Bb - Hb	Bb - Ib	Db - Fb	Db - Hb	Db - Ib				No cons
Type 1	**Work**	6%	16%	5%	4%	28%	6%	14%	3%	2%	0%	0%	0%	16%
Type 1	**Education**	6%	18%	8%	3%	28%	8%	11%	3%	3%	0%	0%	0%	14%
Type 1	**Shopping**	6%	16%	5%	4%	28%	6%	14%	3%	2%	0%	0%	0%	16%
Type 2	**Work**	6%	13%	6%	4%	23%	7%	15%	3%	3%	0%	0%	0%	21%
Type 2	**Education**	5%	15%	9%	3%	23%	9%	12%	3%	4%	0%	0%	0%	18%
Type 2	**Shopping**	5%	15%	9%	3%	23%	9%	12%	3%	4%	0%	0%	0%	18%
Type 3	**Work**	5%	9%	14%	1%	14%	13%	7%	2%	14%	0%	0%	0%	22%
Type 3	**Education**	4%	9%	19%	1%	12%	15%	5%	2%	17%	0%	0%	0%	17%
Type 3	**Shopping**	5%	9%	14%	1%	14%	13%	7%	2%	14%	0%	0%	0%	22%



Link	Mode	#Travellers
A-A	Walk	1806
I-I	Walk	2212
A-A	Bike	420
A-B	Bike	329
A-D	Bike	587
F-I	BIke	373
H-I	Bike	107
A-F	Transit	148
A-H	Transit	50
A-I	Transit	1579
B-F	Transit	19
B-H	Transit	48
B-I	Transit	262
D-F	Transit	206
D-H	Transit	9
D-I	Transit	372
F-I	S-B	139
H-I	S-B	100
I-I	S-B	216

Figure 7.23: Multimodal mode choice distribution in the morning with tour-based mode-chain approach (leaving the round-trip constraint)



Link	Mode	#Travellers
A-A	Walk	1806
I-I	Walk	2212
H-H egress	Walk	454
H-H access	Walk	454
I-I	Bike	0
I-H (station)	Bike	33
I-H (shopping)	Bike	181
I-F	Bike	266
H- H egress	Bike	0
H -H access	Bike	74
H-E	Bike	0
H-I	Bike	0
H-F	Bike	107
B-A	Bike	329
D-A	Bike	587
A-A	Bike	420
I-A	Transit	1252
H-A	Transit	125
F-A	Transit	148
I - B	Transit	402
H -B	Transit	121
F -B	Transit	19
I - D	Transit	508
H-D	Transit	63
F-D	Transit	186
I-I	S-B	216
I-H (station)	S-B	29
I-H (shopping)	S-B	154
I-F	S-B	55
H-H	S-B	0
H-H (Access	S-B	100
H-E	S-B	39
H -I	S-B	0
H-F	S-B	15

Figure 7.24: Multimodal mode choice distribution in the evening with the tour-based mode-chain approach (leaving the round-trip constraint). People that rented a shared-bike in F

7.4 CONCLUDING REMARKS

The case-study was performed to quantitatively illustrate the limitations of the two-step mode-choice approach used in Visum. Furthermore, it was possible to test if the tour-based mode-chain and station choice approach was capable of addressing the limitations of the two-step mode-choice approach. Conclusions can be drawn based on each of the scenarios.

7.4.1 MODELLING THE RELATION BETWEEN SB-BIKE-SHARING AND THE DEMAND FOR TRANSPORT

Promoting multimodal transport is used to make public transport more attractive. This can attract car travellers to use public transport. For this reason it is crucial for strategic transport models that they are able to estimate the relation between multimodal policy measures and the demand for public transport. Therefore, the first scenario was related to promoting the egress leg of multimodal tours by reducing the price of SB-bike-sharing.

The Visum model clearly shows its limitations. The pricing only affected the number of SB-bike-sharing users and did not affect the demand for public transport in any case. On the other hand the pre-specified mode-chain approach proved to be able to model effects of pricing on the public transport demand.

7.4.2 MODELLING THE EFFECT OF SOCIO-DEMOGRAPHICS ON THE DEMAND OF SB-BIKE-SHARING

The second scenario tested how both models deal with the fact that some person groups are more interested in multimodality compared to other user groups. More specifically, Students are more likely to use SB-bike-sharing compared to other groups. This means that the model must be able to consider that more students in the population also results in more SB-bike-sharing users.

Both models show an effect of the number of students on the public transport usage. Higher public transport usage leads in both models to an increase of SB-bike-sharing demand. In the Visum model the number of bike-sharing users increases proportional to the number of public transport users. In the tour-based mode-chain approach bike-sharing demand increases faster than the public transport demand.

For this reason there can be concluded that only in the tour-based mode-chain approach the relation between the number of students and the demand for SB-bike-sharing is explicitly modelled.

7.4.3 MODELLING MODE CHOICE CONSISTENCY

The last scenario was related to the mode-choice consistency limitation. Mode-choice consistency refers to the fact that the transport model considers in each stage of the tour what transport modes are available. Furthermore mode-choice consistency can constraint people in their available travel alternatives. This can for example be because people have to return to a station that is used earlier in a tour. It is tested for both models when the input attributes of the evening trip change compared to the morning trip, if they still have consistent results.

The base scenario assumes that people only perform simple tours (“home-activity-home”). Furthermore, the travel times for the outgoing and the returning trip were exactly similar. With these circumstances, both modelling approaches showed that all travellers which used SB-bike-sharing in the morning returned to the same station in the evening.

When the travel times of a public transport line increased only for the evening trip, the Visum model showed an increase of the number of bike-sharing users in the evening, while the number of bike-sharing users in the morning kept constant. Therefore, people that did not have a bike available, were using a bike according to the model. On the other hand the tour-based mode-chain model proved to have consistent results. Higher travel times in the evening resulted in a higher share of bike-sharing users for the morning trips as well as the evening trip. Furthermore, all bikes were returned to the station where they are rented.

For more complex tours the problem becomes even more evident for the Visum model. When people perform a sub-activity in a zone which is close to the main-activity, theoretical sound behaviour would be that people having a bike available, would bike from the main-activity to the sub-activity before returning to the station. The Visum model predicts zero travellers performing this behaviour, whereas the tour-based mode-chain model considers that a significant share of the travellers choses this alternative. The tour-based mode-chain model was also able to model consistency in the station choice.

Besides, the tour-based mode-chain model also proved that it is possible to test policy scenarios to see if it is interesting to leave the round-trip constraint. Currently, the model did not expect a significant effect of this policy measure.

All in all, it can be concluded that the tour-based mode-chain approach is able to address the limitations of the current two-step mode-choice approach used in Visum.

8. CONCLUSIONS AND RECOMMENDATIONS

This chapter will summarize the main conclusion found in this research and will discuss some research limitations and recommendations for future research. The starting point of this research was to use SB-bike-sharing as an interesting and tangible case-study to address a limitation of the modelling software P.T.V Visum 2021. More specifically, this study focussed on the method that P.T.V Visum uses to combine multimodality and tour-based mode choice. Conclusion can be drawn regarding the research objectives.

First of all it can be concluded that this study has quantitatively illustrated that the current Visum two-step mode-choice approach has limitations to combine multimodality and tour-based mode choice. This is shown by implementing SB-bike-sharing in the current modelling setup and testing three relevant scenarios on a small-scale theoretical case-study. There are limitations to model multimodal mode-choice consistency, to model heterogeneity in travel preferences in the population and to model the relation between promoting multimodality and the demand for public transport.

For this reason a new approach is created to model the combination of multimodality and tour-based mode choice. The new approach is called the "tour-based mode-chain and station choice approach" (in short tour-based mode-chain approach). This is because it pre-defines multimodal mode-chains at tour level. Besides, the model explicitly considers station choice at tour level.

Given the three relevant scenarios regarding SB-bike-sharing tested on a small case-study it can be concluded that the "tour-based mode-chain and station choice approach" is capable of addressing the limitations of the current two-step mode choice approach. For this reason the new approach is from a theoretical perspective better capable to model the combination of tour-based mode choice and multimodality and is therefore more appropriate to model SB-bike-sharing.

The next paragraph will start off with summarizing all research findings by answering the set of research questions that are formulated in the introduction. This next paragraph also explains the conclusions about the research objectives more in depth. Then the limitations of the tour-based mode-chain modelling approach are discussed from a theoretical perspective. Afterwards, some practical considerations are discussed for applications of the new modelling approach. There is then also elaborated about the possibilities of modelling SB-bike-sharing in practice. Lastly, there is discussion about what future research is needed to further explore the opportunities of the new modelling approach.

8.1 THE MAIN RESEARCH FINDINGS

This paragraph will summarize the main finding of the research based on the set of research questions that is formulated in the introduction.

How to create an approach that combines multimodality and tour-based mode choice in order to realistically implement SB-bike-sharing in strategic transport models?

1. *What are the modelling requirements to realistically model SB-bike-sharing?*
2. *How can SB-bike-sharing be implemented in the Visum modelling approach?*
3. *What are the limitations of the Visum modelling approach looking at the requirements to model SB-bike-sharing?*
4. *How to create an approach that combines multimodality and tour-based mode choice?*
5. *Is the created modelling approach able to address the limitation of the current Visum approach to model SB-bike-sharing?*

1. *What are the modelling requirements to realistically model SB-bike-sharing?*

First of all, the model must be tour-based. A tour is defined as a trip chain starting at some location and eventually returning to the same location after a series of trips to perform activities (Hasnine & Nurul Habib, 2020).Modelling tours instead of trips makes it possible to capture consistency between multiple trips within a tour in order to model the fact that a person which uses a bike for the outgoing trip has to return the bike later in the tour.

Secondly, the model must be multimodal**.** "Multimodal trips are trips using two or more vehicular modes between which a transfer is necessary" . SB-bike-sharing functions as a last-mile alternative for public transport. Therefore, bike-sharing has to be modelled, considering characteristics of the complete multimodal tour. This means that policies regarding SB-bike-sharing influence the demand for public transport and vice versa.

Lastly, the model should be disaggregated. Modelling disaggregated means that the decision making unit in the model are groups of people with the same characteristics from a certain area. Modelling disaggregated is needed to model heterogeneity regarding perceptions about SB-bike-sharing. Different socio-demographics can greatly influence the chance if someone uses SB-bike-sharing.

2. How can SB-bike-sharing be implemented in the Visum modelling approach?

SB-bike-sharing is implemented in a created model in Excel using the modelling procedure used in P.T.V Visum 2021 to illustrate that this modelling approach has some limitations regarding the combination of the aforementioned modelling requirements. The model uses a two-step mode-choice approach to combine multimodality and tour-based mode choice. In this approach people first make a choice for a main transport mode that is used for the complete transport tour. Conditioned to this choice people make a choice on trip-level about multimodal trips. So on tour level the model calculates the share of people that choses public transport versus the car. Then for all people that use public transport the model calculates what multimodal trips people make. This means for example that the number of people that use a bike to reach a station is calculated in the second step of the mode-choice approach.

It is assumed that SB-bike-sharing is only used for multimodal transport. This means that SB-bike-sharing is modelled in the second step of the two step-mode choice approach. SB-bike-sharing is implemented by adding new transfer links between public transport and the biking network to the multimodal transport network. The transfer links contain information about the transfer time, the transfer cost and the resistance to transfer between public transport and SB-bike-sharing. The information about the transfer resistance is represented by a penalty for SB-bike-sharing in the utility function of multimodal routes. With the added transfer link the route-set generation will find paths that use SB-bike-sharing. Based on the travel utility of the multimodal paths that use SB-bike-sharing compared to other path alternatives, it can be calculated what share of people uses the system.

3. **What are the limitations of the Visum modelling approach looking at the requirements to model SB-bike-sharing?**

There are some limitations to realistically model SB-bike-sharing in the two-step mode choice approach used in Visum. For each of the limitations there is explained why the limitation exists given the modelling structure and there is given quantitative evidence of the problem based on a small-scale case study. The case-study used a theoretical multimodal transport network containing 9 nodes.

The consistency limitation means that there is no consistency in the use of SB-bike-sharing. In reality, a person that uses SB-bike-sharing for the egress part of an outgoing trip, has to return the bike later in the trip to the same station. When there is no consistency, the person that used a bike could leave the bike at the activity location or could return the bike to another station. The problem occurs because multimodality is modelled at trip-level instead of tour-level. The main mode choice is on tour level, this gives consistency for the main-mode. People that go to work by car will also use the car to return from work. However, because multimodality is modelled at trip level, the consistency between access and egress modes within a tour is not explicitly modelled.

The case study further illustrated this problem. First a scenario is analysed for a simple tour. A simple tour refers to tours that assume that a person leaves home to perform one activity and then directly returns home again. When the travel-times for the outgoing and returning trip are completely similar, the model calculates consistent results. However, when the travel time for the evening trip is adjusted by increasing the travel time from a public transport link, the problem becomes evident. Due to the increased travel time of the public transport line, more people decide to use SB-bike-sharing as an alternative during the evening trip. At the same time, the number of bike-sharing users in the morning kept constant. Therefore, people that did not have a shared-bike available, were using a bike according to the model.

In reality, people also perform more complex tours. Complex tours refer to tours where people perform multiple activities before returning home (home-work-shopping-home). When modelling complex tours more limitations from the Visum approach become evident. When people perform a sub-activity in a zone which is close to the main-activity, theoretical sound behaviour would be that people having a bike available, would bike from the main-activity to the sub-activity before returning to the station. The Visum model predicts zero travellers performing this behaviour.

