The Integrated Station

A transfer quality assessment model for multi-modal stations

Jan Siblesz

Master Thesis

The Integrated Station

A transfer quality assessment model for multi-modal stations

by

Johannes Maarten Siblesz

to obtain the degree of Master of Science
in Transport, Infrastructure & Logistics
at the Delft University of Technology,
to be defended publicly on Tuesday September 21, 2021 at 16:00.

Thesis committee:

Prof. dr. G. P. (Bert) van Wee	TU Delft, Faculty of Technology, Policy and Management	Chair
Dr. W. W. (Wijnand) Veeneman	TU Delft, Faculty of Technology, Policy and Management	Daily supervisor
Dr. Ir. N. (Niels) van Oort	TU Delft, Faculty of Civil Engineering and Geosciences	Daily supervisor
Dr. Ir. T. (Ties) Brands	TU Delft, Faculty of Civil Engineering and Geosciences	Project supervisor

TU Delft

Preface

When I started thinking about my graduation project two years ago I already knew that it would be a major challenge. After completing this project I can say it was. Especially working at home alone in times of a pandemic was often not easy or fun. Luckily I had good help from my supervisor and from the people around me, mainly my room mates and closest friends.

This project started for me with a brain storm with one of my supervisors and quickly the outline for the project was set. Shortly after I met my other daily supervisor who hooked me up with a company to potentially cooperate with. I had a nice meeting with this company but unfortunately the pandemic shortly after that. This meant that I had to start over and write a research proposal for an in house research project at TU Delft.

Over the past year I have carried out my research and written this document. The process has had some ups and downs. My small room and my working style do not seem to be fitted towards working from home well so the various stages of lockdown were always hard. I am happy to have found a place at the library when it was open. I have to thank Niels, Wijnand and Ties for their support especially during the several lock downs, arranging possibilities to work at the university when this was not easy and being there for me in our weekly meetings.

I look forward to challenges ahead of me. Doing this research has put me into contact with a lot of interesting people and has helped me in finding my first job. After a short vacation I will start my work at ProRail.

Jan Siblesz
Delft, September 2021

Contents

Summary

Transport is the lifeblood of cities. A well functioning transport system is a key prerequisite for the success of an (urban) area. Public transport (PT) is a vital part of this system. It allows all members of the population to fully take part in society and fulfill their potential. PT can also help to solve some of the major problems that face us in the 21st century. Replacing private cars on the road by people using PT saves resources, pollution, and space. A well constructed PT-system consists of several layers of hierarchically ordered interconnected modalities. The interfaces between these modalities have been identified as the weakest point of the system (see figure 1). The figure depicts the difference between the experience of being at home or at one's destination and the experience of being in transit. The gap resembles the opportunity cost of travelling. It is known that people are affected most by bad experiences, these are often the only parts one remembers. Hence raising the floor level of the experience can majorly increase the attractiveness of the system.

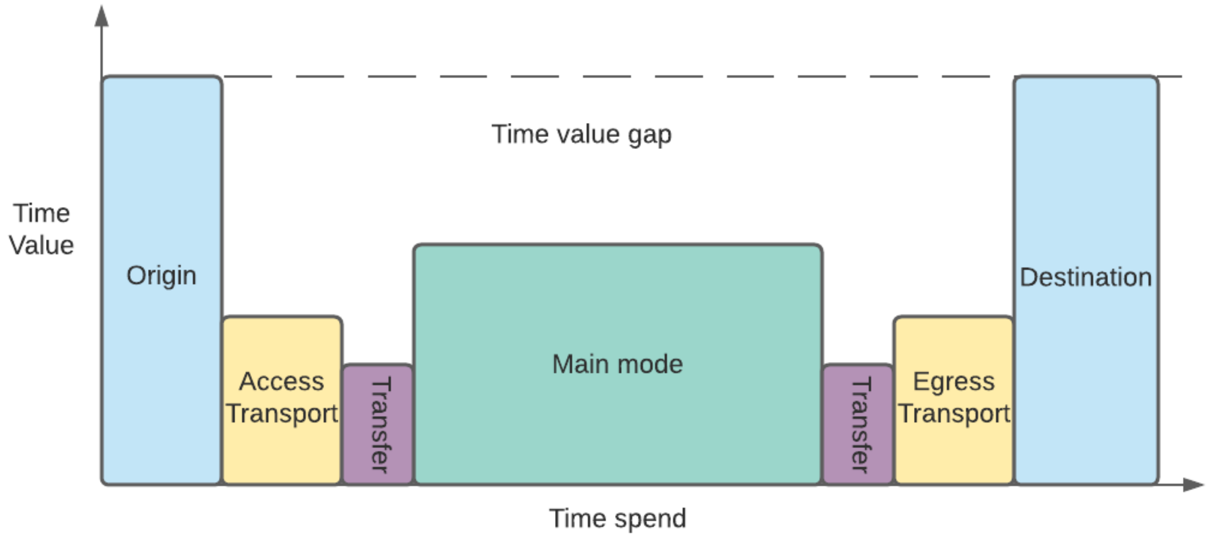


Figure 1: Graphical representation of the time value gap (Peek and Van Hagen, 2002)

A strategy to overcome the perceived obstacle of connecting between two different modalities has been developed. Integrated public transport aims to remove the barriers by addressing organizational, operational, and physical integration between various modalities and operators. This research will focus on the mapping of physical integration. The goal of this research is to develop a model that is able to quantify a station's ability to facilitate multi modal transfers. The main research question that this project strives to answer is formulated as follows:

How can we measure a public transport station's ability to facilitate an efficient and comfortable multimodal transfer?

Literature Review

The literature review consists of two main parts. First an existing framework for station assessment is studied and the contribution of this research to the framework is defined. Then an interdisciplinary

literature study is conducted with the aims of finding a comprehensive list of factors that describe design factors influencing a station's ability to facilitate transfers.

The node place model

A well functioning station combines the transport demand of an urban area with the transport supply of the PT-systems it connects to. Both spatial activity resulting in demand, the place value, and transport supply, the node value, can be quantified. These scores can indicate the development state of a station. This type of model is known as the node place (NP) model. Traditionally NP-models look at the stations themselves as black boxes. The stations here are merely seen as bridges between the transport system and the urban system without looking at the processes taking place within the station. Theoretically extensions of this model with more local design characteristics have already been thought out. These ideas formed the basis of table 1 below. Recently efforts have been made to quantify processes within the station in the model. However this has only been done for the quality of the waiting accommodation at stations, the local place value. This research aims to enrich the model with an operationalization of the transfer quality within stations. The place of this new element within the existing model framework is shown in table 1 below highlighted in boldface, in the bottom left corner, the local node value. The contribution to the NP-model is the main scientific contribution of this project.

	Node Values	**Place Values**	**Model Properties**
Network Properties	Classical Node Value	Classical Place Value	Traditional NP-model components
	Transport supply	Transport demand	Station is a black box
	Network contextual node value	Urban contextual place value	Location quality
Local Properties	**Transfer quality**	Station Experience	Analyzing stations as micro systems
	Independent Node Quality	Independent Place Quality	Focus on processes within the hub
	Interchange Walking	Interchange Waiting	Design Quality

Table 1: Elements of the extended node place model (inspired by Peek (2006), Peek and Louw (2008))

Factor search

The second part of the literature study consists of the gathering of factors that will be used in the model. To do this several scientific fields studying station and PT performance were studied. From these fields of research factors are taken and combined in a final list that will be used as a model building block.

There were six fields of research identified that were used to find factors. The first was the study of PT integration. This research looks into the administrative and political organisation of the PT-market and studies its effects on system performance. This is relevant for our research because we have identified the interfaces between systems as the main weak point of the entire system. The strategy of PT integration tries to combat this weak points. The second field was customer satisfaction research. The figure used in the introduction of this chapter stems from this school of thought. This is a field rooted in psychology and marketing research. Factors for this category are divided in two groups. Dissatisfiers are factors that negatively impact experiences when expected levels are not met, factors you need to have. Satisfiers are factors that effect experience positively when present, these factors are nice to have. The third field was utility based traveller research. This research comes from the econometrical science and has been used in transportation for a long time. People are seen as utility maximizers and the effect of every factor (attribute) is expressed as the contribution it has to the overall utility. The fourth researched field of science was simulation modelling. This field studies the effects of design on pedestrian flow within a station. The fifth and sixth fields consist of large scale station analyses. Survey and usage based research are used here to gain a better understanding in the workings of current stations.

From all these scientific fields factors were gathered. Many overlapped but some fields offered unique insights. The gathered factors that will be used are listed in table 2 below. From the literature conceptual factors were gathered. In the next section these factors will be translated into measurable factors.

	PT integration	Customer satisfaction	Utility	Simulation	Transfer numbers	Case studies
Transfer distance	x	x	x	x	x	x
Transfer flow	x	x		x		x
Traffic crossings	x				x	x
Route weather protection	x	x	x			
Wait weather protection		x	x			
Elevators and escalators		x				x
Bottleneck capacity				x	x	
Signage	x		x			x
Real time information	x		x			x
Service availability	x	x	x		x	x
Location of services		x		x		
Design priority		x		x		x

Table 2: List of all relevant factors and their source field .

Model Design

In this section the building blocks of the model will be laid out. First elements and the way they are obtained will be defined, concluding with the full mathematical structure of the model. The conceptual representation of the model can be found in figure 2. In line with existing models from the NP-model family and with other similar station assessment models it was chosen to use a multi criteria analysis. In a multi criteria analysis every scenario or design option is represented as a collection of criteria (factors). All factors can then be scored and weighed to achieve a total score. In this research it is chosen to work with four final scores since many design aspects are unrelated: a shorter walking connection can not mitigate bad signage.

The left side of the figure represents the structural components of the model. This side is the model proper and can be seen as one of the deliverables of this project. This part explains what inputs the tool needs and how this inputs should be collected. The right side shows the inputs that will vary per case. In this project a case study will be used to test the model. The left side will be addressed in this section, the right side in the next section.

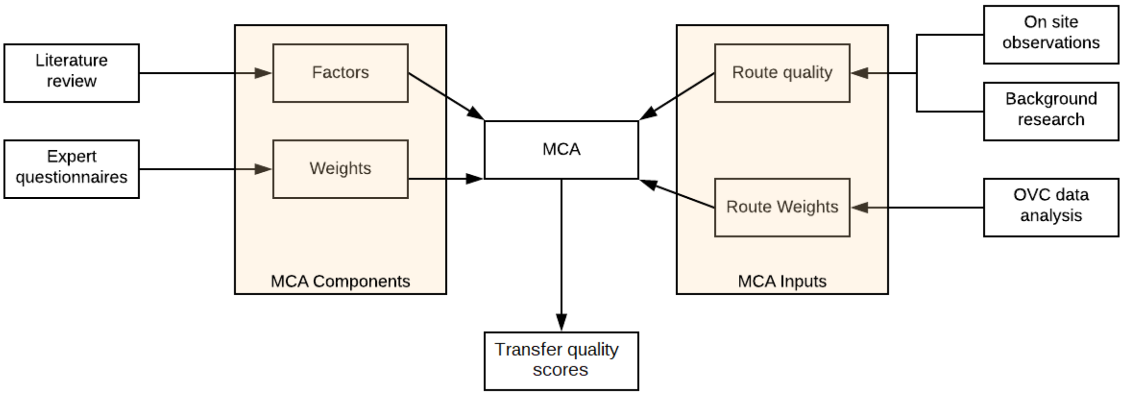


Figure 2: Conceptual representation of the model structure

Factor definitions

Factors that are used in an MCA need to adhere to three main criteria. They should have minimal overlap, need to be easily obtainable, and be limited in numbers. This meant that the chosen methodology of case study research with on site observations also had its influence on the final definition of factors. The complete used list of factors and their definitions can be found in table 3 below.

For further analysis the factors will be aggregated into four categories. Distance will stay its own category because of the direct effect on travel time which is known to be very important. This was chosen due to the relative ease of measuring distance compared to time. Traffic crossings, route and wait weather protection, and the presence of elevators and escalators together form the category path quality. Fixed signage and dynamic information form the category information provision. Finally shops, toilets, staffed desks, and detour make up the category of service.

Values for these thirteen factors can be obtained via a combination of an on site survey and online background research. This finally provides a value for every factor for every connection between a pair of modalities.

Factor name	**Definition**
Distance	Walking distance between the platforms of two modalities.
Traffic crossings	Describes whether there are crossings with other forms of traffic.
Route weather protection	How are walking passengers protected against the elements?
Wait weather protection	How are waiting passengers protected against the elements?
Presence of elevators	Do elevators cover all height changes in a route?
Presence of escalators	Do escalators cover all height changes in a route?
Fixed signage	Is the presented fixed signage complete and correct?
Dynamic information	Is the presented dynamic information complete correct and on time?
Shops	Are convenience stores present?
Toilets	Are public toilets present?
Staffed desks	Are staffed desks for tickets and information present?
Detour	How far is the detour from the ideal route to visit a shop?

Table 3: The thirteen model factors and their definitions.

Gathering factor weights: the Best Worst Method

To obtain factor weights for the MCA it was chosen to use the best worst method (BWM). BWM provides and efficient way to use expert opinions to systematically compute factor weights. The base of the BWM is a pairwise comparison of every factor with two reference factors, the most important (best) and least important (worst) factors in its category.