The aggregation limitation means that the model cannot consider person type specific preferences when modelling the demand for SB-bike-sharing. For this reason the model cannot consider that students are more likely to use the system compared to other person groups. The aggregation problem occurs because the person specific and activity purpose specific matrices are aggregated (summed) to one matrix before the trip-based multimodality is modelled. When modelling the main-mode choice on tour-level, the model is disaggregated. So at this stage, persontype specific travel behaviour can be taken into account. However, between the main-mode choice step and the multimodal mode-choice step the matrices are aggregated, leading to the aggregation problem.

The case study illustrated this problem by looking at the effect of changes in the socio-demographics in the population. The case-study used three person types; working people without a car (type 1); working people with a car (type 2) and student without a car. Students are relatively attracted to public transport, multimodality and bike-sharing. Person type 2 is mainly interested in using the car. The case-study analysed the effect of increasing the number of students while decreasing the number of people that have a car available (type 2).

The changed socio-demographics resulted in an increase of public transport usage. As a result, also the number of SB-bike-sharing users increased. However, the number of bike-sharing users only increased proportionally to the number of public transport users. This means that the relation between the number of students and the usage of SB-bike-sharing is not explicitly modelled.

The travel demand problem refers to the fact that the model does not consider the relation between SB-bike-sharing and the demand for public transport. Promoting SB-bike-sharing is an interesting policy measure to increase public transport ridership. Nevertheless, the effect of this kind of policy measures cannot be tested with the current Visum approach due to the travel demand problem. The travel demand problem exists because of the assumption that is made about the attributes assigned to the skim-matrices to model the main-mode-choice . It is assumed that the value assigned to the skim-matrices is based on the path with the lowest weighted cost that only uses the unimodal public transport network. This means that the path only combines walking and public transport to calculate the share of people that use public transport.

The case study illustrated the travel demand problem by decreasing the price for SB-bike-sharing. The Visum model clearly shows its limitations. The pricing only affected the number of SB-bike-sharing users and did not affect the demand for public transport in any case. Even when SB-bike-sharing was free of charge there was no change in the public transport demand.

All problems discussed can be generalised to other multimodal transport concepts and policies. The consistency problem is also a problem for park and ride facilities and for normal bikes. The aggregation problem is for all multimodal transport relevant. Some groups use more multimodal transport alternatives compared to others. Therefore socio-demographics can be an important explanatory variable for the amount of multimodal transport that is used in a particular area. Because of the aggregation problem the models miss out on explanatory power regarding multimodality. The travel demand problem is relevant for all promoting policies regarding SB-bike-sharing. Examples of such policies are smooth transfers in park and ride facilities or improved biking lanes towards stations.

4. How to create an approach that combines multimodality and tour-based mode choice?

The previous sub-question discussed the problems of the Visum modelling approach. To address these problems, this study proposes "the tour-based mode-chain and station choice approach". The main difference compared to the Visum approach is that components that need consistency on tour-level are modelled at tour-level instead of trip-level. The model uses a set of discrete choices. The discrete choices are based on Random utility maximization principles. The choices upstream are all calculated based on the expected utility of choices downstream (Logsum). The decision making unit for the discrete choices are groups of people with the same characteristics (each person type). There is a set of three discrete choices

- **The first choice** is what **pre-specified mode-chain** is used. It is assumed that there is only a limited number of multimodal mode combinations available. For this study the mode combinations used are: walk/public transport/walk, bike/public transport/walk, walk/public transport/bike and bike/public transport /walk. This means that the set of pre-specified modes is used in a tour. The walk/public transport/bike chain refers to a tour that uses walking at the access-side of a tour, public transport as its main transport mode and biking at the activity-side of a tour.
- **The second choice** is the **station choice**. People that use a (shared) bike to reach a station have to return to the same station as they used earlier in a tour. Consequently, the station choice has to be optimized at tour level in order to find the most efficient station considering the complete tour.
- **The last choice** is about using a **normal bike or SB-bike-sharing**.

The model performs the discrete choice models for complete tours. The input is derived from a shortest path algorithm through a constrained tour-based transport network. The optimization process is constrained per station and mode-chain. In the end this leads to attributes for each combination of stations and mode-chain that is available in the choice-set. To find the available stations, the model looks at a maximal travel-time radius with the bike and what stations are available for each origin and destination. When the optimal path is found for each station, the method reviews if an alternative is dominated by another alternative. In this way, only relevant stations are considered in the choice model.

5. **Is the created modelling approach able to address the limitation of the current Visum approach to model SB-bike-sharing?**

The tour-based mode-chain approach is tested on the same case-study compared to the Visum approach. This gives the opportunity to compare if the new approach is able to address the mentioned set of limitations. The results of the three scenarios were very promising:

- First of all, the case study **proves that the tour-based mode-chain approach can deal with the consistency problem**. For the simple tour as well as the complex tour, the model gives consistent results. All bikes that are rented during the morning trip are returned in the evening trip at the same station. When increasing the travel-time of an important public transport link for the evening trip, it results in more bike-sharing demand during the morning trip. Hence, people consider the complete tour when making a decision about the use of SB-bike-sharing. This also means that the model assumes that travellers have full information about the transport tour they will perform when making a decision about their morning trip.
  In the complex tours the model can handle situations where people have a bike available at the egress-side of a public transport tour and perform a sub-activity close to their main activity. As you would expect, the optimal paths assume that a person bikes from the main-activity to the sub-activity before returning to the station.

- Secondly, the case study **proves that the tour-based mode-chain approach can deal with the aggregation problem.** When the number of students increases the model considers an increase of public transport usage as well as an increase of SB-bike-sharing usage. This means that the number of SB-bike-sharing increases faster compared to the number of public transport travellers. When the number of students increased from 2000 to 2500 the number of public transport tour increased with 13%, at the same time the number of SB-bike-sharing users increased with 23%.

- Lastly, the case study **proves that the tour-based mode-chain approach can deal with the travel demand problem.** When the price of SB-bike-sharing decreased, the model estimated a significant increase in public transport demand. When SB-bike-sharing is free of charge, public transport ridership increased 16% compared to the situation with the normal price (€3,85). At the same time, free SB-bike-sharing results in 63% of the travellers that would use the shared-bike for their egress trip leg. There is no hard-data available to estimate at this point if these are realistic quantitative effects. The increase of public transport use seems unrealistic, as it is hard to change travel habits. For this reason people are normally not very willing to switch from the car to public transport. The increase of SB-bike-sharing use could be realistic. There is a stated preference research that indicates for a popular public transport line in Utrecht that 60% would be willing to switch to SB-bike-sharing when it is free of charge (Steegnan, 2016).

The results of the case study show that the two research objectives formulated in the introduction are fulfilled.

1. *Implementing SB-bike-sharing in a two-step mode-choice approach to quantitatively illustrate the limitations of modelling tour-based mode choice and multimodality in Visum.*
2. *Create an approach to combine tour-based mode choice and multimodality in order to address the limitations of the current Visum modelling approach.*

The implementation of SB-bike-sharing to the current two-step mode-choice approach in Visum gave limitations concerning modelling consistency, modelling heterogeneity in travel preferences in the population and modelling the relation between policy measures to promote multimodality and the demand for public transport. Therefore the tour-based mode-chain and station-choice approach was designed. The new approach is tested on a case-study regarding SB-bike-sharing and proved to be able to address the set of limitations. Nevertheless, the tour-based mode-chain and station choice approach used in this study comes with its own limitations. These limitations are discussed in the next paragraph.

8.2 STUDY LIMITATIONS

There are a set of limitations regarding the new tour-based mode-chain and station choice approach. There are limitations concerning the assignment method used in this study, there are no capacity and congestion effects modelled and there are also some limitations about the current way of modelling multimodality.

8.2.1 FREQUENCY BASED ASSIGNMENT METHOD

The tour-based mode-chain and station choice approach uses a frequency-based representation of the public transport network. The approach uses a shortest-path algorithm to find an optimal tour in the frequency-based network. Frequency-based assignment procedures can have its limitations to calculate travel times of public transport trips and tours. This is due to the fact that transfer times between multiple public transport lines can be over- or underestimated. There are two reasons for this. First the time-table is not explicitly considered. In reality, low frequent services can be perfectly connected, resulting in low transfer time. These kinds of dynamics are not considered in frequency-based assignments. Besides, the frequency-based assignment does not consider the common lines problem. The common lines problem means that when there are multiple lines available to travel between a set of transit stops, there are also multiple vehicles that a passenger could board to reach its destination. Hence, the waiting time in that case depends on the combined service frequency of the attractive lines (Tan, 2016). Given the set of limitations of the frequency-based assignment it is interesting to see if the tour-based mode-chain and station choice approach is also capable of handling other assignment structures.

8.2.2 THE STATION CHOICE ALGORITHM AND AVAILABLE MODE-CHAINS IN THE CHOICE SET

The second limitation is regarding the computational efficiency of the model. The size of the choice set for each origin and destination is an important determinant for the computational efficiency of the tour-based mode-chain approach. This is because for each combination of stations and mode-chains the approach searches for an optimal tour. As a consequence, limiting the choice-set is an important challenge for this approach.

To start with, this has implications for the algorithm that is used to find the possible stations for each origin and destination. In this research it is assumed that each station that is within a certain radius from an origin and destination and has bike-parking facilities is added to the possible station set. Some stations are considered more attractive compared to others, therefore two types of stations were distinguished. In the small-scale case-study this was a feasible assumption as the number of available stations was limited. However, in case of a real-size network in an urbanized area the number of available stations could grow substantially.

Furthermore, it has consequences for the number of possible mode-chains that can be considered. Each available mode-chain leads to a new set of stations. Each extra station leads to a new tour that must be optimized. In reality, multimodality does not only concern combinations of the bike and public transport as this research assumes. People could as an example use a car to reach a park and ride facility. The catchment area to reach stations increases significantly when using a car. So also considering the car in the pre-specified mode-chains would already increase the choice set substantially. It is crucial for further application to find a balance between mode-chains that need to be considered to replicate reality on one side and keep the model computationally feasible on the other side.

8.2.3 LIMITATIONS REGARDING MODELLING MULTIMODALITY

In paragraph 4.4 challenges to model multimodality were described. The tour-based mode-chain approach has some limitations regarding the modelling challenges. First of all, because the available set of possible multimodal tours is pre-specified in mode-chains it is not possible to consider the full range of mode combinations.

Another challenge was that the route-choice and mode-choice become correlated when modelling multimodality. The tour-based mode-chain approach can partly deal with this challenge. The mode choice and route-choice are separate choices. However, the station-choice is an important element within the route-choices. The station choice and the mode-choice are correlated in the tour-based mode-chain approach.

Multimodal transport choices involve many extra choice dimensions, such as choosing access and egress modes and boarding and alighting stations. The higher number of choice dimensions and travel alternatives also leads to more complex correlation structures between unobserved factors of different travel alternatives. These correlation structures are not completely considered in the tour-based mode-chain approach. The choice between a set of stations uses a path-size logit. This means that for the station choice the model does consider correlations on link level between multiple paths. However, the choice between the different mode-chains uses a nested logit. Hence, it cannot be considered that some mode-chains share more characteristics in their paths and stations choices compared to others.

The last important limitation is regarding capacity constraints in transfer facilities. In case of SB-bike-sharing this refers to capacity problems of the system. Shared-bikes can be out of stock, meaning that people have to use another facility or transport mode. This aspect is not considered in the current model, this is caused by the fact that the model only uses a single iteration to determine the transport demand. When there are multiple iterations, the demand in the first iteration influences the resistance to use SB-bike-sharing in the second iteration until convergence is reached. This way, capacity constraints could be considered. For the road-network multiple iterations make it possible to model congestion effects. Congestion can be a reason to switch to multimodal transport options. For this reason, considering congestion in the road-network by performing multiple iterations is also relevant to model multimodality.

8.3 CONSIDERATIONS FOR USING THE TOUR-BASED MODE-CHAIN APPROACH IN PRACTICE

Given the set of limitations of the two-step mode-choice approach and the promising results of the tour-based mode-chain approach it is relevant to discuss some practical considerations about this study for transport planning practice. The choice for a transport model or to change a modelling approach is always about finding a balance between modelling urgency and extra modelling effort. This paragraph will first discuss the importance of the limitations of the current Visum modelling approach. Then considerations are discussed about feasibility of the new modelling approach. Lastly there is discussed how the model could be integrated to the current model of Visum.

8.3.1 MODELLING URGENCY OF THE TOUR-BASED MODE-CHAIN APPROACH

First of all, it is important to know all application areas of the mentioned limitations. The consistency problem is relevant for all modes that are used to access or egress public transport and urges people to return to the same station later in the tour. The most apparent examples of this are park and ride facilities and normal bikes. For “free floating” shared mobility or ride-sharing this problem is for example not relevant. The aggregation problem is relevant for all multimodal transport. When the matrices are not aggregated before multimodality is handled, there is more explanatory power to estimate travel behaviour. Lastly, the travel demand problem is relevant for all policy measures regarding multimodal transport. Examples of such policies are smooth transfers in park and ride facilities or improved biking lanes towards stations.

Then one must consider the criticalness of the problems. This gives insights about future research directions:

- For the consistency problem there must be reviewed if the current Visum model has dissimilarity between the multimodal morning demand and evening demand. Furthermore it is interesting to know the amount of transport tours that use the bike to reach multiple activities before returning to the station. This is because the limitation of the current Visum modelling approach is most apparent when modelling this kind of complex tours.
- For the aggregation limitation it is relevant to research if the fact that heterogeneity is not considered when modelling multimodality does have implication for the modelling results.
- For the travel demand problems research on the elasticity of access and egress trip legs to the demand of public transport and road traffic is relevant. When there is no elasticity between policy measures regarding multimodality and the demand for the main transport mode, there is also not a problem regarding the Visum model.

8.3.2 MODELLING EFFORT

Modelling effort is assessed from a computational perspective, a storage perspective and from a data needs and model estimation perspective.

The computational effort depends on the effort of performing a shortest path search in the transport network and the number of shortest path searches that has to be performed. As elaborated, the number of mode-chains and stations considered determines the number of optimizations (shortest path searches) that is performed per origin and destination pair. For all mode-chains that only have to optimize one station choice (W-T-B and B-T-W), the number of optimizations increases linearly with the number of stations. Limiting the number of available stations is most relevant for the B-T-B mode-chain. The number of optimizations increases quadratically with the number of stations available at each side of the transport trip. To give a rough example about the number of extra optimizations that has to be performed per OD pair we assume that the four mode-chains as used in this study and that each origin and destination have three potential stations. This would give $(1+3+3+3^2)*4=43$ optimizations that have to be performed per OD pair. This also demands more storage capacity from the models. All optimizations have to be saved in skim-matrices to calculate the utilities in a later step.

The shortest path algorithm itself also becomes computationally more challenging. This is because the network is copied as many times as there are activities in a specific transport tour. Therefore the network-size can increase substantially. To limit the number of possible alternatives, it could be beneficial to generate SKIM-matrices for the public transport network between each set of stations in advance. Compared to other modelling approaches the tour-based mode-chain approach has a computational advantage in the fact that it does rely on a route-set generation. This is because it only uses the shortest path.

From a data needs perspective the model does not give significant changes compared to the input data in the current Visum modelling approach. Estimating the model seems also feasible. For each discrete choice the model can use the model output for parameter estimation. When there is for example data available about the occurrence of each mode-chain the model can calibrate the percentages obtained from the model.

8.4 FUTURE RESEARCH DIRECTIONS

Future research is suggested to address some of the mentioned set of limitations and to get more insights about the practical considerations. Furthermore it would be interesting to use another application area. Therefore new research is suggested to model park and ride facilities with the tour-based mode-chain approach. For park and ride facilities modelling congestion becomes an even more relevant topic. Consequently, modelling the park and ride facilities is a good opportunity to test whether the model is capable of dealing with an iterative assignment.

For future work there is also suggested to reconsider the method that is used to create the station-set for each origin and destination. The method should be able to estimate the attractivity of each station for a specific origin a destination. An important example is that when two stations have the same characteristics and are serving the same set of public transport lines people would always chose to bike to the station that is closer to their home or destination. Currently the tour-based mode-chain approach does filter this kind of irrelevant stations when testing dominance criteria. However, this means that the method already optimized the complete tour for a station that is irrelevant. Filtering this kind of stations before performing the optimization is essential in real-size networks.

Given the set of limitation of the frequency-based assignment it is interesting to see if the tour-based mode chain and station choice approach is also capable of handling other assignment structures. An interesting option is to use hyper-paths between each set of stations. The expectation is that the generation of multimodal transport tours must be calculated in two stages. First the generalised cost based on the hyper paths between each set of stations is calculated and saved in skim-matrices. Than based on the travel times between each set of stations, the utility of the complete tour is minimized. Performing the multimodal tour distribution in two steps also makes it computationally less challenging to find a shortest path in the tour-based network. Since, the travel time between a set of stations is already established, the number of different travel alternatives decreases significantly.

To get more insights about the practical applicability of the tour-based mode chain approach there is suggested to test the model on a real case-study and to create a full consistent model instead of modelling only one single Origin and Destination relation.

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APPENDICES

APPENDICES A – EXPERT INTERVIEWS

The following list gives an overview of expert in the field of Transport planning that were interviewed to obtain more knowledge about current practice in strategic transport modelling. The performed interviews were used to see what modelling requirements are needed to model SB-bike-sharing.

Frank Hofman – Senior Advisor strategic transport models – Rijkswaterstaat
Reason for interview: Getting insights about The Dutch national and regional strategic transport models LMS and NRM.
Topics: *The level of disaggregation/modelling multimodality/Implementing shared-mobility to LMS*

Maaike Snelders – Prinicple Scientes – TNO
Reason for interview: Learning about Feathers, the Activity-based transport model for Rotterdam
Topics: *Reason for activity-based models/applicability of activity-based models/combining activity-based modelling with a macroscopic assignment/implementing shared-mobility to the model.*

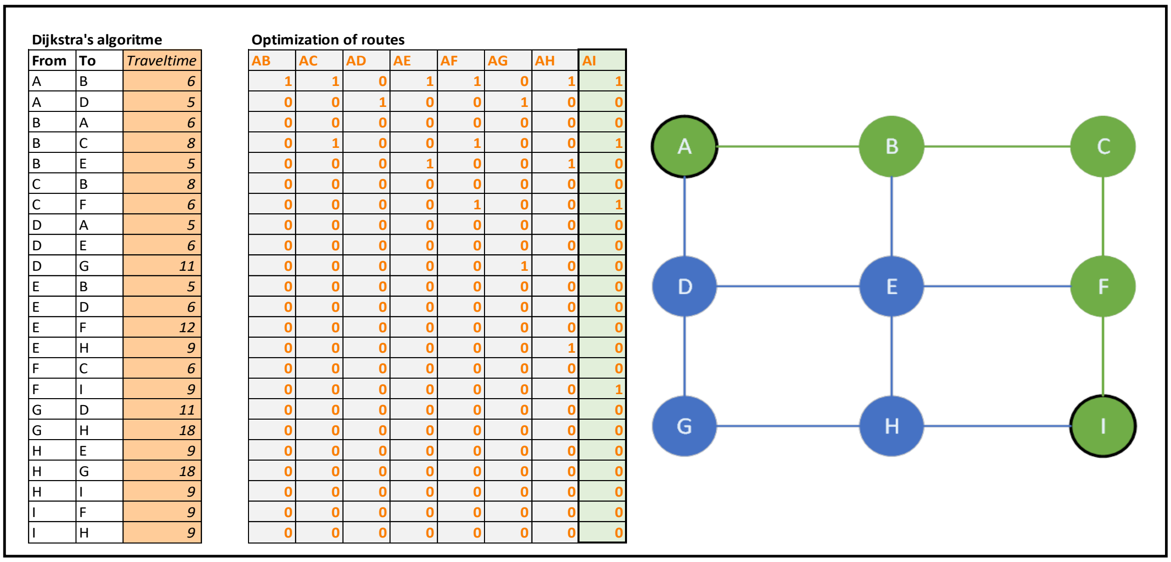
Gijs van Eck and Rick van Grol – Advisors – Significanse
Reason for interviews: Implementing MaaS to LMS and NRM and getting insight about the super network approach.
Topics: *Technical advantages of the super network approach/Applicability problems super network approach/Maas and shared-mobility in LMS and NRM/Tour-based modelling*

Guus Tamminga – Advisor – Sweco
Reason for interview: Learning about Stravem, a strategic transport model that combines multimodality and tour-based mode choice.
Topics: *Tour-based molling/Combining tour-based modelling and multimodality (Two-step mode chocie approach)/level of dissaggregation.*

APPENDICES B – CALCULATING THE MAIN MODE CHOICE

B.1 SKIM MATRICES

The optimization process in Excel for the car is presented in figure B1. The cost C (vw) to travel between each node v and w is derived from the input about the transport network. For each set of origins (i) and destinations (j) in the table "optimization of nodes" there is indicated what links X(vw) are part of the shortest path. The objective function is to minimize the sum of the products (SUMPRODUCT() in Excel) of all links X(vw) and costs C(vw). In Excel, optimization problems can be handled with the solver tool. As an illustration, the shortest path from A to I is visualised in the transport network in figure B.1.



Dijkstra's algoritme

From	To	*Traveltime*
A	B	*6*
A	D	*5*
B	A	*6*
B	C	*8*
B	E	*5*
C	B	*8*
C	F	*6*
D	A	*5*
D	E	*6*
D	G	*11*
E	B	*5*
E	D	*6*
E	F	*12*
E	H	*9*
F	C	*6*
F	I	*9*
G	D	*11*
G	H	*18*
H	E	*9*
H	G	*18*
H	I	*9*
I	F	*9*
I	H	*9*

Optimization of routes

AB	AC	AD	AE	AF	AG	AH	AI
1	1	0	1	1	0	1	1
0	0	1	0	0	1	0	0
0	0	0	0	0	0	0	0
0	1	0	0	1	0	0	1
0	0	0	1	0	0	1	0
0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	1
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Figure B.1: Finding the shortest path in the car network

The optimization processes of the bike and walk network work similarly to the car network. As mentioned, the transit network is a bit more complicated as it has discontinues services. To model the fact that a link between a set of nodes is served by a specific transit line, the number of the transit line is included before the letter of the node as can be seen in figure B.3. The connection from A to B with line 2, is presented as a connection 2A to 2B. The connection from B to E is a presented as 3B to 3E. This way it is not automatically possible to travel from A to E. First one has to make a transfer in B. A transfer means that the number in front of the letters changes. In the case of the transfer in B, the transfer is from 2B to 3B as shown in figure B2.. The transfer links contain information about transfer times, the transfer penalty and starting cost for the new transit leg. Like with the car network the impedance function is optimized. In this case, this means that each link X (vw) is now multiplied with all factors in the impedance function and then summed over all links X(vw).

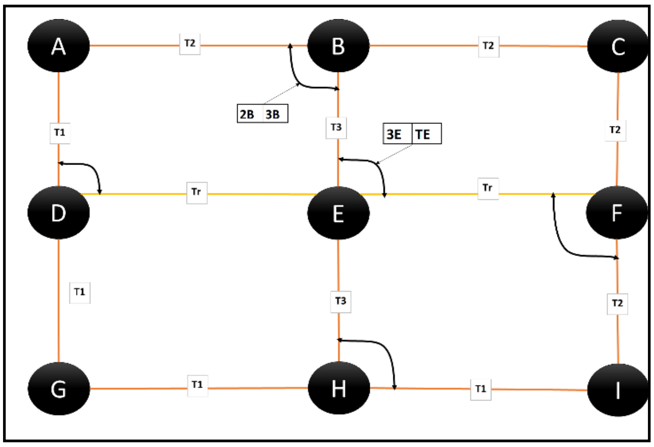
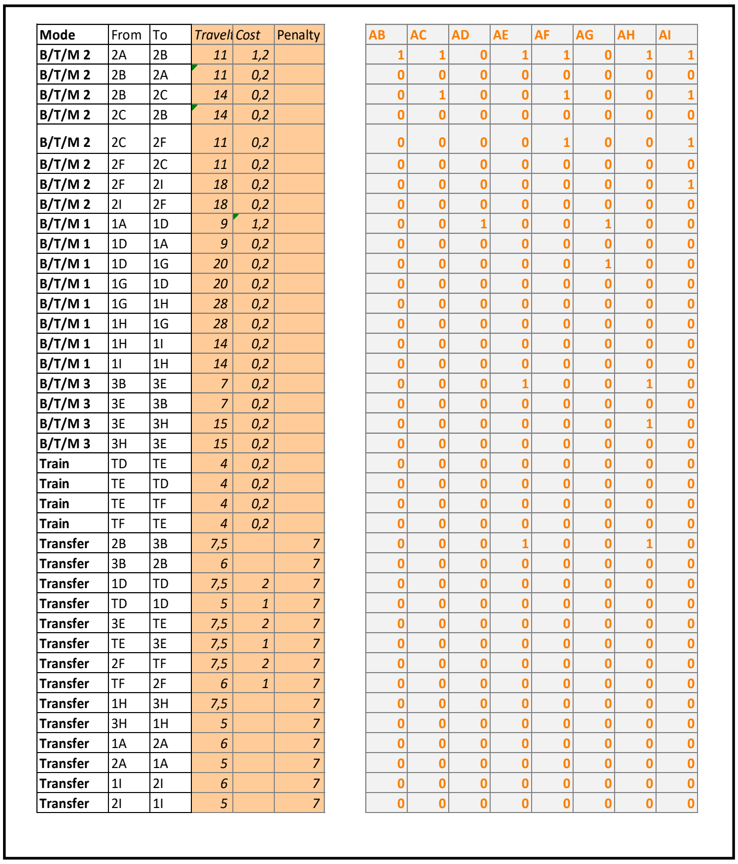


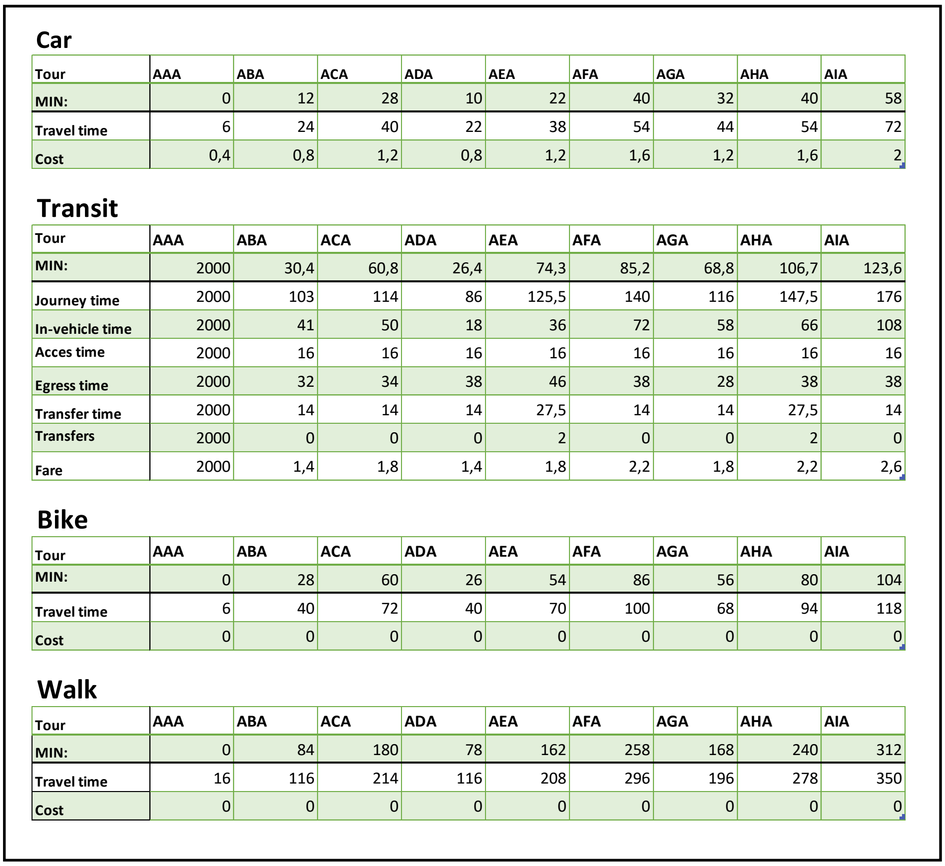
Figure B.2: The transit network with transfer links