To obtain the weights fifteen PT-experts were interviewed. These professionals work in academics, government, operations, and consultancy. Interviews were conducted via video conference and along with the answer of the questionnaire notes were taken on the respondent's reasoning for certain answers. Many respondents either explicitly or implicitly noted the idea of satisfiers and dissatisfiers when answering the questionnaire. Results of all fifteen experts were finally aggregated by taking the geometric means for every factor and rescaling the weights within every category. For every category a total of one point is available that will be allocated between all factors in the category. Final outcome of this process can be found in table 4 below.

Factor	Distance	Traffic crossings	Route weather protection	Wait weather protection	Elevators	Escalators	Bottle neck capacity	Shops	Toilets	Staffed desks	Detour	Fixed Signs	Dynamic information
Weight	1.000	0.221	0.096	0.227	0.123	0.110	0.224	0.297	0.275	0.241	0.187	0.618	0.382
Category	Distance	Path Quality						Service				Information Provision	

Table 4: The thirteen model factors and their final weights

Route weights

The second part of the input side of the model is the route weights vector. In the model the share of transfers on a specific connection is used as a marker for the importance of the route. In busy stations allocation of space to the most important routes is key. Using a value weighted for the usage of every route can address this design priority.

Model statement

The core functionality of the model is that it combines the values of every single observation with two weights. The scores for every route are weighed by the route weight that is based on a route's usage share. The observations for every factor are weighed by the factor weights obtained from the bwm.

Mathematical representation of this can be found in formula 1 below. Where s_{ij} represents the element score, f_{ij} the value of the original observation, and r_i and w_j the weights for routes and factors.

$$s_{ij} = f_{ij} * r_i * w_j \tag{1}$$

After obtaining the score of a single element there are several options of aggregating the outcomes. It is possible to compute the scores (C_{ik}) across several categories (k) for all routes (i). After this we can aggregate for all modalities to calculate the score of a category for that station (S_k) or we can keep more detailed scores for for example every modality.

$$C_{ik} = \sum_j f_{ij} w_j \qquad \forall j \in G_k$$

$$S_k = \sum_i C_{ik} r_i \qquad or \tag{2}$$

$$S_k = \sum_i \sum_j s_{ij} \qquad \forall j \in G_k \tag{3}$$

Case study

Now that we have defined the structure of the model it is time to fill in the model with data. This data will be obtained from a case study. For this research Amsterdam was chosen as a case study. In 2018 the new north south metro line (Dutch Noord-Zuidlijn: NZL) was opened. Alongside came a major restructuring of the PT-network in the entire city. To accommodate the new line several stations had to be altered and new stations were built. Adding new components to already complex stations can lead to a decreased performance. The model that we have established will be used in this case to study the effects the addition of the new line has on the performance of the entire stations. In Amsterdam three cases were picked as study objects: Amsterdam Centraal is the city's main railway station. An international hub connecting (intercity) trains to all regional and local modalities serving commuters as well as tourists. Amsterdam Zuid is the second busiest railway station in Amsterdam. The station serves the Zuidas financial district as well as universities and other educational facilities. The station connects (intercity) trains to local and regional modalities. Amsterdam Noord is a station that was newly built as the northern terminus of the NZL. Along with it a large bus station connecting regional busses was erected. An overview of the three studied stations can be found in table 5 below. From these case study objects we will gather two types of model inputs. On site observations describing the station's design and transfer data to obtain the route weights.

	Train	Metro	Tram	Bus
Centraal Station	x	x	x	3 ops
Zuid	x	x	x	2 ops
Noord		x		3 ops

Table 5: Overview of the three stations and their connections, for busses the number of connecting operators is noted

On site observations

All stations were surveyed twice. Once in the morning peak and once in the evening peak on different days of the week. It is important to note here that this entire project was conducted during the Covid-19 pandemic and traveller numbers were down to forty percent of pre-Covid levels during this period. Measurements were done like this because during rush hours stations experience the maximum level of stress of users and thus weak points will show up more easily during this period.

Transfer data analysis

To obtain route weights transfer data has to be analyzed. In this project we had access to a data set containing all transfers made in the Amsterdam area made from September till December 2019. More than a year after the opening of the new line and well before the arrival of the pandemic in western

Europe. This large data set was aggregated into a transfer OD-matrix for every station for the relevant period. From these OD-matrices intermodal transfers were eliminated to finally come to a route weights vector as can be seen in the rightmost column of table 6 for Amsterdam Noord below.

The model in practice

Now that all individual model elements have been obtained and the theoretical structure of the model has been listed all results can now be aggregated by the model. The technical working of the model can be found in figure 3 below. In the figure squares describe sets of data and ovals describe processes of data collection and manipulation.

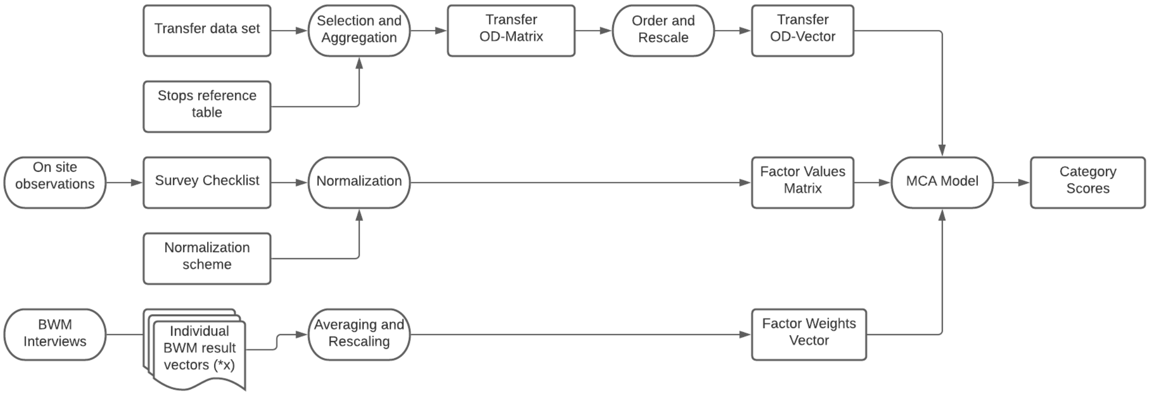


Figure 3: Conceptual view of all steps taken towards the execution of the final model

Most data analysis steps were done via python code, some of the smaller steps were done in excel. The selection and aggregation was done in python. Here a selection was made from over five hundred thousand lines of data. First a selection specific for the station was made and then for the time of day. From this twice selected data transfer numbers were aggregated by the OD-pairs. The final operations were done in excel to get the OD-vectors needed. The second path of data analysis, the middle branch in figure 3, consisted of the processing of the case study observations. This process started with the observations yielding a filled in survey checklist. Via a step of normalization that translated all measurements on a scale from 0 (low) to 1 (excellent) this yielded a factor values matrix. The third step of the analysis consisted of the processing of the data from the BWM interviews. The outputs of each interview were individually optimized and geometric averages were taken of all interviews. This yielded a complete weights vector.

Case study results

Before going to the aggregated results of all stations first some specific results of a single case will be presented to highlight the working of the model. In table 6 the individual factor scores and route weights for the case of Amsterdam Noord can be found. Here we can see the scores for all categories for every route before a possible final aggregation step.

	Distance	Cross	Route	Wait	Elevators	Escalators	Cap	**PQ**	Shop	Toilet	Desk	Detour	**Service**	Signs	Dyna Info	**Info**	**Route Weight**
Metro-BusE	**0.73**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.09	**0.44**	0.62	0.10	**0.71**	**0.32**
BusE-Metro	**0.73**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.09	**0.44**	0.00	0.38	**0.38**	**0.27**
Metro-BusW	**0.77**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.62	0.10	**0.71**	**0.20**
BusW-Metro	**0.77**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.00	0.38	**0.38**	**0.17**
BusE-BusW	**0.63**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.00	0.38	**0.38**	**0.02**
BusW-BusE	**0.63**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.00	0.38	**0.38**	**0.02**

Table 6: Overview of the model results for Amsterdam Noord

Results can now be aggregated in several ways. Here we will use the highest level of aggregation, the station level, and compare the three cases against each other.

	Asd	**Asdz**	**Nrd**
Distance	0.45	0.38	0.74
Path quality	0.89	0.59	0.84
Service	1	0.88	0.48
Info	0.86	0.85	0.55

Table 7: Aggregated model results

Amsterdam Centraal (Asd) stands out as a well functioning large station. Having a high score on most quality aspects but a lower score on transfer distance. Amsterdam Zuid (Asdz) scores lower across the board. Indicating the station has not kept up with increasing usage and its current status as the city's second main station. Plans are however on their way to address these problems. Noord (Nrd) is a more compact station that scores lower than the other stations on some categories. Noord is however a very different station from the two train stations with users that expect different levels of service. This also indicates the limitations of a model such as this that is normative in nature.

Conclusion

The main question that this research tries to answer was:

How can we measure a public transport station's ability to facilitate an efficient and comfortable multi-modal transfer?

To answer this question this project developed a measurement tool. Using the methodological tradition of NP-models the choice was made to use the structure of a MCA for this tool. This was combined with usage numbers as weights for the routes. The tool consists of a list of design factors and a manual on how to obtain them combined with a list of factor weights obtained by interviewing experts. The tool was used on a case study consisting of three stations in Amsterdam that were recently altered to accommodate a new metro line. The tool provided interesting insights in the design of these stations, a notion supported by current plans to tackle problems that were also found by the tool. Another main finding was the overall low scoring of outside locations, not only on weather protection but especially on information provision busses and trams stand out in a negative way.

Although the developed tool managed to satisfy most of the question asked more research could be done: The first idea would be to test the tool more and use more data to feed the model. The current sample of fifteen experts can be made larger or be altered by using local experts familiar to the case. Secondly the tool could be integrated in existing NP frameworks to provide a more integral station assessment toolbox. Changing the use case from an exploratory measurement tool to a complete station audit framework. Finally the type of inputs of the model could be altered to make the model useful for predictive research. One of the main strengths of MCA's is their ability to objectively compare scenario's. Replacing the currently used observations with model outputs the tool could be used to assess the quality of proposed designs instead of only the ex post analyses it can currently.

Finally some remarks have to be made on the execution and scientific quality of this research. A large part of this research relies on the opinion of experts given during interviews with them. First of all the selection of these experts could have been done more systematically. Experts were handpicked by the researcher through his contacts and that of the supervising team. Secondly, during the interviews it was noted that respondents did not always completely understand the interviewer. It was noted that the skill of the interviewer increased when the project progressed which showed in the results. The input of this tool partially consists of data collected during on site observations. Although it was tried to do these observations in a standardized way and to survey every station twice this still left the feeling that some observations were based on rather random occurrences influencing the replicability of the research. The last point that has to be made is that the process of developing this model lacked an actual validation step. A sort of preemptive validation was included as part of the interviews but an actual audit of the final model would have improved the quality.

List of Figures

List of Tables

1

Introduction

1.1. Problem Analysis

1.1.1. The Role of Public Transport in the 21st Century

A good transportation system is a vital part of a well functioning city or area (Vuchic, 2005). Uncapped private transport has caused a lot of problems over the years. Mainly the mass introduction of private cars has introduced problems such as air pollution (RIVM, 2013) and urban sprawl (Bertolini, 1999), inefficient usage of space and non renewable (fossil) resources. Public Transport (PT) is increasingly seen as a viable and necessary alternative to private cars and its usage is thus being encouraged. More positive arguments for public transport come from its ability to transport everyone. Not everybody has access to a private car, whether they are too young or too old, don't have the financial means, physically aren't able to drive or simply choose to not own a car, it is still important for these people to have access to transport to fully take part in society, education, work etc (Delbosc and Currie, 2011, Guzman and Oviedo, 2018, Manaugh and El-Geneidy, 2012), this property makes it truly *public* transport.

Through the years many efforts have gone into promoting the usage of PT versus that of private cars. This has often proved to be very difficult because many people feel a strong emotional connection to their car (Harms et al., 2007), or otherwise are heavily influenced by a small number of negative encounters with the PT-system (Harms et al., 2007). To convince people to start using more public transport large efforts have been made to improve quality, frequency and capacity of public transport (Saliara, 2014). This includes the large scale roll out of new urban light rail systems and (inter)national high speed rail systems (Bruinsma et al., 2008). One of the main perceived benefits of car transport is the perceived freedom and independence it allows its user (Harms et al., 2007). To make for a competitive PT product the PT system has to be upgraded to combat this feelings. Increasing the frequencies of a line can decrease the urge to keep looking at the timetable and one's watch (Harms et al., 2007). Next to the improvement of individual modalities and lines there's an overarching strategy that's increasingly used. One of the strong points of a car is it's ability to, in most cases, deliver door to door transport, PT however connects stops and especially train networks connect cities, this makes access and egress transport always an extra consideration when planning a PT trip (Harms et al., 2007). It is not economically feasible to have a complete network of point to point connections (Rivasplata, 2003), an efficiently organised PT-network consists of several forms of hierarchically ordered modalities connected at hubs (Saliara, 2014). The weakest points of these systems are the interfaces between several modalities within and connected to the PT-system, either physical when interchanging, or operational when having to buy multiple tickets for different parts of one journey. To combat these problems the strategy of integrated public transport has been developed (Saliara, 2014). Integrated public transport calls for cooperation and integration between operators usually coordinated by a neutral government party. An overview of the theory of integrated PT can be found in table 1.1. The overall goal of this strategy is to provide seamless journeys with minimal interruptions (Saliara, 2014). These strategies can also include the active modes, walking and cycling, to cover the first and last parts of the trip from and to the transit stop. This holistic view on a PT trip helps to improve the competitiveness of PT with respect to the usage of private cars.