Mode	From	To	Travelt	Cost	Penalty	AB	AC	AD	AE	AF	AG	AH	AI
B/T/M 2	2A	2B	*11*	*1,2*		1	1	0	1	1	0	1	1
B/T/M 2	2B	2A	*11*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 2	2B	2C	*14*	*0,2*		0	1	0	0	1	0	0	1
B/T/M 2	2C	2B	*14*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 2	2C	2F	*11*	*0,2*		0	0	0	0	1	0	0	1
B/T/M 2	2F	2C	*11*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 2	2F	2I	*18*	*0,2*		0	0	0	0	0	0	0	1
B/T/M 2	2I	2F	*18*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 1	1A	1D	*9*	*1,2*		0	0	1	0	0	1	0	0
B/T/M 1	1D	1A	*9*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 1	1D	1G	*20*	*0,2*		0	0	0	0	0	1	0	0
B/T/M 1	1G	1D	*20*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 1	1G	1H	*28*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 1	1H	1G	*28*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 1	1H	1I	*14*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 1	1I	1H	*14*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 3	3B	3E	*7*	*0,2*		0	0	0	1	0	0	1	0
B/T/M 3	3E	3B	*7*	*0,2*		0	0	0	0	0	0	0	0
B/T/M 3	3E	3H	*15*	*0,2*		0	0	0	0	0	0	1	0
B/T/M 3	3H	3E	*15*	*0,2*		0	0	0	0	0	0	0	0
Train	TD	TE	*4*	*0,2*		0	0	0	0	0	0	0	0
Train	TE	TD	*4*	*0,2*		0	0	0	0	0	0	0	0
Train	TE	TF	*4*	*0,2*		0	0	0	0	0	0	0	0
Train	TF	TE	*4*	*0,2*		0	0	0	0	0	0	0	0
Transfer	2B	3B	*7,5*		*7*	0	0	0	1	0	0	1	0
Transfer	3B	2B	*6*		*7*	0	0	0	0	0	0	0	0
Transfer	1D	TD	*7,5*	*2*	*7*	0	0	0	0	0	0	0	0
Transfer	TD	1D	*5*	*1*	*7*	0	0	0	0	0	0	0	0
Transfer	3E	TE	*7,5*	*2*	*7*	0	0	0	0	0	0	0	0
Transfer	TE	3E	*7,5*	*1*	*7*	0	0	0	0	0	0	0	0
Transfer	2F	TF	*7,5*	*2*	*7*	0	0	0	0	0	0	0	0
Transfer	TF	2F	*6*	*1*	*7*	0	0	0	0	0	0	0	0
Transfer	1H	3H	*7,5*		*7*	0	0	0	0	0	0	0	0
Transfer	3H	1H	*5*		*7*	0	0	0	0	0	0	0	0
Transfer	1A	2A	*6*		*7*	0	0	0	0	0	0	0	0
Transfer	2A	1A	*5*		*7*	0	0	0	0	0	0	0	0
Transfer	1I	2I	*6*		*7*	0	0	0	0	0	0	0	0
Transfer	2I	1I	*5*		*7*	0	0	0	0	0	0	0	0

Figure B.3: finding the shortest path in the transit network

The attributes from the generated shortest paths are saved in skim-matrices.



Car

Tour	AAA	ABA	ACA	ADA	AEA	AFA	AGA	AHA	AIA
MIN:	0	12	28	10	22	40	32	40	58
Travel time	6	24	40	22	38	54	44	54	72
Cost	0,4	0,8	1,2	0,8	1,2	1,6	1,2	1,6	2

Transit

Tour	AAA	ABA	ACA	ADA	AEA	AFA	AGA	AHA	AIA
MIN:	2000	30,4	60,8	26,4	74,3	85,2	68,8	106,7	123,6
Journey time	2000	103	114	86	125,5	140	116	147,5	176
In-vehicle time	2000	41	50	18	36	72	58	66	108
Acces time	2000	16	16	16	16	16	16	16	16
Egress time	2000	32	34	38	46	38	28	38	38
Transfer time	2000	14	14	14	27,5	14	14	27,5	14
Transfers	2000	0	0	0	2	0	0	2	0
Fare	2000	1,4	1,8	1,4	1,8	2,2	1,8	2,2	2,6

Bike

Tour	AAA	ABA	ACA	ADA	AEA	AFA	AGA	AHA	AIA
MIN:	0	28	60	26	54	86	56	80	104
Travel time	6	40	72	40	70	100	68	94	118
Cost	0	0	0	0	0	0	0	0	0

Walk

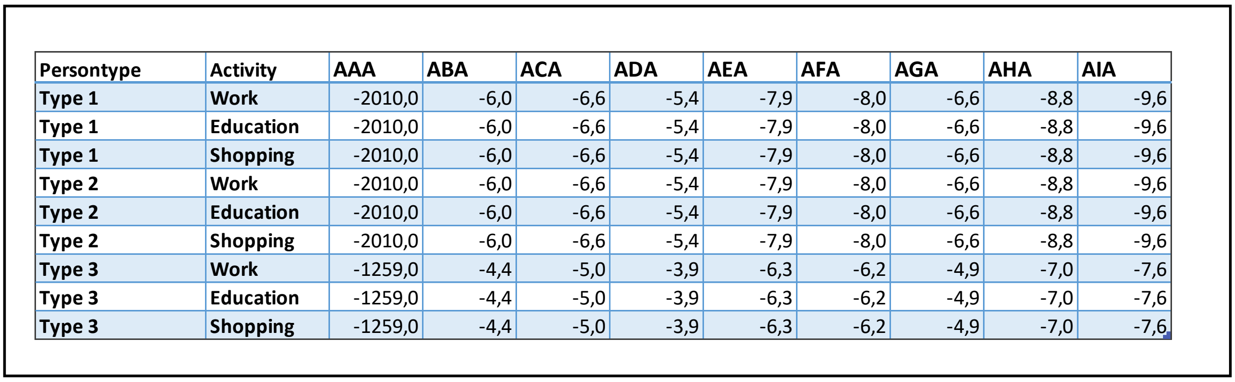
Tour	AAA	ABA	ACA	ADA	AEA	AFA	AGA	AHA	AIA
MIN:	0	84	180	78	162	258	168	240	312
Travel time	16	116	214	116	208	296	196	278	350
Cost	0	0	0	0	0	0	0	0	0

Figure B.4: Skim matrices per transport mode

B.2 THE MODE CHOICE MODEL

Based on the attributes in the skim-matrices and the utility functions, utility values for each transport mode can be obtained. Transit is illustrated as an example.

Transit	$V_{trasnit} = ASC_{transit} + \beta_3 * Tiv_{transit} + \beta 4\ (Ta_{transit} + Te_{transit}) + \beta 5\ {*}Ttr_{tranist} + \beta 6 * D_{tc} * Ct_{transit} + \beta 7 * Ntr_{\ transit} + D_{st} * ASC_{st\ ,transit}$

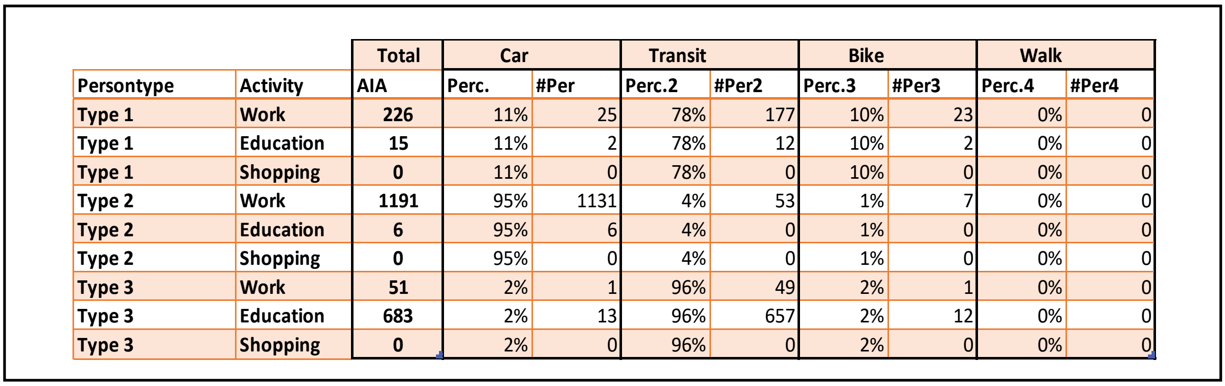


Persontype	Activity	AAA	ABA	ACA	ADA	AEA	AFA	AGA	AHA	AIA
Type 1	Work	-2010,0	-6,0	-6,6	-5,4	-7,9	-8,0	-6,6	-8,8	-9,6
Type 1	Education	-2010,0	-6,0	-6,6	-5,4	-7,9	-8,0	-6,6	-8,8	-9,6
Type 1	Shopping	-2010,0	-6,0	-6,6	-5,4	-7,9	-8,0	-6,6	-8,8	-9,6
Type 2	Work	-2010,0	-6,0	-6,6	-5,4	-7,9	-8,0	-6,6	-8,8	-9,6
Type 2	Education	-2010,0	-6,0	-6,6	-5,4	-7,9	-8,0	-6,6	-8,8	-9,6
Type 2	Shopping	-2010,0	-6,0	-6,6	-5,4	-7,9	-8,0	-6,6	-8,8	-9,6
Type 3	Work	-1259,0	-4,4	-5,0	-3,9	-6,3	-6,2	-4,9	-7,0	-7,6
Type 3	Education	-1259,0	-4,4	-5,0	-3,9	-6,3	-6,2	-4,9	-7,0	-7,6
Type 3	Shopping	-1259,0	-4,4	-5,0	-3,9	-6,3	-6,2	-4,9	-7,0	-7,6

Figure B.5: Example of utilities values for each person type and activity purpose for the mode Transit

The mode shares P^m_{ij} to travel with mode m between zones i and j, can be obtained by dividing the utility for each mode m with the SUM of the utilities of all modes in the mode set M. As an example, the results of this calculation for tour AIA are presented in figure B.6.

$$Pm(ij) = \frac{Um(ij)}{\sum_{r\in M} Ur(ij)}$$

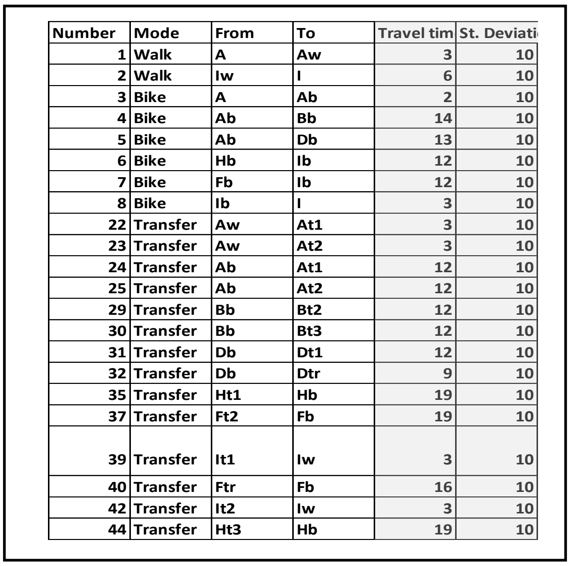


		Total	Car		Transit		Bike		Walk	
Persontype	Activity	AIA	Perc.	#Per	Perc.2	#Per2	Perc.3	#Per3	Perc.4	#Per4
Type 1	**Work**	**226**	11%	25	78%	177	10%	23	0%	0
Type 1	**Education**	**15**	11%	2	78%	12	10%	2	0%	0
Type 1	**Shopping**	**0**	11%	0	78%	0	10%	0	0%	0
Type 2	**Work**	**1191**	95%	1131	4%	53	1%	7	0%	0
Type 2	**Education**	**6**	95%	6	4%	0	1%	0	0%	0
Type 2	**Shopping**	**0**	95%	0	4%	0	1%	0	0%	0
Type 3	**Work**	**51**	2%	1	96%	49	2%	1	0%	0
Type 3	**Education**	**683**	2%	13	96%	657	2%	12	0%	0
Type 3	**Shopping**	**0**	2%	0	96%	0	2%	0	0%	0

Figure B.6 : Mode shares and number of travellers per mode for Tour AIA

APPENDICES C – THE MULTIMODAL NETWORK FOR THE TWO-STEP MODE-CHOICE APPROACH

Compared to the optimization problem in figure A.3 the links in figure A.4 are added to the optimization problem to obtain the multimodal transport networks.