Organizational Integration	**Operational Integration**	**Physical Integration**
Bilateral agreements between operators	Network layout	Access to facilities
A neutral governing body overseeing all operations	Schedules and Transfers (see also Schakenbos et al. (2016))	Location of facilities (see also Bertolini (2008))
	Information	Design of stations (see also Daamen (2004) and Groenendijk et al. (2018))
	Fares and Tickets	Control of vehicle movements
		On site information (Bryniarska and Zakowska, 2017)

Table 1.1: Three types of PT integration, adapted from Saliara (2014)

In table 1.1 several strategies and possible fields of cooperation are described. If these steps are followed the largest perceived downsides for travellers making intermodal trips can be eliminated or at least mitigated. For this research the focus lies on station design. Because of this we will focus on the components of physical integration. More on this in paragraph 2.2.1.

1.1.2. Transfers in a PT journey

In the previous section we described the interfaces between various elements of the public transport system as the weakest links in the entire system. Schakenbos et al. (2016) describe a transfer as the least appreciated part of a PT journey, a view shared by Peek and Van Hagen (2002) (see figure 1.1). Bryniarska and Zakowska (2017) add that transfers introduce extra effort, uncertainty, and waste of time to a journey. Lee et al. (2014) add unreliability, especially in low frequency systems, Schakenbos et al. (2016) also describe the relationship between frequency and and transfer penalty. These notions connect to the point of view of seeing a transfer as a disutility, an added perceived penalty within a journey. Wardman et al. (2001) operationalizes the transfer penalty with three components, the pure penalty is the penalty associated with the transfer itself, one has to pack up their stuff and get out of the initial vehicle, the second component is the walking time and its value, the third is the waiting time and its value. Strategies to valuate and improve these components will be discussed later in this research. Transfers as a disutility also tie into the broader view that transport is a disutility. The time value gap as presented in figure 1.1 represents the amount of money, time and effort spend whilst travelling. Strategies to improve traffic will often try to decrease this gap, in our case we focus on the value of the lowest part of the journey, the transfer. It is important to note that PT integration alone is mostly not enough to make PT competitive. Integration measures should be combined with system wide improvements in capacity, frequency and quality of the different PT-modes (Ibrahim, 2003, Saliara, 2014). The effect of these measure can easily be seen when looking at figure 1.1, these measures will improve the value of the biggest block showing the main mode. The transfers only take a short period of time but are valued very low. Especially when basic needs (for more on this see 2.2.2) such as safety and reliability are not met this can create a very negative impression of the entire journey and cause negative memories influencing the perception of the entire PT system (Harms et al., 2007).

Schakenbos et al. (2016) found a difference in preferences between intermodal transfers and train-train transfers. They found that the preferred time one has to transfer is higher for intermodal transfers. This again indicates that there is still a perceived inter system barrier. In his thesis Schakenbos (2014) indicated that there were large differences in preferred transfer times between the several cases that were studied in his research. Especially the case of Amsterdam Amstel station where there is the possibility to transfer cross platform from train to metro and vice versa gave a desired value for metro-train connections that was the same as for train-train connections at other stations. This shows that layout, design and operations of a station can clearly contribute to the elimination of perceived inter system barriers and can result in faster and more comfortable journeys.

In the Netherlands the current leading paradigm on determining station quality is that of the node place model (NP-model) (Groenendijk et al., 2018), this model has been developed originally by Bertolini (1999). More on this model can be found in paragraph 2.1. Recently an extended NP-model has also been adopted by dutch rail infrastructure manager Prorail to assess station performance and promote integral design (ProRail, 2019). Peek (2006) describes this model as a versatile framework that can be tailored to measure the qualities relevant for the researcher. This can be a real estate party, a government, an operator or a scientific party. The current models however hardly look at the stations itself but mainly on their positions in the transportation and urban networks they are attached to. Groenendijk et al. (2018) have operationalized the waiting experience on stations. Peek and Louw (2008) have stated the idea and defined the concept of the connector station, a station design optimised for the flow of passengers within the station optimally connecting different modalities. They did however not operationalize the evaluation of this design direction. This is the scientific gap this research aims to fill. By adding a component valuating the station's performance to facilitate transfers to the NP-model. This contribution makes the NP-model better equipped to express the quality of a station as a part of a multi modal journey that does not begin or end at the evaluated station.

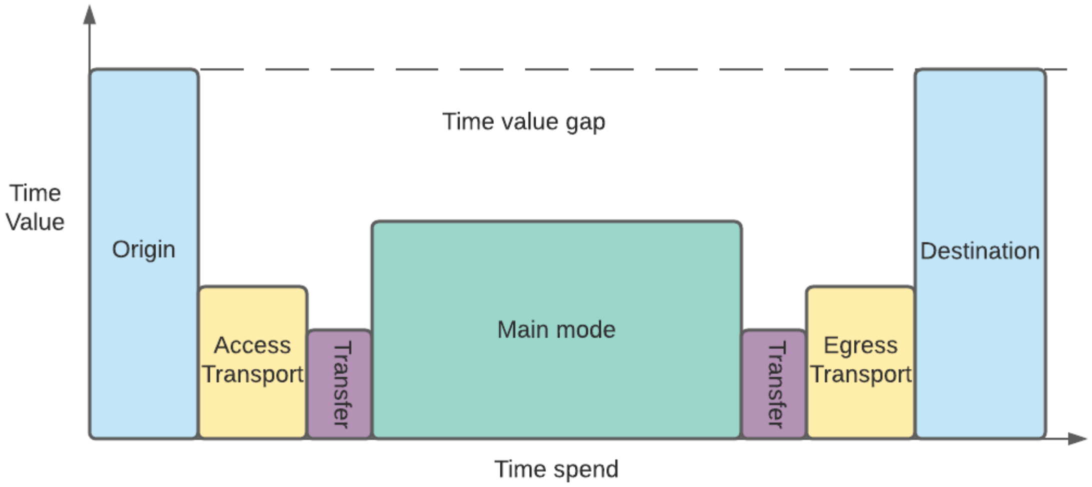


Figure 1.1: Time valuation of a PT journey (Peek and Van Hagen, 2002)

1.2. Research Design

Now that we have identified the transfer as the main perceived bottle neck in a multi modal PT journey we will answer the question how we can contribute to a better understanding of this problem and how this research will help find a solution for this problem. As we have seen in table 1.1 this problem runs across multiple lines. In this research we will focus on the physical component of PT-integration: station design.

1.2.1. Research Objective

The main goal of this research is to contribute to a better understanding of the role of functional station design in a multi modal transport journey. Secondly this increased understanding of the role of integration in station usage can contribute to a better design which will eventually help to increase the competitiveness of the entire PT-system by offering improved better integrated journeys.

The current paradigm on station performance assessment, the node place model (NP-model), see also paragraph 2.1, offers a very versatile model framework that suits most actors in a station environment. This research tries to add a component to this model from the perspective of the transportation researcher. We want to quantify a station's ability to facilitate multi modal transfers by developing a tool for the scoring of transfer quality.

We want to develop a model that is to be able to assess different designs for a specific station case without going into detailed simulation and to compare different stages of a station's development and design process. This research will focus on the design, development, implementation and reflection on the usefulness of this model.

1.2.2. Research Questions

How can we measure a public transport station's ability to facilitate an efficient and comfortable multi-modal transfer?

To answer the main research question the problem is split up in the following sub questions and elements:

1. What design factors influence a station's performance to facilitate multi-modal transfers?
2. How can we develop a measurement model to combine and weight the design factors into performance scores?
    (a) How can we measure and quantify the design factors?
    (b) How do we compare and weight these factors?
    (c) How can we integrate the importance of different modalities in a hub in the model?
3. Can we use this measurement tool to accurately determine a stations actual quality to facilitate transfers?
4. What design lessons, positive and negative, can be drawn from the analysis of hubs using this tool?

1.2.3. Scope

The goal of this research is to add a component to the existing node place model. Because this research focuses especially on multi modal transport it will be used for hubs with at least one form of rail based transport and at least one form of more local transport, usually bus. Additionally we focus on purpose build station buildings. Here we differ from previous studies such as Bryniarska and Zakowska (2017) who developed a model for the evaluation of road side tram and bus stops.

To test the functioning of our model this research will use the model on a case study of Amsterdam. In 2018 a new metro line called the 'Noord-Zuidlijn' (NZL) was opened. This new metro line directly connects the two main railway stations, the central and south station, and runs through the city centre. Along with it the entire PT-system of the city and surrounding area was reordered, and a new major bus hub was created at the terminus of the line, metro station Amsterdam Noord. This forms a very interesting case for the evaluation of different stages of hub development and for the comparison of newly build and preexisting stations of various sizes. TU Delft currently participates in a larger project to research the impact of the new line on several aspects of transport and spatial development in and around Amsterdam. Through this project we can have access to valuable data and contacts key to the completion of this project. The three stations, Centraal, Zuid, and Noord, will be the main objects of study for the case study.

1.2.4. Methodology

The goal of this research is to develop a model that can combine the various elements of station design into aggregated scores. This valuation of transfer quality can then be used to compare different stations or design scenarios of one station. Secondly it can be an added component to pre-existing NP-models giving a more complete view of station quality than the current generation of models do, see also paragraph 2.1. Further development steps include the validation and testing of this model on a real life case.

To achieve the goal of obtaining one aggregated score there are multiple possibilities. For this research a multi criteria analysis (MCA) will be used. This fits in with current variants of the NP-model and allows for easy valuation and weighting of different design components (factors). Another option that is popular when evaluating stations is the approach of choice models (Schakenbos et al., 2016, Wardman et al., 2001). With this method the direct utility contribution of a station is determined and the factors are determined from there. We will not do this because of multiple reasons. The method requires a lot of input data from questionnaires, this is very difficult without a field partner that can aid in distribution. This method would deliver a more concrete number of the utility contribution, where the current NP-models use a more abstract score. The MCA method is less data intensive, a couple of well chosen experts can already fulfill this requirements. A third option would be a large scale questionnaire directly valuating several design factors. An example of this type of research in a scientific context is Hernandez et al. (2016), commercially this is also done by railway operator NS (NS Stations and ProRail, 2021). These researches gather data from users of every point of interest needing a high amount of data when trying to generalise the results of a study. This scalability is a main advantage of tha MCA. Our MCA will consist of four main components as can be seen in figure 1.2. The four components and the way these are obtained will now be presented shortly. The numbers in the figure correspond with the sub questions that concern these model elements.

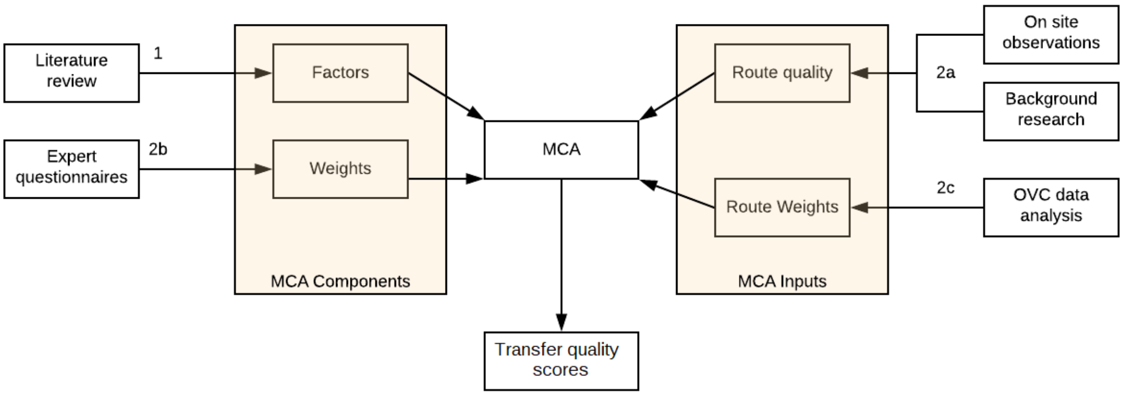


Figure 1.2: Outline of the steps of MCA data collection

The first component of the MCA is formed by the factors. From literature on PT-integration, customer satisfaction, choice model based traveller research and pedestrian flow simulation models we hope to find a set of factors describing all relevant station design parameters. A second component is formed by the values of these parameters. These values will be obtained in a combination of background desk research on station properties and on site observations into how the station is actually being used.

To accurately determine the contribution of a specific factor to the overall integration quality we will attach specific weights to every factor. To obtain these weights we will approach field experts with scientific, government, and operational backgrounds. These experts will be given a questionnaire to determine the relative weights of all parameters. Asking experts gives us also the option to differentiate the scores of the different fields of expertise and to perform a control experiment testing our methodology alongside the main questions.

The fourth component that is very specific to this research is the route weight. The factor values used as input for the model will be mode pair specific. That means that for every OD-pair within the station a route score will be obtained by combining the route factors and weights. Because we want to evaluate the design choices that have been made we will check for the priorities in the design in this step. The route weights will be based on the actual observed number of transfers made between specific pairs of modalities. These transfer observations will be made based on smart card data. Through the larger NZL research project we have access to various data sets of transfers made at several stations in Amsterdam. By using the relative flows within the station as weights for the route scores we can incorporate the value of prioritisation within the station design.

A case study will be conducted to assess the practical usage of our model and to answer the sub questions of research question four. More on the contents of this case study can be found in the latter part of paragraph 1.2.3. Here we will compare a new station, Noord, with a station that was severely changed to accommodate the NZL, Amsterdam Centraal and a station that only saw a service change, Amsterdam Zuid. These three stations will be analyzed with our model. And the two preexisting stations will do this for their designs before and after the introduction of the NZL. The case study research will consist of the digital and on site surveying of the stations using the checklist formed by the MCA factors.

1.3. Thesis Outline

The following chapters will layout the steps taken to build up the model and will answer the research questions. In chapter 2 first some more scientific background outlining the scientific gap this study strives to fill is given. In the second part of chapter 2 several scientific fields studying station performance and traveller behaviour will be outlined to build up a theoretical framework of criteria that can be used in the model. Chapter 3 will outline the structure of the model. By first defining all elements of the model in a theoretical mathematical way the outline of the model will be drawn. In chapter 4 this outline will be filled in by testing the model on a case study. In the last chapters we will reflect on the model itself and then on the project in its entirety and finish of by answering the main research question that started this project.

2

Literature Review

In this chapter we will set out the scientific background against which our to be developed model is set. First we will cover the development of the Node Place-model (NP-model) that our model will add a component to. Then we will go over current scientific ideas on station interchange assessment and try to find useful elements in these existing ideas. Finally we will come up with the list of factors derived from existing literature to act as our surveying checklist for the stations. At the end of this chapter we aim to have answered the first sub-question:

1. What design factors influence a station's performance to facilitate multi-modal transfers?

For this literature review we started with a lot of tips given by supervisors and other contacts and with sources that I had encountered over the past years in my studies. Early on in the project several other master theses like Groenendijk (2015), Schakenbos (2014), and Hoekstra (2018) were very helpful in methodology, general project design, and scientific content. Next to these known starting points google scholar was used to find sources. Here I started searching for literature considering station design. Quickly it was noticed that the term station was used in many fields besides public transport. After this 'public transport station' was used as a search term. To get more results station was then replaced by interchange, hub, and node. As a third step in this cycle the already mentioned combinations were combined with the search terms assessment, evaluation, and analysis to look for analytical works. To look for more specific literature 'public transport transfer penalty' and 'public transport transfer (flow) simulation' were used. Next to these primary searches snowballing from the already found literature was performed, using the listed sources and sources listing found literature. Looking for other works of known authors also proved a valuable source of new information. Especially in the early phase of the project I also used sources and searches in Dutch, especially for policy documents and government produced content this was useful, even dissertations from the beginning of this century can still be in Dutch.

2.1. Station Performance Assessment: the Node Place Model

Over the last twenty years the node place model (NP-model) as first posed by Bertolini (1999) has been the leading paradigm in station quality measurement in The Netherlands (Groenendijk et al., 2018). What began as a spatial land use model has been tailored to fit the needs of governments, real estate developers, and PT-operators (Peek, 2006). These model adaptations and extensions have lead to the emergence of what we will call the NP-model family. Overviews of the development of the NP-model family have been made by Peek (2006) and Caset et al. (2019) describing both the development of data components being measured as well as the wide array of visual representations used to present the gathered data. Groenendijk et al. (2018) noted that this model was not only used in the original context of analyzing the station and surrounding area to discover development potential or address potential weak points, but also to evaluate the quality of the station itself. An extended NP-model is currently also being used by Dutch rail infrastructure manager ProRail (2019).

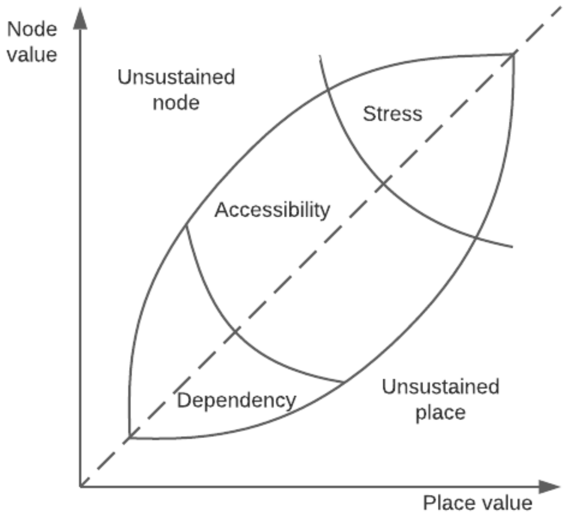


Figure 2.1: Conceptual model of the classical NP-model (Bertolini, 1999)

The core principle of the NP-model is the notion of the ambivalent nature of a station. A well functioning station is more than just a railway hub, but it is also more than just a shopping mall. In a good station (area) the transport supply of the PT-network and the demand of urban spatial activity support each other. This notion of balance can be seen in figure 2.1. This theory of node and place connects to the broader idea of the land use transport feedback cycle (Wegener and Fürst, 1999). This feedback cycle implies that transport demand, spatial activity: living and working and transport supply: public and private, will follow each other resulting in an equilibrium over time. This indicates the point of view of the original NP-model. Peek and Van Hagen (2002) describe the station as a geographical entity in the traditional NP-model. The processes within the station are a black box. This is a model aimed at evaluating (urban) areas where the stations themselves are only a small part of the consideration. Traditionally the model is build up by combining two types of input data, data on accessibility by PT as well as by cars and active modes, and data on land use activity: living, working, education, etcetera. When we however want to investigate the role of the station from the point of view of a researcher looking at the performance and competitiveness of the PT-system as a whole there seem to be some components missing in the current generation of models to allow for an assessment of the actual performance of stations. The NP-models, before Groenendijk et al. (2018), described only the quality of the location, the node quality described the position a station had in the public and private transport networks and the place quality described the station's position in the urban fabric. Efforts have been made in the past years to address the actual processes going on in the station and to add them to the model (Groenendijk et al., 2018). They added the experience value that captures the place value of the station itself, describing the quality of the station when waiting. Peek and Louw (2008) already described a fourth component, the connector. This is the type of station that is optimised for interchanging passengers who stay in the PT-system. This research focuses on an operationalization of this concept so we can complete the NP-model by providing a valuation of the fourth model component. Combined with the experience value of Groenendijk et al. (2018) and the two classical components from Bertolini (1998) this completed model aims to give a balanced outlook on the performance of the station with respect to it's complex position. In table 2.1 which is an extension of the concept of the four part NP-model (Peek, 2006, Peek and Louw, 2008) several ideas, operationalizations, and properties of these categories are listed providing an insight of how this added fourth component fits into the current paradigm.

	Node Values	**Place Values**	**Model Properties**
Network Properties	Classical Node Value (Bertolini, 1998)	Classical Place Value (Bertolini, 1998)	Traditional NP-model components
	Accesibility Premium (Bertolini, 2008)	Urban Centre (Peek and Louw, 2008)	Station as a geographic entity (Peek and Van Hagen, 2002)
	Transportation Node (Peek and Louw, 2008)	Transport Demand	Focus on processes and networks outside the station
	Transport Supply	Urban contextual place value	Used for land use and real estate analyses (Peek, 2006)
	Network contextual node value		Station is a black box
			Location quality
Local Properties	Connector (Peek and Louw, 2008)	Meeting Place (Peek and Louw, 2008)	Analyzing stations as micro systems
	Transfer quality (this research)	Station Experience (Groenendijk et al., 2018, Van Hagen, 2011)	Focus on processes within the hub
	Transfer Machines (Peek, 2006)	Independent Place Quality (Peek, 2006)	Station as a vital link within the PT-system
	Independent Node Quality (Peek, 2006)	Interchange Waiting	Design Quality
	Interchange Walking		

Table 2.1: Elements of the extended node place model (inspired by Peek (2006), Peek and Louw (2008))

This research aims to operationalize and valuate the quadrant of the local node value. Here the goal is to assess the contribution of the station itself to the connectivity of the system. To find the relation between station design and performance for travellers.

2.2. Transfer Quality

In the previous paragraph we have established that this research sets out to fill the the gap in the existing theoretical framework on station quality assessment by operationalizing the previously only conceptual property of the station as a connector. To do this we will have to find a list of factors that we can use in an MCA to derive aggregated scores that express a station's transfer quality. These factors have to be clearly measurable and obtainable through online or on site surveying of the stations. When station performance was researched several types of research came up, that each have a common denominator either methodologically or use the same scientific theories. These types of research or scientific fields were used to structure the literature review. These fields include research on political PT-integration (Saliara, 2014), PT customer satisfaction research (Peek and Van Hagen, 2002, Van Hagen, 2011), choice model based traveller research (Schakenbos et al., 2016, Wardman et al., 2001), (micro) simulation of pedestrian flows (Daamen, 2004, Li, 2000), and research using traveller numbers and spatial layout (Pitsiava-Latinopoulou and Iordanopoulos, 2012). More complete assessments on overall performance of nodes can also be found. Hernandez et al. (2016) did a large scale survey based research into the customer satisfaction of the Moncloa railway and metro station in Madrid Spain. Bryniarska and Zakowska (2017) built an MCA-tool based on customer surveys for the assessment of urban tram and bus stations in Krakow Poland. All these researches have elements that can be useful for our model, both content and methodology wise. We will now present these methods and their examples and distill useful elements for our own model. After that we will combine and list all relevant factors and start operationalizing them towards measurable criteria in the next chapter.

2.2.1. PT integration

The concept of PT integration revolves around taking away (perceived) barriers between various modalities and operators. The goal here is to decrease hassle and effort by travellers and provide for an overall more comfortable and more reliable journey (Saliara, 2014). We have already presented these ideas in the introduction and summarized this in table 1.1. For the station's environment not all of these factors are relevant. We will consider all factors from the physical integration category. Saliara summarizes her paragraph on physical integration with the following sentence: "Physical integration aims to plan the system carefully through good station design, convenient walking paths and station amenities in order to speed up and secure transfers, improve accessibility towards and inside the intermodal transit system for all traveler groups, facilitate the users' movement and minimize the discontinuities inside the system." (Saliara, 2014, p.538). Another example of the importance of walking path quality is given by Ibrahim (2003) who describes the example of covered walkways. This also connects to the idea of improving the weakest link in a connection, when transferring from an indoor station to a covered bus shelter an outdoor walking path will be remembered. Next to the factors originally mentioned by Saliara (2014) we have added 'on site information' this consists of signage and real time information. Currently many operators have their own signage system which is visible at system interfaces, secondly operator installed information and signage does not always give complete information on other modalities at the station. Even if it is managed by a neutral party good signage still requires attention (Bryniarska and Zakowska, 2017). Having access to real time information while making a multi-modal transfer can be crucial to relieve stress and uncertainty for travellers (Ibrahim, 2003). It is important to note here that design always involves trade offs. A very simple example from a physical integration design trade of is formed by the choice between a regulated level crossing and an under/overpass. A level crossing can form a direct connection from the platform to the outside area and vice versa. But when the crossing is closed because of a passing train travellers will have to wait. This causes added uncertainty and a safety risk from people trying to cross anyway. When choosing to substitute this level crossing with a grade separate alternative, the time and effort for travellers will increase, what was a direct connection is now replaced with one or two sets of stairs, and a solution will have to include extra features such as elevators to meet standards for inclusiveness and accessibility. From these ideas we will select and list the topics relevant for our research. At the end of this chapter these topics will be converted to factors that will form the base of the checklist for on site surveying.

- Convenient walking paths
- Station amenities
- Accessibility inside the system
- Traffic crossings
- Signage
- Real time information

2.2.2. Customer satisfaction research

The PT-market is in constant competition with private means of transport, mainly private cars. To assess the perception of the usage of both modalities consumer satisfaction research is done. This field of research has some similarities with choice model and utility based traveller research but is more abstract in nature. A picture showing the central problem addressed by this type of research was already shown in chapter 1 (see picture 1.1). Peek and Van Hagen (2002) have summarized and visualized the needs of customers in the pyramid model (figure 2.2, left side). The main idea of this pyramid was based on the classic pyramid of human needs developed by Maslow. The key idea of this model is that like a building the foundation has to function for the top to succeed. The bottom three rows consist of the so called dissatisfiers, these are factors that have to be met in order for users to start noticing positive experiences. Beautiful architecture will hardly be noticed in a smelly station. We can also extend this metaphore to the design process of a station. Here too function goes over form. First the basic functions of the station have to be set up well before considering aesthetics. In practice this does not always happen. Daamen (2004) describes the process of designing the new Rotterdam Central Station. The starting point of this design was a master plan drawn up by an architect. Good looking, but when analyzed by Daamen lacking basic functions and not facilitating a reliable flow of passengers. A good functional design will design from the bottom up with the users in mind. In the current guidelines for station design in the Netherlands, set out by infrastructure manager ProRail (2005), a translation of this principal is made to the rough design of a station. For the functions in the pyramid space in a station is allocated in concentric rings around the main area that is to be purely used for boarding, alighting, and transferring. This concentric approach is a clear example of giving design priority to essential functions by allocating the most valuable space, nearest to the vehicles to the most important functions (figure 2.2.