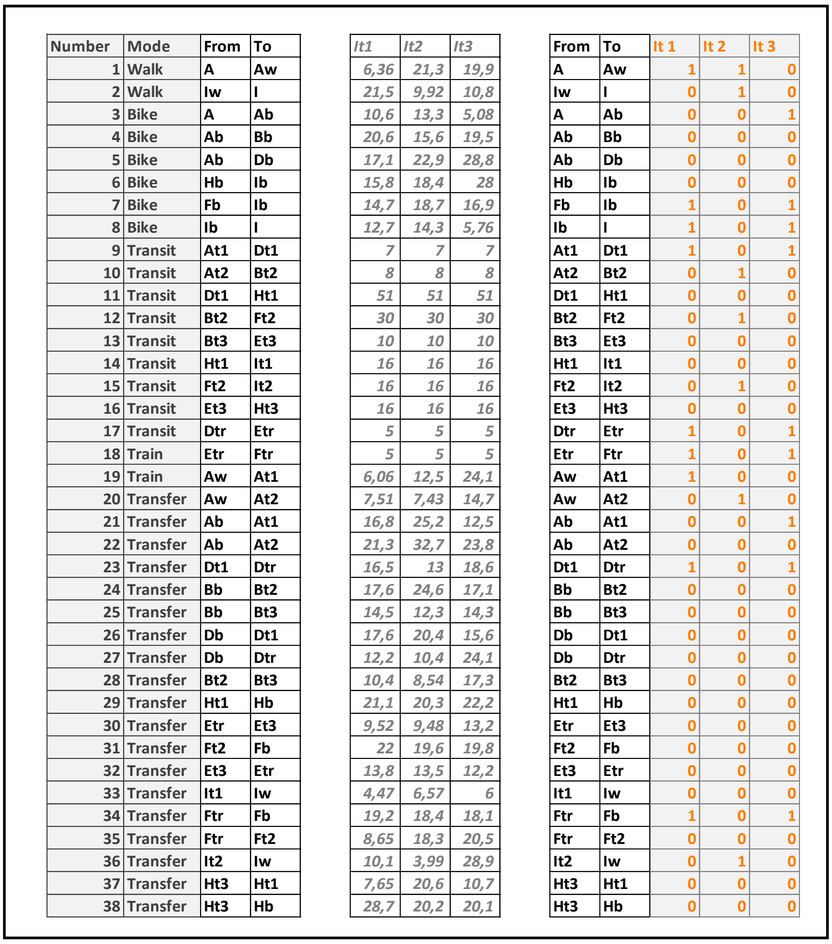


Number	Mode	From	To	Travel tim	St. Deviati
1	Walk	A	Aw	3	10
2	Walk	Iw	I	6	10
3	Bike	A	Ab	2	10
4	Bike	Ab	Bb	14	10
5	Bike	Ab	Db	13	10
6	Bike	Hb	Ib	12	10
7	Bike	Fb	Ib	12	10
8	Bike	Ib	I	3	10
22	Transfer	Aw	At1	3	10
23	Transfer	Aw	At2	3	10
24	Transfer	Ab	At1	12	10
25	Transfer	Ab	At2	12	10
29	Transfer	Bb	Bt2	12	10
30	Transfer	Bb	Bt3	12	10
31	Transfer	Db	Dt1	12	10
32	Transfer	Db	Dtr	9	10
35	Transfer	Ht1	Hb	19	10
37	Transfer	Ft2	Fb	19	10
39	Transfer	It1	Iw	3	10
40	Transfer	Ftr	Fb	16	10
42	Transfer	It2	Iw	3	10
44	Transfer	Ht3	Hb	19	10

Figure C.4: Added links to the multimodal transit network

The travel times used in figure C.4 are assumed to be the minimal travel times. The value obtained from the normal distribution is added to the value of the minimal travel times. There are 40 draws of the normal distribution for all transport links. This means that there are 40 iterations in which Dijkstra's algorithm is used to obtain shortest paths.

When 40 shortest paths are generated, only the unique paths are interesting to include in the choice set. Therefore a function is included that filters the optimized routes in Excel. An example of three iteration of the procedure is shown in figure C.5 below.



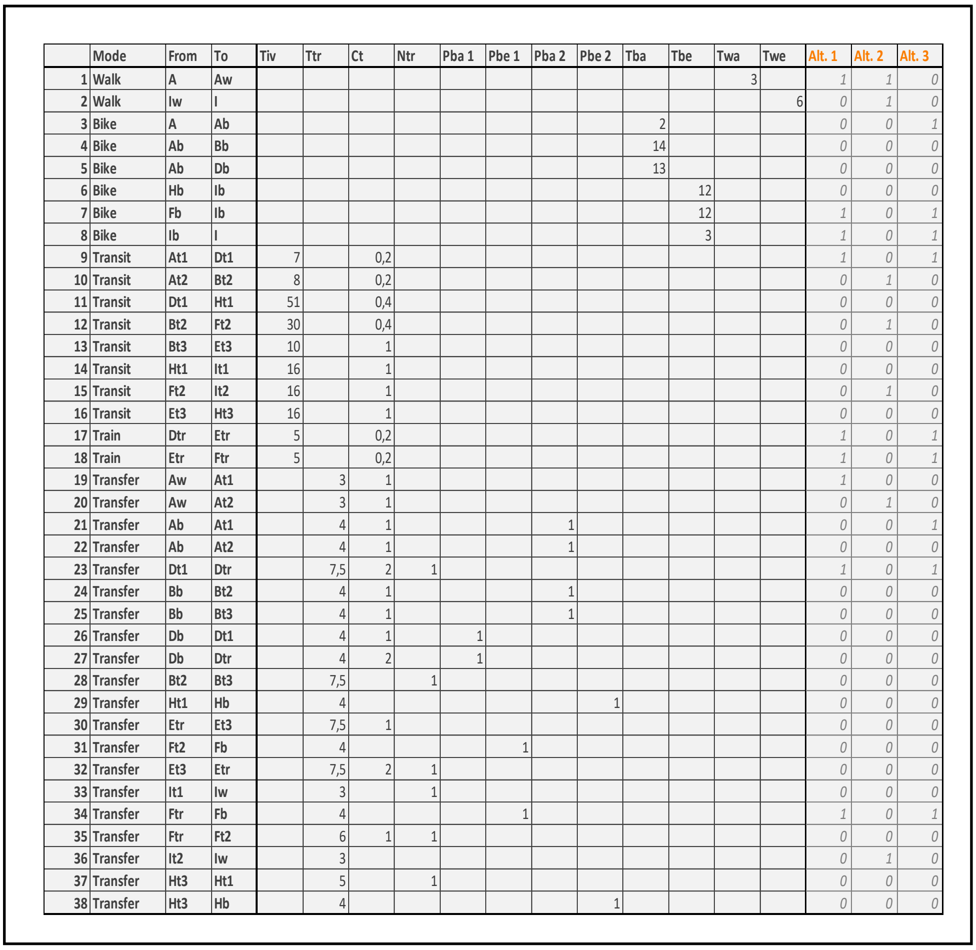
Number	Mode	From	To
1	Walk	A	Aw
2	Walk	Iw	I
3	Bike	A	Ab
4	Bike	Ab	Bb
5	Bike	Ab	Db
6	Bike	Hb	Ib
7	Bike	Fb	Ib
8	Bike	Ib	I
9	Transit	At1	Dt1
10	Transit	At2	Bt2
11	Transit	Dt1	Ht1
12	Transit	Bt2	Ft2
13	Transit	Bt3	Et3
14	Transit	Ht1	It1
15	Transit	Ft2	It2
16	Transit	Et3	Ht3
17	Transit	Dtr	Etr
18	Train	Etr	Ftr
19	Train	Aw	At1
20	Transfer	Aw	At2
21	Transfer	Ab	At1
22	Transfer	Ab	At2
23	Transfer	Dt1	Dtr
24	Transfer	Bb	Bt2
25	Transfer	Bb	Bt3
26	Transfer	Db	Dt1
27	Transfer	Db	Dtr
28	Transfer	Bt2	Bt3
29	Transfer	Ht1	Hb
30	Transfer	Etr	Et3
31	Transfer	Ft2	Fb
32	Transfer	Et3	Etr
33	Transfer	It1	Iw
34	Transfer	Ftr	Fb
35	Transfer	Ftr	Ft2
36	Transfer	It2	Iw
37	Transfer	Ht3	Ht1
38	Transfer	Ht3	Hb

It1	*It2*	*It3*
6,36	*21,3*	*19,9*
21,5	*9,92*	*10,8*
10,6	*13,3*	*5,08*
20,6	*15,6*	*19,5*
17,1	*22,9*	*28,8*
15,8	*18,4*	*28*
14,7	*18,7*	*16,9*
12,7	*14,3*	*5,76*
7	*7*	*7*
8	*8*	*8*
51	*51*	*51*
30	*30*	*30*
10	*10*	*10*
16	*16*	*16*
16	*16*	*16*
16	*16*	*16*
5	*5*	*5*
5	*5*	*5*
6,06	*12,5*	*24,1*
7,51	*7,43*	*14,7*
16,8	*25,2*	*12,5*
21,3	*32,7*	*23,8*
16,5	*13*	*18,6*
17,6	*24,6*	*17,1*
14,5	*12,3*	*14,3*
17,6	*20,4*	*15,6*
12,2	*10,4*	*24,1*
10,4	*8,54*	*17,3*
21,1	*20,3*	*22,2*
9,52	*9,48*	*13,2*
22	*19,6*	*19,8*
13,8	*13,5*	*12,2*
4,47	*6,57*	*6*
19,2	*18,4*	*18,1*
8,65	*18,3*	*20,5*
10,1	*3,99*	*28,9*
7,65	*20,6*	*10,7*
28,7	*20,2*	*20,1*

From	To	It 1	It 2	It 3
A	Aw	1	1	0
Iw	I	0	1	0
A	Ab	0	0	1
Ab	Bb	0	0	0
Ab	Db	0	0	0
Hb	Ib	0	0	0
Fb	Ib	1	0	1
Ib	I	1	0	1
At1	Dt1	1	0	1
At2	Bt2	0	1	0
Dt1	Ht1	0	0	0
Bt2	Ft2	0	1	0
Bt3	Et3	0	0	0
Ht1	It1	0	0	0
Ft2	It2	0	1	0
Et3	Ht3	0	0	0
Dtr	Etr	1	0	1
Etr	Ftr	1	0	1
Aw	At1	1	0	0
Aw	At2	0	1	0
Ab	At1	0	0	1
Ab	At2	0	0	0
Dt1	Dtr	1	0	1
Bb	Bt2	0	0	0
Bb	Bt3	0	0	0
Db	Dt1	0	0	0
Db	Dtr	0	0	0
Bt2	Bt3	0	0	0
Ht1	Hb	0	0	0
Etr	Et3	0	0	0
Ft2	Fb	0	0	0
Et3	Etr	0	0	0
It1	Iw	0	0	0
Ftr	Fb	1	0	1
Ftr	Ft2	0	0	0
It2	Iw	0	1	0
Ht3	Ht1	0	0	0
Ht3	Hb	0	0	0

Figure C.5 : Three iterations of the stochastic shortest path algorithm

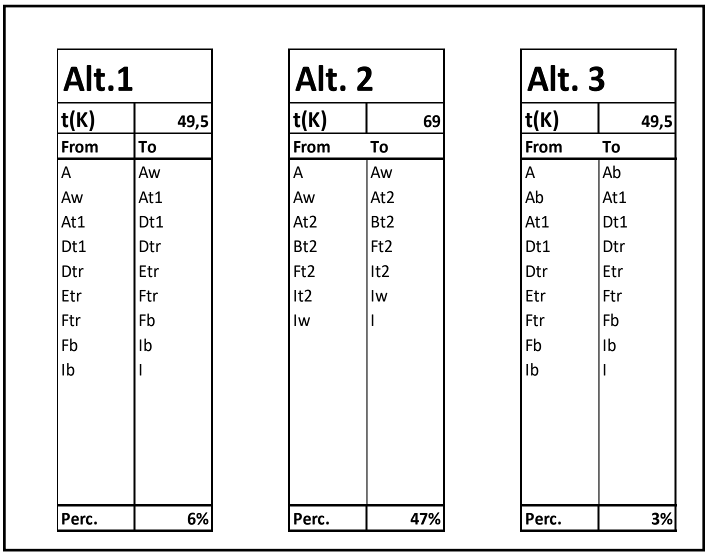
When the routes are obtained the following setup is used to derive utility values for each generated alternative:



	Mode	From	To	Tiv	Ttr	Ct	Ntr	Pba 1	Pbe 1	Pba 2	Pbe 2	Tba	Tbe	Twa	Twe	Alt. 1	Alt. 2	Alt. 3
1	Walk	A	Aw											3		1	1	0
2	Walk	Iw	I												6	0	1	0
3	Bike	A	Ab									2				0	0	1
4	Bike	Ab	Bb									14				0	0	0
5	Bike	Ab	Db									13				0	0	0
6	Bike	Hb	Ib										12			0	0	0
7	Bike	Fb	Ib										12			1	0	1
8	Bike	Ib	I										3			1	0	1
9	Transit	At1	Dt1	7		0,2										1	0	1
10	Transit	At2	Bt2	8		0,2										0	1	0
11	Transit	Dt1	Ht1	51		0,4										0	0	0
12	Transit	Bt2	Ft2	30		0,4										0	1	0
13	Transit	Bt3	Et3	10		1										0	0	0
14	Transit	Ht1	It1	16		1										0	0	0
15	Transit	Ft2	It2	16		1										0	1	0
16	Transit	Et3	Ht3	16		1										0	0	0
17	Train	Dtr	Etr	5		0,2										1	0	1
18	Train	Etr	Ftr	5		0,2										1	0	1
19	Transfer	Aw	At1		3	1										1	0	0
20	Transfer	Aw	At2		3	1										0	1	0
21	Transfer	Ab	At1		4	1				1						0	0	1
22	Transfer	Ab	At2		4	1				1						0	0	0
23	Transfer	Dt1	Dtr		7,5	2	1									1	0	1
24	Transfer	Bb	Bt2		4	1				1						0	0	0
25	Transfer	Bb	Bt3		4	1				1						0	0	0
26	Transfer	Db	Dt1		4	1		1								0	0	0
27	Transfer	Db	Dtr		4	2		1								0	0	0
28	Transfer	Bt2	Bt3		7,5		1									0	0	0
29	Transfer	Ht1	Hb		4						1					0	0	0
30	Transfer	Etr	Et3		7,5	1										0	0	0
31	Transfer	Ft2	Fb		4				1							0	0	0
32	Transfer	Et3	Etr		7,5	2	1									0	0	0
33	Transfer	It1	Iw		3		1									0	0	0
34	Transfer	Ftr	Fb		4				1							1	0	1
35	Transfer	Ftr	Ft2		6	1	1									0	0	0
36	Transfer	It2	Iw		3											0	1	0
37	Transfer	Ht3	Ht1		5		1									0	0	0
38	Transfer	Ht3	Hb		4						1					0	0	0

Figure C.6: Table to calculate utility of the travel paths

For each of the alternatives this results in a utility value. With the path-size logit the route-shares for each travel path can be found in figure C.7.