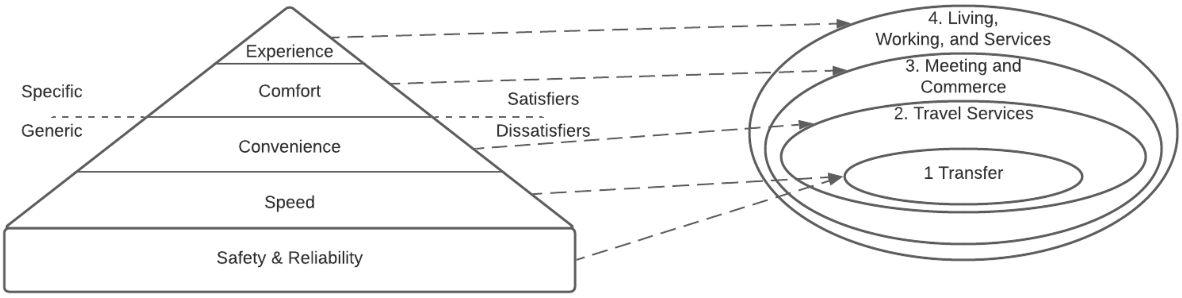


Figure 2.2: Pyramid of customer needs and its design implications (Peek and Van Hagen, 2002, ProRail, 2005)

Peek and Van Hagen (2002) presented three design strategies to increase the satisfaction of PT-consumers. This study did not only focus on the PT-system itself but also stretched out into urban planning. These three strategies are acceleration, concentration and enhancement. These three strategies work for entire trips but are also applicable on the design and layout of stations themselves. The first strategy, acceleration, aims at accelerating connections, keeping the point to point distances the same. For interchange connections within stations there are two main solutions to comply with this strategy. The first is ensuring a free flow of passengers throughout the station, we will elaborate on the topic of pedestrian flow in the upcoming section on simulation, paragraph 2.2.4. The second solution is the increasing of speed through technical means. For public transport stations this mostly means having escalators and sometimes moving walkways, but a larger scale application of this can be seen at airports in the mass application of moving walkways and the use specific infrastructure such as underground people movers to connect several parts of the terminal. The second main strategy is concentration, in the original research this meant promoting mixed use development to offer living spots close to where people work and promoted TOD to avoid access and egress transport. For station design this means that several modalities have to be connected efficiently space wise. Station areas are busy urban spaces and this usage can cause spatial stress (Bertolini, 1999). This spatial stress can lead to the scattering of multiple modalities around a station. Concentrating these modalities can be achieved by several means. By aligning the routes of various modalities especially when done in a platform like style connections between modalities can be shortened. Another benefit here is that connections, access and egress can happen via one shared concourse crossing all modalities' lines. Recent examples of this development can be found at Zwolle and at Amsterdam Centraal busstation IJzijde. At both these examples the busses stop at a platform that runs parallel to the ones used by the trains, access is via the main tunnel(s). Both examples also show increasing usage of the often less crowded back sides, the sides not facing the inner cities, of railway stations. Another clever more local solution can be found in several places in Rotterdam such as metro and bus station Zuidplein. This is the separating of alighting and boarding stops for busses. Having one quick drop-off bus platform strategically placed at for example the ticketing hall level of a metro station can greatly speed up the connection from bus to metro, whilst still having a larger clear bus station for boarding passengers further away or underneath the metro. The last example of a concentrating station layout strategy we will show is vertical stacking. As goes for highly used urban areas building in the sky or underground can be a good option at stations. By stacking multiple modalities vertically short walking connections can be offered whilst still separating different transport lines. Traditionally we can observe this in train stations that also serve as metro stations. Many examples in the Netherlands and abroad offer connections between train and metro under the same roof. Another example of vertical stacking can be found at The Hague Central Station. In this station the bus platforms are located on top of the train platforms and are accessible via stairs and escalators in the shared head house. Next to the busses there are also elevated light rail platforms with lines running perpendicular to the train platforms running through the head house above the main station hall. The third strategy is enhancement, this mainly evolves around the improvement of convenience, comfort, and safety in and around the station. Bitner (1992) listed several elements that influence waiting experience The first is the improvement of the environment when walking and waiting in the station. This includes ambient conditions like weather protection, lighting, heating and social safety (Groenendijk et al., 2018). The second is the supply of services to let passengers make better use of their downtime in the stations. These services include station wide services such as WiFi and localised facilities such as shops. These services allow passengers to spend time usefully decreasing the time value gap. For all this aspects it is also important that they are properly placed. Station renewal projects in the Netherlands have for example shown that moving services traditionally found in the headhouses of stations towards the concourses and even onto the platforms can lead to an increased accessibility of services for transferring passengers, this is also an example of a concentration strategy, the strategic placement of services alongside main routes. The Dutch Railways state on their website that it is their vision to make stations the beating heart of cities and that they want to achieve this together with entrepeneurs and visitors (NS, 2021a). This also underlines the importance of location based place value being acknowledged by operators. We will now summarize this paragraph by defining new factors to add to the surveying checklist.

- Transfer route length
- Service availability
- Service location (betweenness of services)
- Route weather protection
- Wait weather protection
- Design priority
- Presence of mechanical accelerating
- Transfer route capacity

2.2.3. Utility based traveller research

The utitlity theory is a central economic behavioural theory and is widely used in transportation research. The central idea is that travelling requires an effort in time, money and mental and physical effort (Van Hagen, 2011). These budgets could also be spend otherwise and this opportunity cost is what defines a utility value. This notion is connected to the idea of the time value gap that we know from customer satisfaction research (see also figure 1.1), but the utility theory is more quantitative in nature. Methodologically this type of research is conducted via large scale stated choice surveys. This models human choices as a discrete and exhaustive set of mutually exclusive choice options from which people choose the alternative that presents the highest utility to them (McFadden, 1974, Train, 2009). Here we can clearly see that this is an economical model as people are presented as utility maximizers. Each choice alternative is build up out of several attributes that vary between alternatives. Attributes can include things like travel time, cost and level of comfort. To determine the effects of various elements (attributes) of an alternative, the attributes of this value can be changed in a choice experiment to test its effects. It is important to note that in utility based travel models the effect of a single attribute is derived from the scoring of the alternative in general. This is very different from for example the NP-model family which is based on MCA. In MCA scores of alternatives are computed by combining attribute levels and weights instead of obtaining a complete score in a questionnaire to obtain attribute weights. This type of research is often used in research where larger contexts matter because utilities allow for calculating values of time and the monetized societal effects of certain measures.

To set up their research Wardman et al. (2001) started with focus group interviews followed by several in depth interviews to gather relevant possible attributes to include in the final alternatives. Schakenbos et al. (2016) developed a set of realistic travel alternatives set within a known context, eg from home to work via a nearby mid-sized station. Both researches focused on a wide array of factors influencing transfer experience and paid great attention to the effects of time tables. Train frequencies and scheduled transfer time proved to be very relevant. They did also find some effects caused by transfer station layout. In the analysis of the questionnaire data Schakenbos et al. (2016) found a small effect of station category, defined by the number of shops and services, on the perceived transfer penalty. It is however important to note that there was no choice option for stations without any services, the assessed difference was between stations with limited (one or two) and more elaborate (three to nine) shops. A more interesting result concerning station layout was found and presented in Schakenbos (2014). Here stated optimal intermodal transfer times of several large stations were compared. It was found that very large stations, mainly Utrecht Centraal, had a higher preferred scheduled transfer time than mid-sized stations, 9 minutes compared to 7,5 on average. An interesting outlier in this data is Amsterdam Amstel. This station provides a cross platform connections between train and metro. This unique connection results in a preferred value of 5,33 very close to the reference value for train-train transfers of 5 minutes. This shows that station design and operation can have a large influence.

$$U_{int} = \alpha I + \beta TT + \gamma WT \tag{2.1}$$

Wardman et al. (2001) followed a slightly different methodology. Their research used an aggregated method combining revealed preference of mode choice as a base scenario and having a questionnaire checking for what attribute changes could change a persons behaviour. The general expression for transfer disutility they used can be found in equation 2.1. This utility is build up of three parts. The first part is the general disutility (I) of having to transfer, this can be interpreted as the effort and cost of the actions and the preparation of having to transfer, a traveller for example has to pack his bags and check the itinerary to find out where to go next (Garcia-Martinez et al., 2018). The second element is the travel time (TT) made during transfer. The third component is the waiting time (WT). All three factors have a corresponding penalty. Most attributes found in this research concern service design and operation, a couple involve station design. Weather protection can influence both travel time and waiting time experience which can be expressed in the perceived penalty. Information provision is a good example of a factor influencing the general transfer penalty, lacking information can increase the uncertainty of having to make a connection and increase the outright penalty. Transfer safety has two main parts, social safety can influence the perception of both waiting and travelling, and the safety of traffic, for example when having to cross active rail lines or car traffic can influence the outright penalty. Schakenbos et al. (2016) also mention the services in a station, these can effect the waiting time experience since one can spend waiting time in a more useful or comfortable way. Combining findings from these studies gives the following list of attributes that will be considered as final model attributes:

- Design compactness
- Service availability
- Wait weather protection
- Walk weather protection
- Information provision

2.2.4. Simulation modelling

Another type of research that is used to directly assess the design quality of a station is simulation modelling. Simulation modelling simulates the flow of passengers through a facility. This can be done on various levels of spatial scale and aggregation. The main goal of this type of research is to aid design decision making and assessment of existing infrastructure by offering quantitative usage data (Daamen, 2004).

In her dissertation Daamen (2004) describes the entire process of the development of a micro simulation passenger flow model. This model simulates the flow of single passengers through a spatial model of the facility. As part of this process several case studies were carried out. Two of these are particularly interesting as they were carried out on two design propositions for the renewal of the Rotterdam Central railway station. This gives a great insight in the design process and in the priorities of the designers in the planning of this station. The model describes three important parameters: size and pattern of pedestrian flows, walking distances, and pedestrian levels-of-service. The size and pattern parameter is derived from either previously observed OD-flows or from OD-matrices resulting from model estimates. These can serve as absolute sizes of flows determining the capacity needed for certain connections. The walking distances are a straightforward design parameter. The pedestrian levels-of-services describe the crowdedness of an area. People tend to move slower in very busy spaces and thus flows not exceeding theoretical capacity can already limit speeds. Secondly disturbances for example at the entrances of shops where people enter, exit, and queue can form zones that are hard to cross and thus form a bottleneck across the concourse. Daamen (2004) also notes here that very low levels of crowdedness are not necessarily optimal as well, for social safety eyes on the street are desired next to these people also prefer a level of pleasant crowdedness (Groenendijk, 2015). Daamen (2004) also describes design trade offs between these attributes. Increasing the footprint of a facility can decrease the crowdedness, for example by unbundling certain flows. But this will inevitably lead to higher walking distances. This can also be seen as an example of spatial stress as defined by Bertolini (1999) where too many functions on a small area lead to sub-optimal outcomes.

Another type of passenger flow simulation is described by Li (2000), Xu et al. (2014). They describe activity based simulation models. The activities are modeled in a flowchart (see figure 2.3). Spatially the station can be depicted as a graph connecting these activities this is a so called queueing network (Xu et al., 2014). A representation of a location based graph can be found in figure 2.4. Every design element, whether it represents an activity or just a connection will have to be included as a node in to include the travel time uncertainty of the connection. Handling times for every node are then calculated through queueing models. The biggest difference between this two types of model is the level of detail. Queueing models can only model interaction between individual travellers in an aggregated way, it can only express the marginal effects of additional travellers. A micro-simulation model will take into account the movement directions passengers and will change the outcome based on whether these passengers are walking alongside each other. meeting head on, or crossing. This increased resolution comes at the price of increased computational complexity.

The important attributes influencing intermodal connectivity within a station that were found by researchers developing simulation models will now be listed:

- Crowdedness
- Bottleneck Capacity
- Walking distances
- Location of services

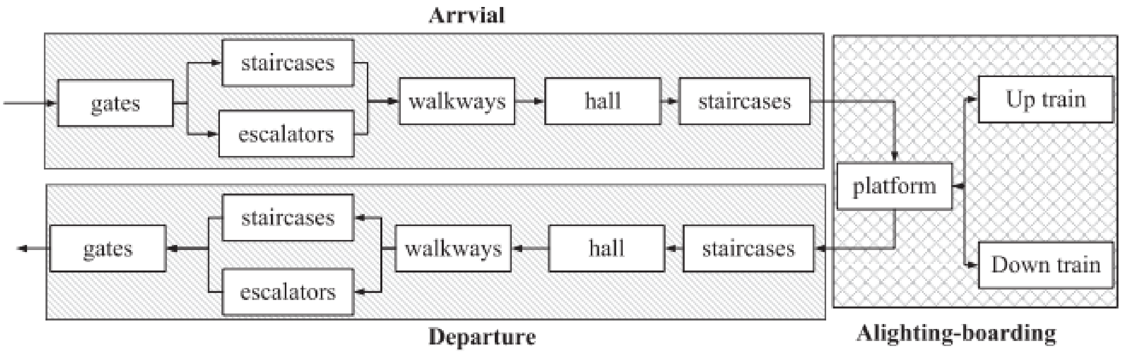


Figure 2.4: Location based network graph (Xu et al., 2014)

2.2.5. Design assessment through actual usage

Based on the position of a station within the network and the city passengers will have certain expectations of the facilities and connections offered at a station. Pitsiava-Latinopoulou and Iordanopoulos (2012) developed a method of ex post design analysis using actual transfer counts. The main conclusion of this research was that the size of an actual intermodal OD-pair was based on the quality of a connection. This connection quality was mainly influenced by the quality of walking connections and some operational features that fall outside the scope of our research. The quality of walking connections was determined by some quantitative measures, mainly length, and some qualitative measures