Alt.1	
t(K)	49,5
From	To
A	Aw
Aw	At1
At1	Dt1
Dt1	Dtr
Dtr	Etr
Etr	Ftr
Ftr	Fb
Fb	Ib
Ib	I
Perc.	6%

Alt. 2	
t(K)	69
From	To
A	Aw
Aw	At2
At2	Bt2
Bt2	Ft2
Ft2	It2
It2	Iw
Iw	I
Perc.	47%

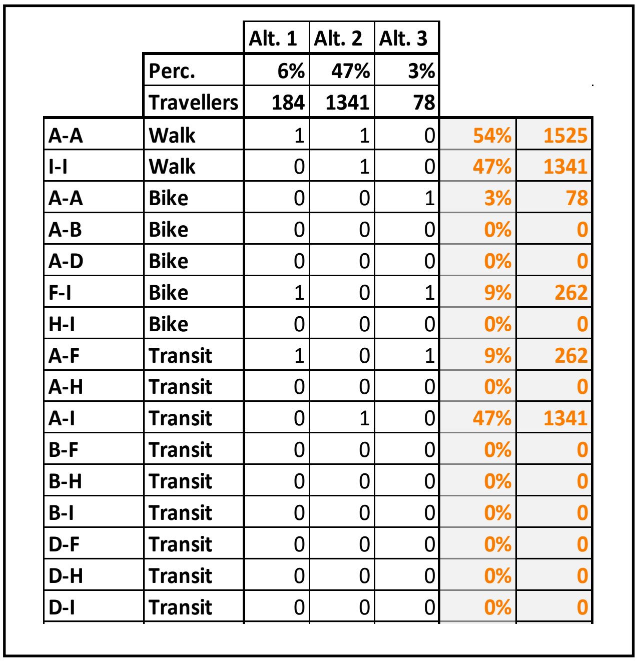
Alt. 3	
t(K)	49,5
From	To
A	Ab
Ab	At1
At1	Dt1
Dt1	Dtr
Dtr	Etr
Etr	Ftr
Ftr	Fb
Fb	Ib
Ib	I
Perc.	3%

Figure C.7: Results of the three path alternatives

To adjust the matrices, the model must exactly know what part of the transport trip is performed with what transport mode. Therefore, the transport trip of each alternative k is divided in trip legs. Z_k is a binary variable which tells if a trip leg is used in alternative k. Figure C8 shows for the three example alternatives which trip legs are part of their multimodal transport trip. The formula below is used to obtain the number of travellers that uses each trip leg.

$$F(Z, ij) \; = \sum_{k \in L} Z(k) * \; P(k) * Q\,(ij)$$

F(Z,ij) = Total number of travellers that use multimodal leg Z to travel between i and j
Z(k) = Binary variable, is one when transit leg Z is used for alternative k
P(k) = Path share for alternative k
Q(ij) = number of travellers between i and j

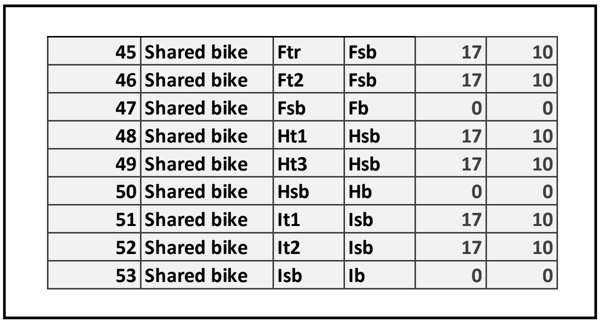


		Alt. 1	Alt. 2	Alt. 3		
	Perc.	**6%**	**47%**	**3%**		
	Travellers	**184**	**1341**	**78**		
A-A	**Walk**	1	1	0	**54%**	**1525**
I-I	**Walk**	0	1	0	**47%**	**1341**
A-A	**Bike**	0	0	1	**3%**	**78**
A-B	**Bike**	0	0	0	**0%**	**0**
A-D	**Bike**	0	0	0	**0%**	**0**
F-I	**Bike**	1	0	1	**9%**	**262**
H-I	**Bike**	0	0	0	**0%**	**0**
A-F	**Transit**	1	0	1	**9%**	**262**
A-H	**Transit**	0	0	0	**0%**	**0**
A-I	**Transit**	0	1	0	**47%**	**1341**
B-F	**Transit**	0	0	0	**0%**	**0**
B-H	**Transit**	0	0	0	**0%**	**0**
B-I	**Transit**	0	0	0	**0%**	**0**
D-F	**Transit**	0	0	0	**0%**	**0**
D-H	**Transit**	0	0	0	**0%**	**0**
D-I	**Transit**	0	0	0	**0%**	**0**

Figure C8: calculation of the access, egress and transit shares for all stations

APPENDICES D – IMPLEMENTING SB-BIKE-SHARING

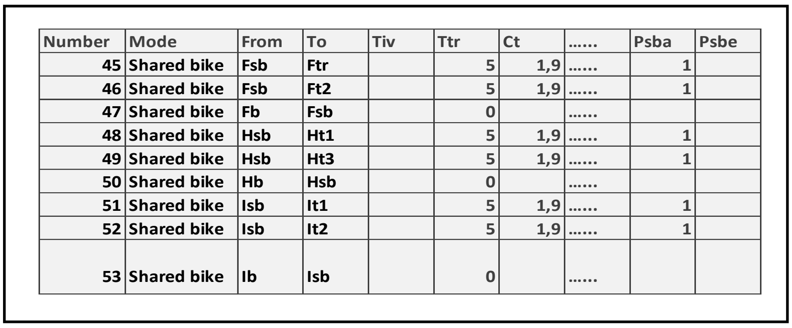
Figure D.1 shows what links are added for the generation of multimodal transit trips A – I compared to the situation in figure C.4.



45	**Shared bike**	**Ftr**	**Fsb**	17	10
46	**Shared bike**	**Ft2**	**Fsb**	17	10
47	**Shared bike**	**Fsb**	**Fb**	0	0
48	**Shared bike**	**Ht1**	**Hsb**	17	10
49	**Shared bike**	**Ht3**	**Hsb**	17	10
50	**Shared bike**	**Hsb**	**Hb**	0	0
51	**Shared bike**	**It1**	**Isb**	17	10
52	**Shared bike**	**It2**	**Isb**	17	10
53	**Shared bike**	**Isb**	**Ib**	0	0

Figure D1: New links added to the route-search algorithm to add Station-Based bike-sharing

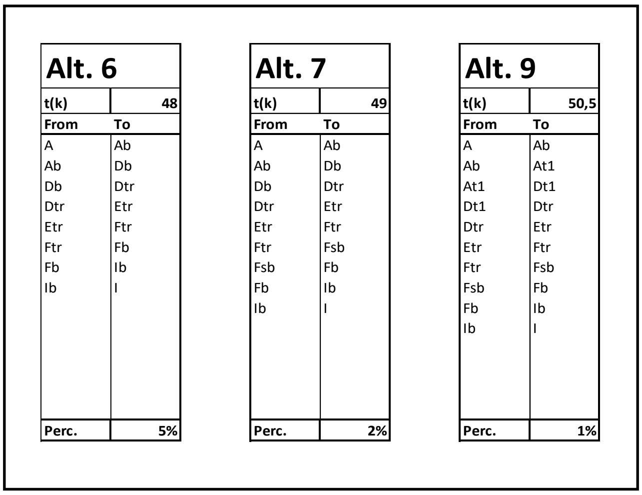
To calculate utility values of paths that contain a SB-bike-sharing trip leg, the following links and attributers are added to the situation in figure C.6.



Number	Mode	From	To	Tiv	Ttr	Ct	......	Psba	Psbe
45	**Shared bike**	**Fsb**	**Ftr**		5	1,9	......	1	
46	**Shared bike**	**Fsb**	**Ft2**		5	1,9	......	1	
47	**Shared bike**	**Fb**	**Fsb**		0		......		
48	**Shared bike**	**Hsb**	**Ht1**		5	1,9	......	1	
49	**Shared bike**	**Hsb**	**Ht3**		5	1,9	......	1	
50	**Shared bike**	**Hb**	**Hsb**		0		......		
51	**Shared bike**	**Isb**	**It1**		5	1,9	......	1	
52	**Shared bike**	**Isb**	**It2**		5	1,9	......	1	
53	**Shared bike**	**Ib**	**Isb**		0		......		

Figure D.2: Added links to calculated the utility with SB-bike-sharing

Figure D.1 gives an example of three alternatives that use SB-bike-sharing as the egress Transit leg.



Alt. 6	
t(k)	**48**
From	**To**
A	Ab
Ab	Db
Db	Dtr
Dtr	Etr
Etr	Ftr
Ftr	Fb
Fb	Ib
Ib	I
Perc.	**5%**

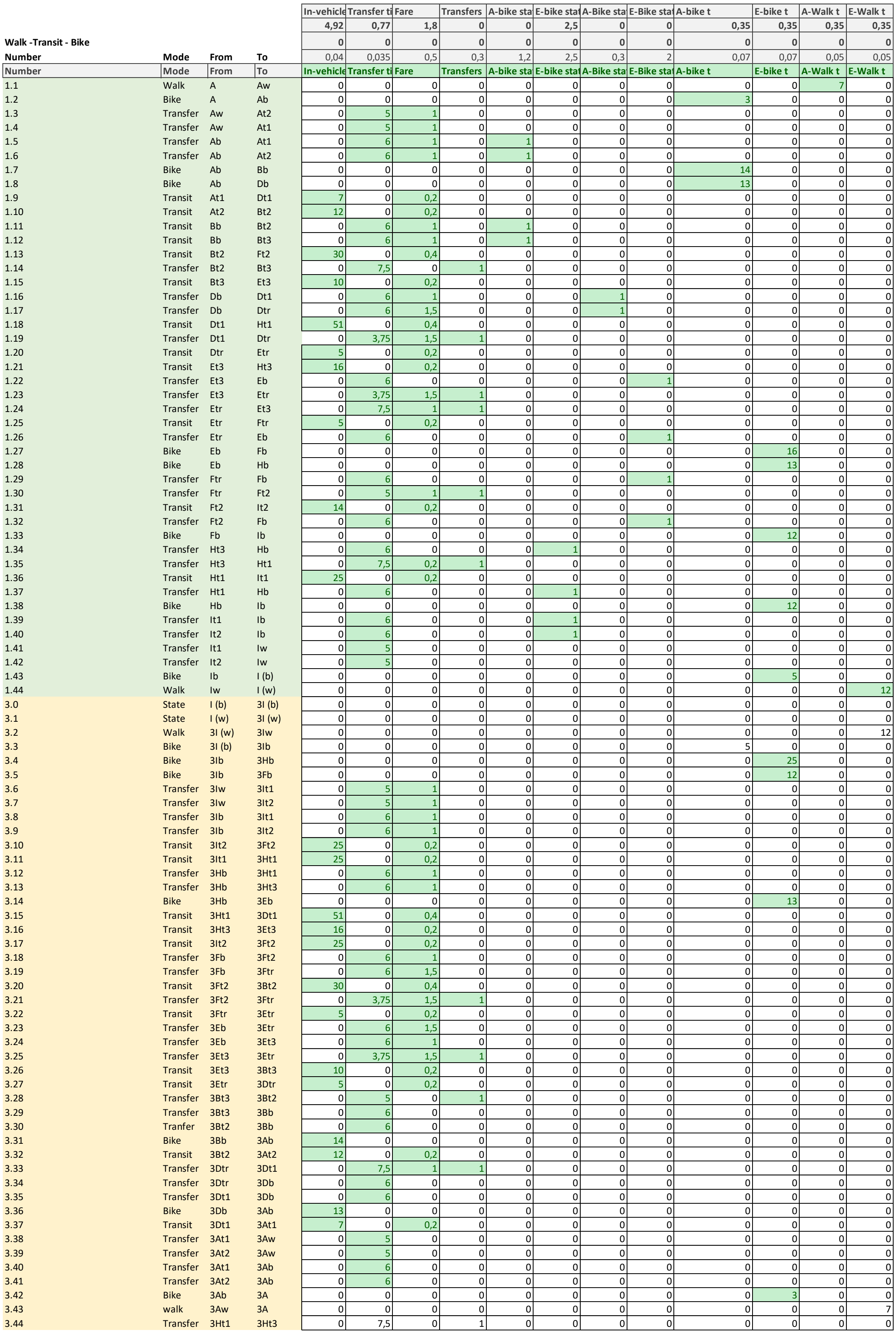
Alt. 7	
t(k)	**49**
From	**To**
A	Ab
Ab	Db
Db	Dtr
Dtr	Etr
Etr	Ftr
Ftr	Fsb
Fsb	Fb
Fb	Ib
Ib	I
Perc.	**2%**