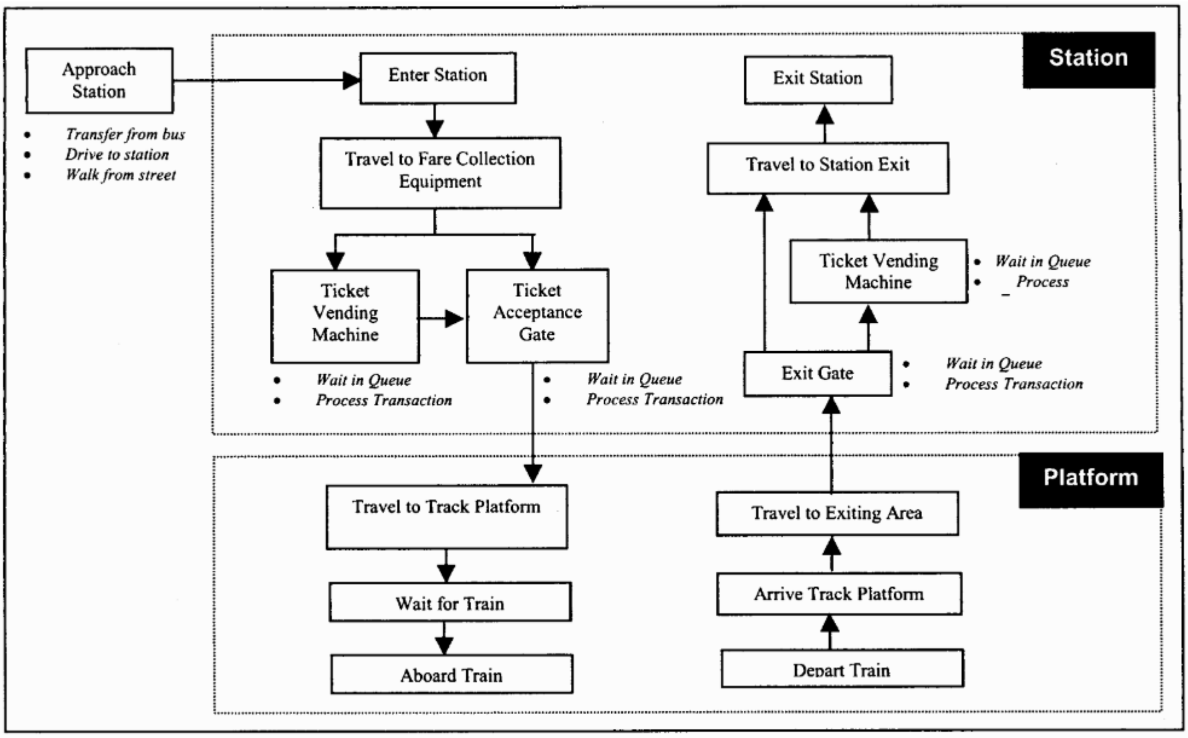


Figure 2.3: Activity based network graph (Li, 2000)

mainly safety and reliability due to having to cross major roads. It was also mentioned that too compact facilities that for example do not fit enough ticket booths also impede the optimal function of intermodal hubs. This research gives us several points that we can use in the final model:

- Walking distances
- Traffic crossings
- Station capacity

2.2.6. Full size case studies, other evaluation frameworks

This paragraph will introduce other researches that have been conducted in order to develop a full size station performance evaluation framework. These studies are very useful to investigate since they are very complete in their methodologies and state the used factors very literally. The first one is a research conducted by Bryniarska and Zakowska (2017). They studied the usage of a number of urban on street PT-hubs in Krakow Poland. The biggest difference with our study lies in this context. Our study researches purpose build facilities with trains or metros where this study researches on street facilities with bus and tram. Methodologically however this study is very relevant because it makes use of a multi criteria analysis to compare and weigh all the factors. To calibrate their model Bryniarska and Zakowska (2017) used a questionnaire with about 1100 respondents. This questionnaire had two parts: part 1 asked respondents for their travel details, this was used to map to flow of passengers within the stop; part 2 asked passengers for their assessment of satisfaction with the interchange in general and with the level of supplied travel information. As second part of the research an elaborate on site survey was carried out determining the values for eight design factors. These eight factors are:

- Spatial integration (walking distance)
- Spatial orientation (visibility)
- Availability of additional facilities
- Quality of basic infrastructure

- Accessibility for disabled
- Information for passengers
- Personal security
- Traffic safety

Next to the literal model component factors there is one more element from Bryniarska and Zakowska (2017) that can be noted as a factor for our research is *design priority* by weighing several factors by travel number the most important routes are counted stronger which makes designing for these routes favourable.

Some of the factors covered in this study are less relevant for our study. Having a roadside open air facility leads to some other relevant factors than we will need for our study of purpose build partially indoor facilities. For our study we will assume that basic standards regarding infrastructure and inclusive accessibility are met since all case stations are purpose build. A measure of direct visibility is very difficult in indoor and multi level facilities, this means that signage and other information will be even more important. Bryniarska and Zakowska (2017) use weighing by transfer numbers for the distance factor. We will use weighting for the assessment of the entire transfer route, also assessing other factors with a route weight. This does however mean that factors for design characteristics will have to be measured for every individual transfer route. An interesting split that was made in a number of the factors that we will also use is the distinction between the quality of transfer and waiting infrastructure. In the recommendations for further research it is suggested that the passenger survey could be partially replaced by using data collected from tickets. This will be done in our research by using OVC data.

The second study that will be discussed is one by Hernandez et al. (2016). In this research an extensive assessment of the Moncloa train and metro station in Madrid Spain was carried out. For this study a 37 question traveller satisfaction questionnaire was carried out. These questions fell in the categories information, movement, experience, and safety. From this large list of factors not all are relevant for our research. Some factors consider ambient qualities that are outside the scope of station design and there is a block of four factors considering design for emergency situations, these will be left out in our research. For the analysis of their obtained data Hernandez et al. (2016) used a two step process. The goal of the first step was to derive the importance of every factor. There are several algorithms available to directly obtain the importance of factors from collected factor values. This has the benefit of not making the questionnaire too long and not run the risk of collecting unreliable data since random respondents often struggle to identify driving factors of their behaviour. This however still is a rather complex mathematical process. In our research we will shortcut this be approaching academic and practical experts and asking them to weigh factors directly. To conclude the analysis and develop design and policy priorities an importance performance analysis (IPA) was conducted by Hernandez et al. (2016). The result of this can be found in figure 2.5. The main idea behind the IPA is that the quadrant on the left top contains factors that score low but are perceived as important, this means that these factors should get design priority if customer satisfaction is to be improved. This analysis can serve as a background or even a hypothesis for the gathering of factor weights, because the importance logically correlates to factor weights, although not all our factors were covered in the research of Hernandez et al. (2016).

Hernandez et al. (2016) used a wide array of factors for their research. Many of them are useful but some are not. Here we focus on transfer related physical design characteristics. We will now list the factors relevant for our research:

- Availablity and clarity of travel information
- Accuracy and reliability of information displays
- Signposting of different facilities and services
- Signposting for transfers between transport modes
- Transfer distances
- Number of elevators, escalators and moving walkways

- Ease of movement inside the interchange due crowding
- Temperature, shelter and ventilation
- Number and variety of shops
- Number and variety of restaurants
- Internal design

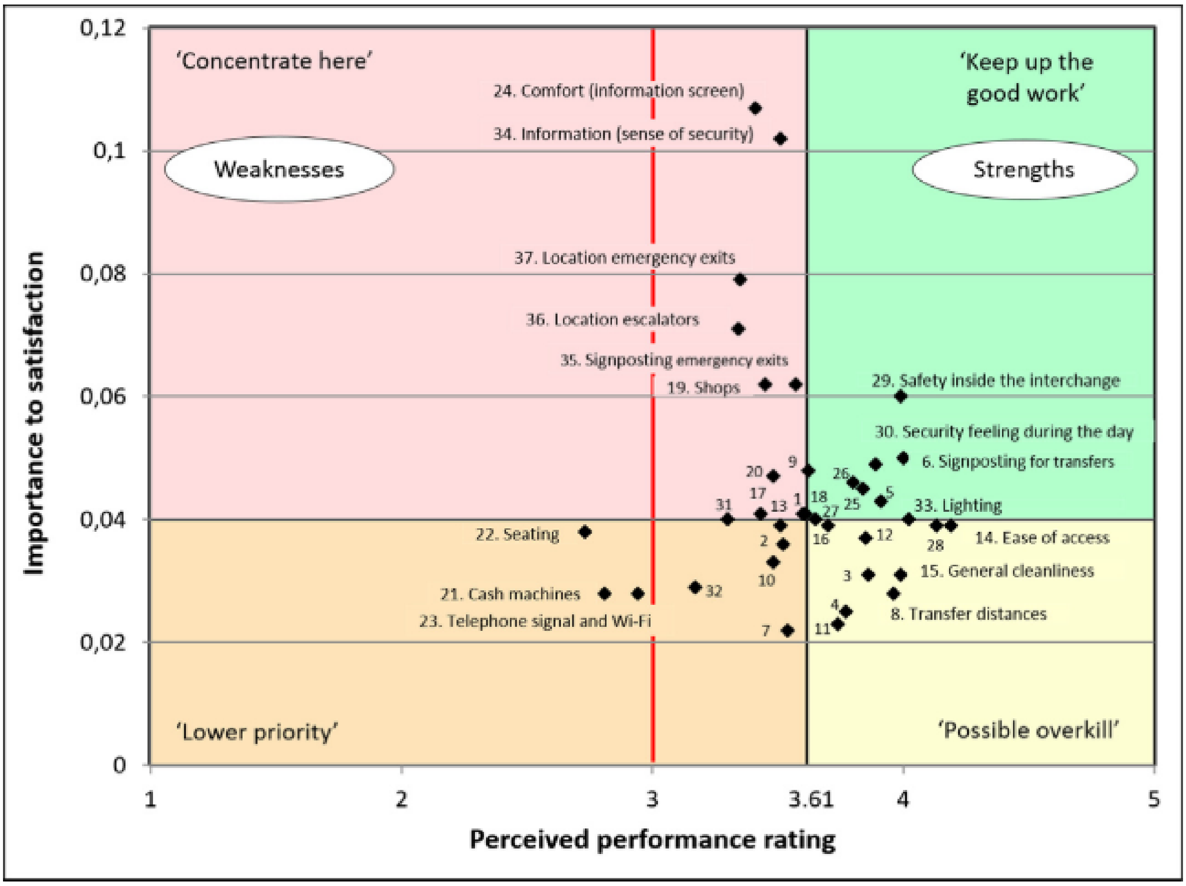


Figure 2.5: IPA grid with results from Hernandez et al. (2016)

2.3. Conclusion

The goal of this literature study was to gather factors relevant for the to be developed MCA-model. In the previous paragraphs we have highlighted several scientific fields that study station performance and traveller behaviour. A summary of this search whis serves as an answer to the central question behind this chapter can be found in table 2.2 below.

	PT integration	Customer satisfaction	Utility	Simulation	Transfer numbers	Case studies
Transfer distance	x^{1}	x^{2}	x^{3}	x^{4}	x^{5}	$x^{6,7}$
Transfer flow	x^{1}	x^{2}		$x^{4,8,9}$		x
Traffic crossings	x^{1}				x^{5}	x^{6}
Route weather protection	x^{10}	x^{2}	x^{12}			
Wait weather protection		$x^{2,11}$	x^{12}			
Elevators and escalators		x^{2}				x^{7}
Bottleneck capacity				$x^{4,8,9}$	x^{5}	
Signage	x^{1}		x^{12}			$x^{6,7}$
Real time information	x^{10}		x^{12}			$x^{6,7}$
Service availability	x^{1}	$x^{2,11}$	$x^{3,12}$		x^{5}	^{6,7}
Location of services		x^{13}		x^{4}		
Design priority		x^{13}		x^{4}		x^{6}

Table 2.2: List of all relevant factors and their source field. 1: Saliara (2014); 2: Peek and Van Hagen (2002); 3: Schakenbos et al. (2016); 4: Daamen (2004); 5: Pitsiava-Latinopoulou and Iordanopoulos (2012); 6: Bryniarska and Zakowska (2017); 7: Hernandez et al. (2016); 8: Li (2000); 9: Xu et al. (2014); 10: Ibrahim (2003); 11: Groenendijk et al. (2018); 12: Wardman et al. (2001);13: ProRail (2005)

2.3.1. Factor Structure

In the first part of this paragraph we have listed the factors that will build up our model. Here it is important to realize that the factors that are used influence the type of model that can be constructed and vice versa. As mentioned before it was chosen to use a multi criteria analysis as the base for our model. This has several advantages over other frameworks such as cost benefit analyses that get their values from utility based research. The main advantage for our research is the disaggregation an MCA allows for. By design CBA methods converge to one final score (Annema et al., 2015) because the goal is to translate the entire project to one monetized score for decision makers to look at. For more exploratory models such as the one that is developed in this study it is not necessary to aggregate all results, secondly giving one single score implies that factors can compensate each other. This is not the case as we know from studies such as Van Hagen (2011) that individual low scoring factors can very negatively impact one's experience beyond what can be compensated for by other well scoring parameters. This is why the choice was made to build a model giving a final score on four categories. The division of factors in every category is roughly based on the factor blocking used in Hernandez et al. (2016) and can be found in figure 2.6 below. The four scores representing the overall capacity of a station in facilitating intermodal transfers will be the distance, path quality (PQ), service availability, and information provision.

We will finish this chapter by looking into the factors themselves a bit more. In an infrastructure design process like that of developing a station design choices can be divided in three categories, *what* do we want, *where* do we want it, and *how* do we want it. In a design process first the choice is made what we want, for a station here the key elements of both the node and place domain are chosen, what facilities do we need to serve the different modalities planned to stop at this station, and what facilities do we want to offer waiting and passing passengers. This is shown in the top part of figure 2.7 below. After the question of what we want where and how come simultaneously. If the chosen layout for example introduces height differences that will raise a 'how question' on how to bridge this level change is raised leading to the choice on whether to install elevators and escalators.

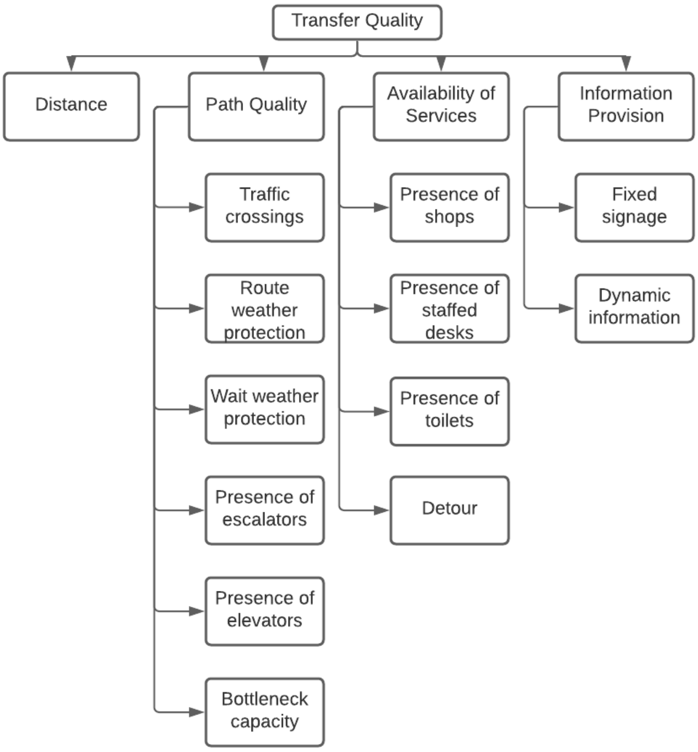


Figure 2.6: Categorization of the thirteen factors

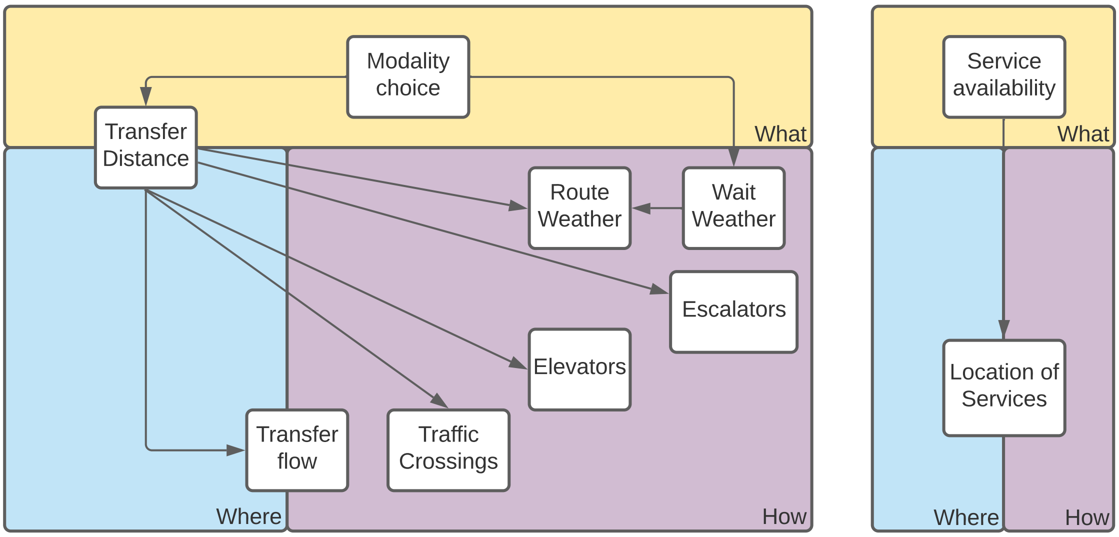


Figure 2.7: Conceptual model of factors and their place in the design process

The factors chosen for the model cover the three design questions and sometimes overlap. As stated above the factors in the what box come first. The question if a certain element has to be present is step one. In measuring these some factors will also get a localised component, transfer distance looks on *what* mode pairs are present in the facility and obtains the distance based on *where* they are located. The factors of information provision both have components of *what, where & how* in the determining of their quality. Information provision has to be complete, present in all relevant locations, correct, and consistent, done well. The factors of path quality and services are shown in figure 2.7. Distance is included in the figure of PQ. In the what bow we find the first strategic choice of what modalities we wish to connect at a station. Then locations of these modalities will be determined and the question on how to shape the stops will be asked. These questions are answered by the factors of transfer distance and wait weather protection. The combination of this yields route weather protection. The other factors all depend on the chosen locations of the modalities and contain information on how several aspects are handled. The factors of services have a rather simple link. First the presence of services has to be determined and then their location and execution. The number of services also directly influences the proximity of services to transfer routes.

3

Model Design

In the previous chapter we have found twelve factors that determine a station's quality to provide intermodal transfers. The goal of this chapter is to answer our second research question:

2. How can we develop a measurement model to combine and weight the design factors into performance scores?

In the following paragraphs we will answer the three sub-questions stemming from research question two. We will start with defining and operationalizing the factors from literature. After this we will elaborate on the process of obtaining factor weights. The third chapter will handle the performed transfer data analysis coming up with the route scores. We will finish this chapter with a general and mathematical outline of the entire model.

3.1. Defining the Factors

In paragraph 2.2 factors influencing the transfer quality of a station from a variety of scientific fields were gathered. Until this point the exact definitions of these factors have been kept vague. This paragraph will first define these factors and then translate them into measurable criteria. To do this guidelines set by Sijtsma et al. (1998) will be followed. To do an effective research the number of factors will have to be limited, this distinction has already been made in the previous chapter and we will continue with the factors listed in table 2.2. Secondly the factors need to have a minimal overlap to avoid double counting of certain characteristics, this has also already been taken care off in the concluding steps of the previous chapter. The third requirement from Sijtsma et al. (1998) will require some action however, the factors need to be practically obtainable. This means that we will have to select the criteria with the desired methodology in mind. For this research the values of different characteristics will be determined through an on site and online survey of the stations. Given the current reality of the COVID-19 pandemic this means that stations will be generally less crowded. After the first pilot survey it was decided to drop transfer flow from the list of factors since crowding in general areas was not observed, bottle neck capacity stays in since crowding was observed after the alighting process of some trains and metros. Furthermore some factors have been split in order to make them practically obtainable. Presence of elevators and escalators are now separate criteria and service availability has been split into the three categories of shops, staffed desks, and availability of a toilet. Design priority will not be measured as a regular model factor but will come back in paragraph 3.3.

In the following table all thirteen criteria are listed and their measurements explained. This table will serve as a legend for the on site surveys. Definitions and factor levels are set up to form an intuitive guideline for the researcher to perform observations on site. It is important to note that the to be developed model explicitly focuses on infrastructure and not on operational decisions by operators or the availability of additional systems. This is for example visible in the factor staffed desks, the presence of a desk is an infrastructural factor, the presence of personnel walking through the station answering questions is an operational decision. The opening hours of a desk can be considered an operational decision. It was however decided to include them when during the pilot they were found to be a differentiating factor.

Factor name	**Definition**	**Measurement levels**
Transfer distance	Average walking distance in metres between the platforms of two modalities. Measured over ground.	Interval variable (metres)
Traffic crossings	This factor describes the presence of level crossings of transferring passengers with other forms of traffic.	Crossings with bicycles (**bike**), Public Transport (**pt**) and **cars** are noted. When multiple crossings are present only one with the lowest score is noted. Routes without crossings are noted as **0**.
Route weather protection	This factor describes whether parts of the connection between two modalities are covered or not	A connection can be completely inside (**full**), covering can be interrupted by a short outside connection (**gapped**), connections from a modality located inside towards a modality located outside are noted as **half**, lastly connections taking place completely outside are noted as **not**.
Wait weather protection	This factor describes the level of shelter of the waiting area of the destination modality of a transfer.	Three levels are observed: **full** is used for completely covered platforms, platforms with shelters are noted as **part**, areas without any cover are noted as **not**.
Presence of elevators	This factor describes whether or not elevators are present for all required height changes.	Complete elevator coverage is noted as **y**, incomplete coverage as **n**. Since this measure describes the inclusivity of a connection there is no in between option.
Presence of escalators	This factor describes whether or not escalators are present for all required height changes.	Complete escalator coverage is noted as **y**, incomplete coverage as **n**.
Bottleneck capacity	This factor describes the negative influence of bottlenecks on passenger flow. Bottlenecks can include but are not limited to doorways, stairwells, and ticket gates. Boarding and alighting processes are seen as part of the operational process and are mainly dependant on material type, this research focuses on infrastructure and hence does not include this processes. This is a directional measure so it can differ between two directions of the OD-pairs.	In a **free** flow situation the bottlenecks en route are no recognizable hindrance for the passengers. When a connection is **crowd**ed people have to negotiate the passage of certain choke points without having to come to a full stop. The final level is **bunch**ing here people have to come to a full stop or queue before being able to pass a choke point.
Fixed signage	This factor describes the level of fixed signage of a connection. Fixed signage includes all static information in a station, this includes signs, maps and departure time listings. Good signage has to be clear, correct, covering, and consistent.	Signage is noted as **full** when it guides travellers along the optimal route between two modes. Signage is marked as not sufficient (**ns**) when at least one of the four of the mentioned criteria is not met.

Real time information	Real time information serves two main purposes for travellers. It guides travellers to the correct platform once they have entered the domain of a certain modality and it comforts passengers by giving them exact information on when rides exactly depart.	Real time information can be on time (**ot**) when good information avoids additional detours or **late** when screens are located after decision points within the domain of a destination mode. A third level covers situations where real time information is **not** present.
Shops	This factor describes the presence of convenience stores in a station. Convenience stores sell drinks (hot and cold), food (packaged and fresh) and maybe other products such as reading materials and tobacco products. This factor is measured for the entire facility at once. Whether or not shops are located in a good place for certain mode pairs is addressed in the detour factor.	For practical purposes the measurements in this category will be aggregated into three categories: no shops (**0**), one to three shops (**+**), and four or more shops (**++**).
Toilets	This factor describes whether a public toilet is present somewhere in the facility or not.	The presence of at least one toilet is noted as **1** and **0** is used when none are available.
Staffed desks	This factor describes the presence and availability of staffed desks for information and tickets. We have noticed that in this time of pandemic many of the desks have limited opening hours compared to the normal situation. This is a directional factor that describes the state of the destination mode of an OD-pair.	When staffed desks are not present the situation is noted as **-**, limited opening hours are noted with **0**, and full opening hours covering all periods of the day where transport is offered are noted as **+**.
Detour	The detour factor describes the location of shops relative to the ideal path of an OD-pair.	The detour is measured in metres deviated from the ideal path.

Table 3.1: The thirteen final model factors, with definitons and measurement levels

With this table we have defined the factors and we have presented a measurement scheme. With this table in hand we are able to perform a survey to obtain the station characteristics. More on this process can be found in chapter 4. To use the results of these checklists we need one more step. For our model the data has to be comparable. To achieve this we will normalize the data. This means that the factors that now have various measurement scales will all be translated to a scale of 0 to 1. This is a normative process since it has to be determined how the observations are rated. We will first go through the reasoning behind the scoring of the factors and then present the normalization table. Generally we can say that factors that can be categorized as dissatisfiers (see fig. 2.2) will drop quickly from the ideal score when desired levels are not met. Satisfiers work the other way round, any presence of these factors will be scored highly. Normalization can also be achieved by assigning values relative to the data that occurs in the data set. This can be very useful for models created for a specific case with extensive data. In this process the highest and lowest scores are used as upper and lower bound, one and zero, and then all other values are placed in between. We will not do this because we want to develop a more generic model that is able to valuate new cases with attribute values that might not occur in the initial case study. For example no cases were found where there was no sheltering at all at platforms.

Transferring distance directly correlates with walking time. People are very sensitive for this, as one interviewee put it 'time is human's most precious good'. With a fixed timetable the walking distance can mean the difference between having to run and being able to grab a coffee. With a frequency based operation one might be able to catch an earlier ride. For the normalization we will use 300 meters as an upper bound. This translates to 3-4 minutes of walking. The lower bound is zero meters since closer is always better. Examples such as Schakenbos and Nijënstein (2014) show the large added value of short distance transfers. Values will be normalized linearly between zero and one, going up with increasing distance.

Traffic crossings influence the safety and reliability of a connection. Therefore crossings with slow modes or PT lines with a lower frequency than regular roads score higher, no crossings of course are used as the upper bound. Furthermore Pitsiava-Latinopoulou and Iordanopoulos (2012) indicate that stops located across main roads feel disconnected from the main facility for users. Since one of the goals of integrated PT is to remove perceived barriers this is penalized extra. Connections with no crossings will receive a score of 1 for this factor, bike crossings that especially in busy dutch station areas can be tricky to negotiate will receive 0.75, PT crossings 0.5, and crossings with general traffic will receive a 0. When multiple crossings occur on a single route only the lowest scoring crossing is noted.