Alt. 9	
t(k)	**50,5**
From	**To**
A	Ab
Ab	At1
At1	Dt1
Dt1	Dtr
Dtr	Etr
Etr	Ftr
Ftr	Fsb
Fsb	Fb
Fb	Ib
Ib	I
Perc.	**1%**

Figure D.1: Results of SB-bike-sharing alternatives

APPENDICES E – THE TOUR-BASED MODE-CHAIN APPROACH IN EXCEL (SIMPLE TOUR)

Step 1 The setup used to obtain shortest paths in the tour-based network for a simple tour;



				In-vehicle	Transfer ti	Fare	Transfers	A-bike sta	E-bike stat	A-Bike sta	E-Bike stat	A-bike t	E-bike t	A-Walk t	E-Walk t
				4,92	**0,77**	**1,8**	**0**	**0**	**2,5**	**0**	**0**	**0,35**	**0,35**	**0,35**	**0,35**
Walk -Transit - Bike				**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Number	**Mode**	**From**	**To**	0,04	0,035	0,5	0,3	1,2	2,5	0,3	2	0,07	0,07	0,05	0,05
Number	Mode	From	To	In-vehicle	Transfer ti	Fare	Transfers	A-bike sta	E-bike stat	A-Bike sta	E-Bike stat	A-bike t	E-bike t	A-Walk t	E-Walk t
1.1	Walk	A	Aw	0	0	0	0	0	0	0	0	0	0	7	0
1.2	Bike	A	Ab	0	0	0	0	0	0	0	0	3	0	0	0
1.3	Transfer	Aw	At2	0	5	1	0	0	0	0	0	0	0	0	0
1.4	Transfer	Aw	At1	0	5	1	0	0	0	0	0	0	0	0	0
1.5	Transfer	Ab	At1	0	6	1	0	1	0	0	0	0	0	0	0
1.6	Transfer	Ab	At2	0	6	1	0	1	0	0	0	0	0	0	0
1.7	Bike	Ab	Bb	0	0	0	0	0	0	0	0	14	0	0	0
1.8	Bike	Ab	Db	0	0	0	0	0	0	0	0	13	0	0	0
1.9	Transit	At1	Dt1	7	0	0,2	0	0	0	0	0	0	0	0	0
1.10	Transit	At2	Bt2	12	0	0,2	0	0	0	0	0	0	0	0	0
1.11	Transit	Bb	Bt2	0	6	1	0	1	0	0	0	0	0	0	0
1.12	Transit	Bb	Bt3	0	6	1	0	1	0	0	0	0	0	0	0
1.13	Transit	Bt2	Ft2	30	0	0,4	0	0	0	0	0	0	0	0	0
1.14	Transfer	Bt2	Bt3	0	7,5	0	1	0	0	0	0	0	0	0	0
1.15	Transit	Bt3	Et3	10	0	0,2	0	0	0	0	0	0	0	0	0
1.16	Transfer	Db	Dt1	0	6	1	0	0	0	1	0	0	0	0	0
1.17	Transfer	Db	Dtr	0	6	1,5	0	0	0	1	0	0	0	0	0
1.18	Transit	Dt1	Ht1	51	0	0,4	0	0	0	0	0	0	0	0	0
1.19	Transfer	Dt1	Dtr	0	3,75	1,5	1	0	0	0	0	0	0	0	0
1.20	Transit	Dtr	Etr	5	0	0,2	0	0	0	0	0	0	0	0	0
1.21	Transit	Et3	Ht3	16	0	0,2	0	0	0	0	0	0	0	0	0
1.22	Transfer	Et3	Eb	0	6	0	0	0	0	0	1	0	0	0	0
1.23	Transfer	Et3	Etr	0	3,75	1,5	1	0	0	0	0	0	0	0	0
1.24	Transfer	Etr	Et3	0	7,5	1	1	0	0	0	0	0	0	0	0
1.25	Transit	Etr	Ftr	5	0	0,2	0	0	0	0	0	0	0	0	0
1.26	Transfer	Etr	Eb	0	6	0	0	0	0	0	1	0	0	0	0
1.27	Bike	Eb	Fb	0	0	0	0	0	0	0	0	0	16	0	0
1.28	Bike	Eb	Hb	0	0	0	0	0	0	0	0	0	13	0	0
1.29	Transfer	Ftr	Fb	0	6	0	0	0	0	0	1	0	0	0	0
1.30	Transfer	Ftr	Ft2	0	5	1	1	0	0	0	0	0	0	0	0
1.31	Transit	Ft2	It2	14	0	0,2	0	0	0	0	0	0	0	0	0
1.32	Transfer	Ft2	Fb	0	6	0	0	0	0	0	1	0	0	0	0
1.33	Bike	Fb	Ib	0	0	0	0	0	0	0	0	0	12	0	0
1.34	Transfer	Ht3	Hb	0	6	0	0	0	1	0	0	0	0	0	0
1.35	Transfer	Ht3	Ht1	0	7,5	0,2	1	0	0	0	0	0	0	0	0
1.36	Transit	Ht1	It1	25	0	0,2	0	0	0	0	0	0	0	0	0
1.37	Transfer	Ht1	Hb	0	6	0	0	0	1	0	0	0	0	0	0
1.38	Bike	Hb	Ib	0	0	0	0	0	0	0	0	0	12	0	0
1.39	Transfer	It1	Ib	0	6	0	0	0	1	0	0	0	0	0	0
1.40	Transfer	It2	Ib	0	6	0	0	0	1	0	0	0	0	0	0
1.41	Transfer	It1	Iw	0	5	0	0	0	0	0	0	0	0	0	0
1.42	Transfer	It2	Iw	0	5	0	0	0	0	0	0	0	0	0	0
1.43	Bike	Ib	I (b)	0	0	0	0	0	0	0	0	0	5	0	0
1.44	Walk	Iw	I (w)	0	0	0	0	0	0	0	0	0	0	0	12
3.0	State	I (b)	3I (b)	0	0	0	0	0	0	0	0	0	0	0	0
3.1	State	I (w)	3I (w)	0	0	0	0	0	0	0	0	0	0	0	0
3.2	Walk	3I (w)	3Iw	0	0	0	0	0	0	0	0	0	0	0	12
3.3	Bike	3I (b)	3Ib	0	0	0	0	0	0	0	0	5	0	0	0
3.4	Bike	3Ib	3Hb	0	0	0	0	0	0	0	0	0	25	0	0
3.5	Bike	3Ib	3Fb	0	0	0	0	0	0	0	0	0	12	0	0
3.6	Transfer	3Iw	3It1	0	5	1	0	0	0	0	0	0	0	0	0
3.7	Transfer	3Iw	3It2	0	5	1	0	0	0	0	0	0	0	0	0
3.8	Transfer	3Ib	3It1	0	6	1	0	0	0	0	0	0	0	0	0
3.9	Transfer	3Ib	3It2	0	6	1	0	0	0	0	0	0	0	0	0
3.10	Transit	3It2	3Ft2	25	0	0,2	0	0	0	0	0	0	0	0	0
3.11	Transit	3It1	3Ht1	25	0	0,2	0	0	0	0	0	0	0	0	0
3.12	Transfer	3Hb	3Ht1	0	6	1	0	0	0	0	0	0	0	0	0
3.13	Transfer	3Hb	3Ht3	0	6	1	0	0	0	0	0	0	0	0	0
3.14	Bike	3Hb	3Eb	0	0	0	0	0	0	0	0	0	13	0	0
3.15	Transit	3Ht1	3Dt1	51	0	0,4	0	0	0	0	0	0	0	0	0
3.16	Transit	3Ht3	3Et3	16	0	0,2	0	0	0	0	0	0	0	0	0
3.17	Transit	3It2	3Ft2	25	0	0,2	0	0	0	0	0	0	0	0	0
3.18	Transfer	3Fb	3Ft2	0	6	1	0	0	0	0	0	0	0	0	0
3.19	Transfer	3Fb	3Ftr	0	6	1,5	0	0	0	0	0	0	0	0	0
3.20	Transit	3Ft2	3Bt2	30	0	0,4	0	0	0	0	0	0	0	0	0
3.21	Transfer	3Ft2	3Ftr	0	3,75	1,5	1	0	0	0	0	0	0	0	0
3.22	Transit	3Ftr	3Etr	5	0	0,2	0	0	0	0	0	0	0	0	0
3.23	Transfer	3Eb	3Etr	0	6	1,5	0	0	0	0	0	0	0	0	0
3.24	Transfer	3Eb	3Et3	0	6	1	0	0	0	0	0	0	0	0	0
3.25	Transfer	3Et3	3Etr	0	3,75	1,5	1	0	0	0	0	0	0	0	0
3.26	Transit	3Et3	3Bt3	10	0	0,2	0	0	0	0	0	0	0	0	0
3.27	Transit	3Etr	3Dtr	5	0	0,2	0	0	0	0	0	0	0	0	0
3.28	Transfer	3Bt3	3Bt2	0	5	0	1	0	0	0	0	0	0	0	0
3.29	Transfer	3Bt3	3Bb	0	6	0	0	0	0	0	0	0	0	0	0
3.30	Tranfer	3Bt2	3Bb	0	6	0	0	0	0	0	0	0	0	0	0
3.31	Bike	3Bb	3Ab	14	0	0	0	0	0	0	0	0	0	0	0
3.32	Transit	3Bt2	3At2	12	0	0,2	0	0	0	0	0	0	0	0	0
3.33	Transfer	3Dtr	3Dt1	0	7,5	1	1	0	0	0	0	0	0	0	0
3.34	Transfer	3Dtr	3Db	0	6	0	0	0	0	0	0	0	0	0	0
3.35	Transfer	3Dt1	3Db	0	6	0	0	0	0	0	0	0	0	0	0
3.36	Bike	3Db	3Ab	13	0	0	0	0	0	0	0	0	0	0	0
3.37	Transit	3Dt1	3At1	7	0	0,2	0	0	0	0	0	0	0	0	0
3.38	Transfer	3At1	3Aw	0	5	0	0	0	0	0	0	0	0	0	0
3.39	Transfer	3At2	3Aw	0	5	0	0	0	0	0	0	0	0	0	0
3.40	Transfer	3At1	3Ab	0	6	0	0	0	0	0	0	0	0	0	0
3.41	Transfer	3At2	3Ab	0	6	0	0	0	0	0	0	0	0	0	0
3.42	Bike	3Ab	3A	0	0	0	0	0	0	0	0	0	3	0	0
3.43	walk	3Aw	3A	0	0	0	0	0	0	0	0	0	0	0	7
3.44	Transfer	3Ht1	3Ht3	0	7,5	0	1	0	0	0	0	0	0	0	0

Figure E1: The setup to generate tour-based paths in the tour-based mode-chain approach

Step 2 : Search for stations that are in the combined travel time radius from the origin and the destinations in the tour.

For the mode-chain W-T-B a shortest path algorithm is performed from station I to all other stations. This gives the travel times as illustrated in figure E.2.

Objective functions	IA	IB	IC	ID	IE	IF	IG	IH	I-I	Totaal
MIN:	**55**	**38**	**26**	**43**	**25**	**12**	**28**	**12**		**239**
Traveltime	60	43	31	48	30	17	33	17	5	279
Cost	0	0	0	0	0	0	0	0	0	0

Figure E.2: The travel times to bike from work location I to each station

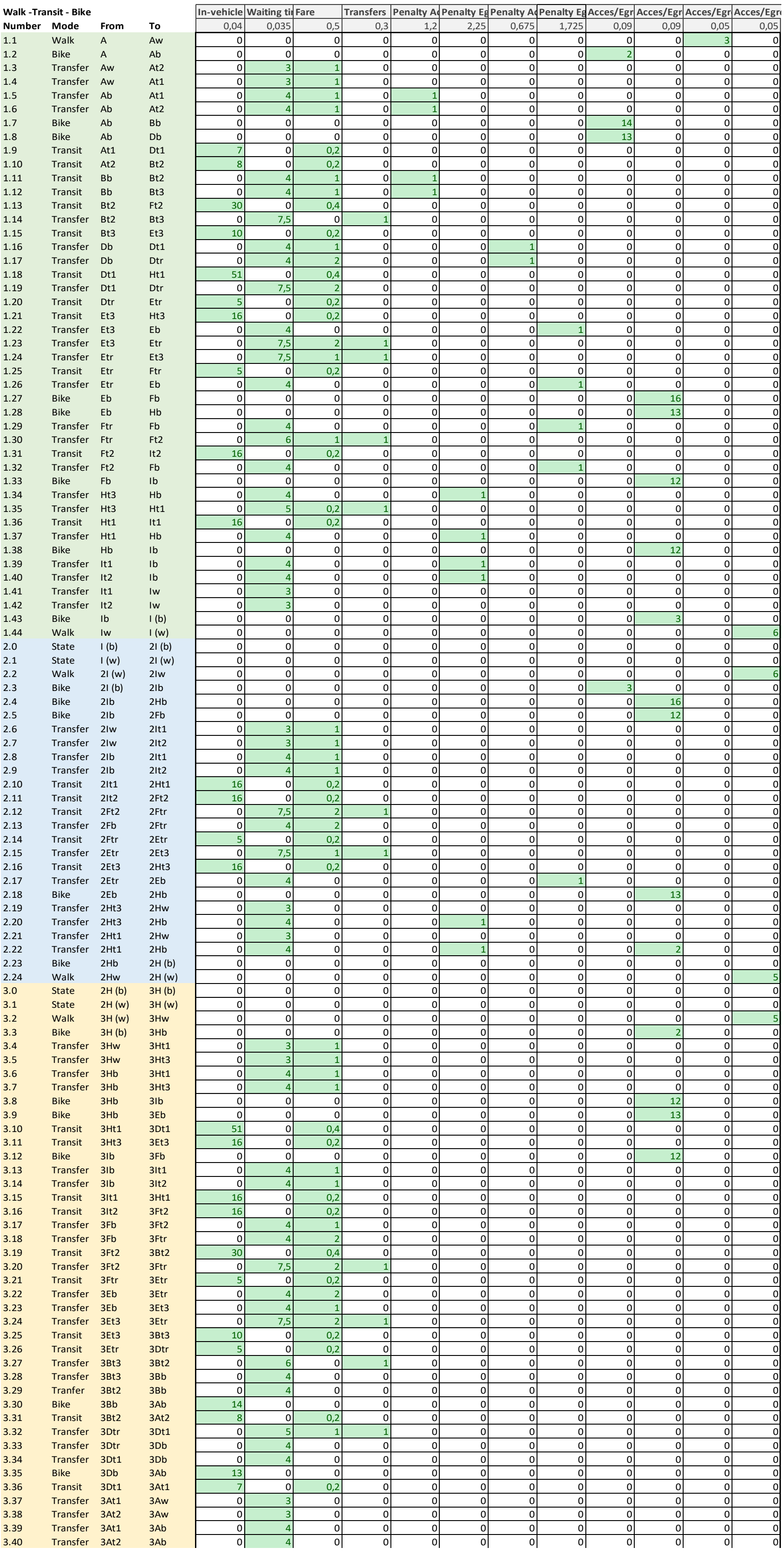
All times are tested on whether they are within the threshold value for the maximal biking time of 18 (type 1) and 24 (type 2) minutes.

	A	B	C	D	E	F	G	H	I
Acces Station type B	1	1	0	1	0	0	0	0	0
Egress Station type B	0	0	0	0	0	1	0	1	1
Acces Station type A	1	1	0	1	0	0	0	0	0
Egress station type A	0	0	0	0	0	1	0	1	1

Figure E.3: Review if the stations are below a threshold value.

Only stations in the optimization can be used that are available according to the station constraint.

APPENDIXES F - THE TOUR-BASED MODE-CHAIN APPROACH IN EXCEL COMPLEX TOUR



Walk -Transit - Bike				In-vehicle	Waiting ti	Fare	Transfers	Penalty A	Penalty Eg	Penalty A	Penalty Eg	Acces/Egr	Acces/Egr	Acces/Egr	Acces/Egre
Number	Mode	From	To	0,04	0,035	0,5	0,3	1,2	2,25	0,675	1,725	0,09	0,09	0,05	0,05
1.1	Walk	A	Aw	0	0	0	0	0	0	0	0	0	0	3	0
1.2	Bike	A	Ab	0	0	0	0	0	0	0	0	2	0	0	0
1.3	Transfer	Aw	At2	0	3	1	0	0	0	0	0	0	0	0	0
1.4	Transfer	Aw	At1	0	3	1	0	0	0	0	0	0	0	0	0
1.5	Transfer	Ab	At1	0	4	1	0	1	0	0	0	0	0	0	0
1.6	Transfer	Ab	At2	0	4	1	0	1	0	0	0	0	0	0	0
1.7	Bike	Ab	Bb	0	0	0	0	0	0	0	0	14	0	0	0
1.8	Bike	Ab	Db	0	0	0	0	0	0	0	0	13	0	0	0
1.9	Transit	At1	Dt1	7	0	0,2	0	0	0	0	0	0	0	0	0
1.10	Transit	At2	Bt2	8	0	0,2	0	0	0	0	0	0	0	0	0
1.11	Transit	Bb	Bt2	0	4	1	0	1	0	0	0	0	0	0	0
1.12	Transit	Bb	Bt3	0	4	1	0	1	0	0	0	0	0	0	0
1.13	Transit	Bt2	Ft2	30	0	0,4	0	0	0	0	0	0	0	0	0
1.14	Transfer	Bt2	Bt3	0	7,5	0	1	0	0	0	0	0	0	0	0
1.15	Transit	Bt3	Et3	10	0	0,2	0	0	0	0	0	0	0	0	0
1.16	Transfer	Db	Dt1	0	4	1	0	0	0	1	0	0	0	0	0
1.17	Transfer	Db	Dtr	0	4	2	0	0	0	1	0	0	0	0	0
1.18	Transit	Dt1	Ht1	51	0	0,4	0	0	0	0	0	0	0	0	0
1.19	Transfer	Dt1	Dtr	0	7,5	2	0	0	0	0	0	0	0	0	0
1.20	Transit	Dtr	Etr	5	0	0,2	0	0	0	0	0	0	0	0	0
1.21	Transit	Et3	Ht3	16	0	0,2	0	0	0	0	0	0	0	0	0
1.22	Transfer	Et3	Eb	0	4	0	0	0	0	0	1	0	0	0	0
1.23	Transfer	Et3	Etr	0	7,5	2	1	0	0	0	0	0	0	0	0
1.24	Transfer	Etr	Et3	0	7,5	1	1	0	0	0	0	0	0	0	0
1.25	Transit	Etr	Ftr	5	0	0,2	0	0	0	0	0	0	0	0	0
1.26	Transfer	Etr	Eb	0	4	0	0	0	0	0	1	0	0	0	0
1.27	Bike	Eb	Fb	0	0	0	0	0	0	0	0	0	16	0	0
1.28	Bike	Eb	Hb	0	0	0	0	0	0	0	0	0	13	0	0
1.29	Transfer	Ftr	Fb	0	4	0	0	0	0	0	1	0	0	0	0
1.30	Transfer	Ftr	Ft2	0	6	1	1	0	0	0	0	0	0	0	0
1.31	Transit	Ft2	It2	16	0	0,2	0	0	0	0	0	0	0	0	0
1.32	Transfer	Ft2	Fb	0	4	0	0	0	0	0	1	0	0	0	0
1.33	Bike	Fb	Ib	0	0	0	0	0	0	0	0	0	12	0	0
1.34	Transfer	Ht3	Hb	0	4	0	0	0	1	0	0	0	0	0	0
1.35	Transfer	Ht3	Ht1	0	5	0,2	1	0	0	0	0	0	0	0	0
1.36	Transit	Ht1	It1	16	0	0,2	0	0	0	0	0	0	0	0	0
1.37	Transfer	Ht1	Hb	0	4	0	0	0	1	0	0	0	0	0	0
1.38	Bike	Hb	Ib	0	0	0	0	0	0	0	0	0	12	0	0
1.39	Transfer	It1	Ib	0	4	0	0	0	1	0	0	0	0	0	0
1.40	Transfer	It2	Ib	0	4	0	0	0	1	0	0	0	0	0	0
1.41	Transfer	It1	Iw	0	3	0	0	0	0	0	0	0	0	0	0
1.42	Transfer	It2	Iw	0	3	0	0	0	0	0	0	0	0	0	0
1.43	Bike	Ib	I (b)	0	0	0	0	0	0	0	0	0	3	0	0
1.44	Walk	Iw	I (w)	0	0	0	0	0	0	0	0	0	0	0	6
2.0	State	I (b)	2I (b)	0	0	0	0	0	0	0	0	0	0	0	0
2.1	State	I (w)	2I (w)	0	0	0	0	0	0	0	0	0	0	0	0
2.2	Walk	2I (w)	2Iw	0	0	0	0	0	0	0	0	0	0	0	6
2.3	Bike	2I (b)	2Ib	0	0	0	0	0	0	0	0	3	0	0	0
2.4	Bike	2Ib	2Hb	0	0	0	0	0	0	0	0	0	16	0	0
2.5	Bike	2Ib	2Fb	0	0	0	0	0	0	0	0	0	12	0	0
2.6	Transfer	2Iw	2It1	0	3	1	0	0	0	0	0	0	0	0	0
2.7	Transfer	2Iw	2It2	0	3	1	0	0	0	0	0	0	0	0	0
2.8	Transfer	2Ib	2It1	0	4	1	0	0	0	0	0	0	0	0	0
2.9	Transfer	2Ib	2It2	0	4	1	0	0	0	0	0	0	0	0	0
2.10	Transit	2It1	2Ht1	16	0	0,2	0	0	0	0	0	0	0	0	0
2.11	Transit	2It2	2Ft2	16	0	0,2	0	0	0	0	0	0	0	0	0
2.12	Transit	2Ft2	2Ftr	0	7,5	2	1	0	0	0	0	0	0	0	0
2.13	Transfer	2Fb	2Ftr	0	4	2	0	0	0	0	0	0	0	0	0
2.14	Transit	2Ftr	2Etr	5	0	0,2	0	0	0	0	0	0	0	0	0
2.15	Transfer	2Etr	2Et3	0	7,5	1	1	0	0	0	0	0	0	0	0
2.16	Transit	2Et3	2Ht3	16	0	0,2	0	0	0	0	0	0	0	0	0
2.17	Transfer	2Etr	2Eb	0	4	0	0	0	0	0	1	0	0	0	0
2.18	Bike	2Eb	2Hb	0	0	0	0	0	0	0	0	0	13	0	0
2.19	Transfer	2Ht3	2Hw	0	3	0	0	0	0	0	0	0	0	0	0
2.20	Transfer	2Ht3	2Hb	0	4	0	0	0	1	0	0	0	0	0	0
2.21	Transfer	2Ht1	2Hw	0	3	0	0	0	0	0	0	0	0	0	0
2.22	Transfer	2Ht1	2Hb	0	4	0	0	0	1	0	0	0	2	0	0
2.23	Bike	2Hb	2H (b)	0	0	0	0	0	0	0	0	0	0	0	0
2.24	Walk	2Hw	2H (w)	0	0	0	0	0	0	0	0	0	0	0	5
3.0	State	2H (b)	3H (b)	0	0	0	0	0	0	0	0	0	0	0	0
3.1	State	2H (w)	3H (w)	0	0	0	0	0	0	0	0	0	0	0	0
3.2	Walk	3H (w)	3Hw	0	0	0	0	0	0	0	0	0	0	0	5
3.3	Bike	3H (b)	3Hb	0	0	0	0	0	0	0	0	0	2	0	0
3.4	Transfer	3Hw	3Ht1	0	3	1	0	0	0	0	0	0	0	0	0
3.5	Transfer	3Hw	3Ht3	0	3	1	0	0	0	0	0	0	0	0	0
3.6	Transfer	3Hb	3Ht1	0	4	1	0	0	0	0	0	0	0	0	0
3.7	Transfer	3Hb	3Ht3	0	4	1	0	0	0	0	0	0	0	0	0
3.8	Bike	3Hb	3Ib	0	0	0	0	0	0	0	0	0	12	0	0
3.9	Bike	3Hb	3Eb	0	0	0	0	0	0	0	0	0	13	0	0
3.10	Transit	3Ht1	3Dt1	51	0	0,4	0	0	0	0	0	0	0	0	0
3.11	Transit	3Ht3	3Et3	16	0	0,2	0	0	0	0	0	0	0	0	0
3.12	Bike	3Ib	3Fb	0	0	0	0	0	0	0	0	0	12	0	0
3.13	Transfer	3Ib	3It1	0	4	1	0	0	0	0	0	0	0	0	0
3.14	Transfer	3Ib	3It2	0	4	1	0	0	0	0	0	0	0	0	0
3.15	Transit	3It1	3Ht1	16	0	0,2	0	0	0	0	0	0	0	0	0
3.16	Transit	3It2	3Ft2	16	0	0,2	0	0	0	0	0	0	0	0	0
3.17	Transfer	3Fb	3Ft2	0	4	1	0	0	0	0	0	0	0	0	0
3.18	Transfer	3Fb	3Ftr	0	4	2	0	0	0	0	0	0	0	0	0
3.19	Transit	3Ft2	3Bt2	30	0	0,4	0	0	0	0	0	0	0	0	0
3.20	Transfer	3Ft2	3Ftr	0	7,5	2	1	0	0	0	0	0	0	0	0
3.21	Transit	3Ftr	3Etr	5	0	0,2	0	0	0	0	0	0	0	0	0
3.22	Transfer	3Eb	3Etr	0	4	2	0	0	0	0	0	0	0	0	0
3.23	Transfer	3Eb	3Et3	0	4	1	0	0	0	0	0	0	0	0	0
3.24	Transfer	3Et3	3Etr	0	7,5	2	1	0	0	0	0	0	0	0	0
3.25	Transit	3Et3	3Bt3	10	0	0,2	0	0	0	0	0	0	0	0	0
3.26	Transit	3Etr	3Dtr	5	0	0,2	0	0	0	0	0	0	0	0	0
3.27	Transfer	3Bt3	3Bt2	0	6	0	1	0	0	0	0	0	0	0	0
3.28	Transfer	3Bt3	3Bb	0	4	0	0	0	0	0	0	0	0	0	0
3.29	Tranfer	3Bt2	3Bb	0	4	0	0	0	0	0	0	0	0	0	0
3.30	Bike	3Bb	3Ab	14	0	0	0	0	0	0	0	0	0	0	0
3.31	Transit	3Bt2	3At2	8	0	0,2	0	0	0	0	0	0	0	0	0
3.32	Transfer	3Dtr	3Dt1	0	5	1	1	0	0	0	0	0	0	0	0
3.33	Transfer	3Dtr	3Db	0	4	0	0	0	0	0	0	0	0	0	0
3.34	Transfer	3Dt1	3Db	0	4	0	0	0	0	0	0	0	0	0	0
3.35	Bike	3Db	3Ab	13	0	0	0	0	0	0	0	0	0	0	0
3.36	Transit	3Dt1	3At1	7	0	0,2	0	0	0	0	0	0	0	0	0
3.37	Transfer	3At1	3Aw	0	3	0	0	0	0	0	0	0	0	0	0
3.38	Transfer	3At2	3Aw	0	3	0	0	0	0	0	0	0	0	0	0
3.39	Transfer	3At1	3Ab	0	4	0	0	0	0	0	0	0	0	0	0
3.40	Transfer	3At2	3Ab	0	4	0	0	0	0	0	0	0	0	0	0

Figure F1: Optimization setup for the complex tour