For the scoring of route weather protection it is important to note that people remember the bad experiences. This means that any deviation from the ideal situation is noticed. A fully covered walkway off course receives the full mark of 1. The lower levels of gapped, half, and not receive scores from 0.5 to 0.

For wait weather protection it is important to look at the context. Since this model covers mid-sized stations and higher the capacity of a shelter as you might find on a local bus stop is often lacking. This means that platforms that only offer shelters will score lower than fully covered platforms. On the other hand having shelters is still better than nothing. This leads to the distribution of 1, 0.5, and 0 scores for the categories fully covered, partially sheltered, and not sheltered.

Elevators and escalators are simple dummy factors. Here a score of 1 is given when the requirement is met and 0 when it isn't.

Bottleneck capacity's three levels are scored gradually. As a dissatisfier, free flow is important for both the reliability and the safety of a station not meeting the standards will lead to a much lower score. But the difference between the crowded situation and the full stop of the bunched state is large as well. This leads to scores of 1 for free flow, 0.5 for crowding, and 0 for bunching.

Fixed signage is treated as a simple dummy. Since one missing sign on a critical location can lead to a person getting lost or not finding the ideal route leading to a missed connection. This leads to the values of 1 for full signage, and 0 for not sufficient signage.

Real time information has a two-fold goal. Firstly it helps navigating within the domain of a modality, secondly it offers the comfort of knowing exactly when rides will depart so one can slow down or speed up. The first goal is a factor contributing to the reliability of the system, this is a dissatisfier thus it is important that it's requirements are met. We allocate a score of 1 to a fully covering system, a score of 0.25 for connections where critical information is presented late leading to possible delays in the transfer connections and the possible missing of rides. The third level where there is no dynamic information present is put at 0, the difference between 0.25 and 0 represents the added comfort value of having dynamic information at all.

Shops can provide an added value to a transfer. Here any service offered is valued highly over zero functions but the marginal value of extra is moderate. This is why we put stations with zero functions at 0, one to three shops at 0.75, and four or more shops at 1.

The presence of toilets is a simple dummy variable. A score of 1 is given when toilets are present and 0 when they are not.

Staffed desks are a service in the current Dutch ticketing system with the OV-chipkaart (OVC) (a tap in tap out smartcard) is the main ticket for most travellers and ticket machines at all stations for additional tickets and to top up the OVC credit. Desks for information and tickets mainly help less experienced passengers. A complication that occurred in the measurement of this factor was the limited opening hours of these facilities after traveller numbers went down due to the pandemic. We observed this in our pilot survey and added the limited opening hours category. This closures mainly limited the opening hours to the middle of the day between the rush hours. This means that rush hours, when mainly daily travellers use the system are most effected and the middle of the day is not. This is why we chose for a score of 1 for all day (first to last scheduled regular ride), 0.5 for significantly limited opening hours, and 0 for when no staffed desks are present.

The detour factor describes the detour that has to be taken from the ideal route between to modalities to visit shops. When facilities are directly en route and require a deviation of less than 20 metres they receive a score of 1, detours between 20 and 100 metres receive 0.5, and further detours 0.

Transfer distance	0 meters = 1	>300 meters = 0	linear in between	
Traffic crossings	zero = 1	bike = 0.75	PT = 0.5	Car = 0
Route weather protection	full = 1	gapped = 0.5	half = 0.25	not = 0
Wait weather protection	full = 1	part = 0.5	not = 0	
Presence of elevators	yes = 1	no = 0		
Presence of escalators	yes = 1	no = 0		
Bottleneck capacity	free = 1	crowd = 0.5	bunch = 0	
Fixed signage	full = 1	ns = 0		
Real time information	ot = 1	late = 0.25	not = 0	
Shops	>=4 = 1	1-3 = 0.5	0 = 0	
Toilets	>=1 = 1	0 = 0		
Staffed desks	+ = 1	0 = 0.5	- = 0	
Detour	<20m = 1	20-100m = 0.5	>100m = 0	

Table 3.2: Full scoring table

Per station these normalized measurements deliver one measurement matrix F_{ij}:

$$F_{ij} = \begin{pmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,13} \\ f_{2,1} & f_{2,2} & \cdots & f_{2,13} \\ \cdots & \cdots & \cdots & \cdots \\ f_{16,1} & f_{16,2} & \cdots & f_{16,13} \end{pmatrix} \tag{3.1}$$

3.2. Factor Weights: the Best Worst Method

Now that we have defined and operationalized the factors that will build up our model we can continue with answering the next sub-question: *2b. How do we compare and weight these factors?* Several methods are available to help obtaining factor weights. Our study deals with a wide variety of factors and it is difficult for a decision maker to judge all factors at once. This is why we will use an algorithm using pairwise comparison. Here decision makers are presented pairs of factors and asked to judge the relative importance from one to the other. Groenendijk et al. (2018) used the best worst method (BWM) developed by Rezaei (2015) for these pairwise comparisons. The BWM uses a limited number of comparisons making data collection faster and easier than traditional methods such as the analytical hierarchy process (AHP) that uses a full pairwise comparison. A complete overview of the theory and workings of the BWM can be found in Rezaei (2015, 2016). We will now explain the theory behind the steps relevant for our research before before going into the practical details of the method. After that we will proceed with the desription of the data gathering process and its results. This already done in this chapter since it is part of the structural side of the model and not a case study specific variable.

3.2.1. BWM theory

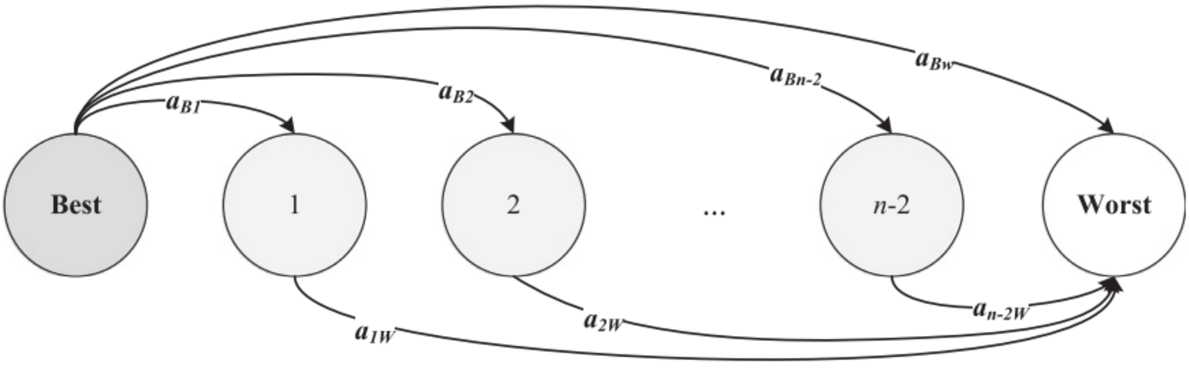


Figure 3.1: Schematic representation of the working of the BWM (Rezaei, 2015)

The main theoretical idea behind the BWM is the psychological idea that when evaluating a set of criteria a decision make will anchor their decisions to the reference criteria. These references are formed by the lower and upper bound of the criteria set, the best and the worst. This leads to the idea that comparisons between two non reference criteria are irrelevant. This has led to the forming of the BWM that only compares between a factor and a reference factor. This means that the BWM can be conducted by presenting *2n-3* pairwise comparison tasks. The schematic working of this method can be found in figure 3.1 above.

Practically the working of the BWM is presented as a five step process. In this research the first and last step will be conducted by the researcher and steps two, three, and four will be conducted in cooperation with field experts.

Step 1. Determine a set of decision criteria. This has been done in chapter 2 and has been finalized in paragraph 3.1.

Step 2. Select the best (most important) and worst (least important) factors from the set of decision criteria defined in step one. This step is conducted by the decision maker(s). These two factors will form the references for the rest of the comparisons.

Step 3. Determine the relative importance of the best factor to all other factors. Here the decision maker is asked to assign a value of 1 to 9 to the relative importance of the reference factor compared to a factor. A value of one means that factors are equally important and a value of nine means that a factor is absolutely unimportant. The result of this step is the best-to-others vector:

$$A_B = (a_{B1}, a_{B2}, ..., a_{Bn}) \tag{3.2}$$

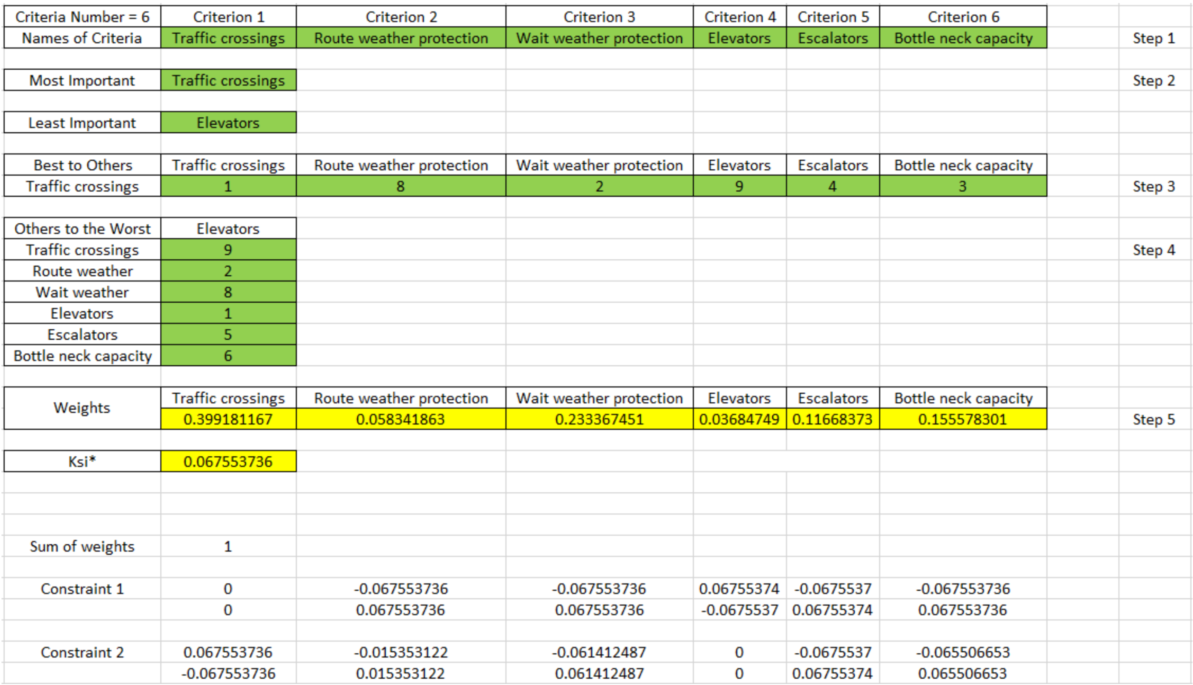
Step 4. Determine the relative importance of all other factors to the worst factor.Here the decision maker is asked to assign a value of 1 to 9 to the relative importance of a factor compared to the reference factor. A value of one here means that the factors are of equal importance, a value of nine means that the factor is absolutely more important than the reference factor. The result of this step is the others-to-worst vector:

$$A_W = (a_{1W}, a_{2W}, ..., a_{nW})^T \tag{3.3}$$

Step 5. Determine the optimal factor weights. In most cases the best-to-others vector and the others-to-worst vector will not be consistent. This means that we will have to find a solution that best fits both vectors. The system is consistent when for every factor j we have $w_B/w_j = a_B j$ and $w_j/w_W = a_j W$. The optimal solution will be the one with the lowest residual (ξ) values between the relative weights (w_x/w_y) and the relative importance ($a_x y$). This optimization can mathematically be represented as follows:

$$
\begin{aligned}
& \min \xi \\
& s.t. \\
& \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, \text{for all } j \\
& \left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, \text{for all } j \\
& \sum_j w_j = 1 \\
& w_j \geq 0, \text{for all } j
\end{aligned}
\tag{3.4}
$$

Solving this system yields the vector of optimal weights $W = (w_1^*, w_2^*, ..., w_n^*)$. In the next section we will describe the practical execution of these steps in our research and its results. The practical working of all steps can be seen in figure 3.2 below. In step 1 the chosen factors are listed and presented to the respondent. Step 2 has the respondent choosing the most and least important factors from the set presented in step 1. Step 3 consists of the comparison of all factors with the best factor, and 4 of the comparison of the other to the worst. Step 5 requires some extra explanation. In the figure we see the final weights values and also the residuals that are used in the optimization. The single value that is optimised for is the ξ (Ksi*) value, this is the largest value from the bottom four rows. The environment that was used to conduct the best worst method questionnaires was an excel template made by Jafar Rezaei developer of the BWM, see also Rezaei (2015, 2016), available trough his website (Rezaei, 2021).



Criteria Number = 6	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	
Names of Criteria	Traffic crossings	Route weather protection	Wait weather protection	Elevators	Escalators	Bottle neck capacity	Step 1
Most Important	Traffic crossings						Step 2
Least Important	Elevators						
Best to Others	Traffic crossings	Route weather protection	Wait weather protection	Elevators	Escalators	Bottle neck capacity	
Traffic crossings	1	8	2	9	4	3	Step 3
Others to the Worst	Elevators						
Traffic crossings	9						Step 4
Route weather	2						
Wait weather	8						
Elevators	1						
Escalators	5						
Bottle neck capacity	6						
Weights	Traffic crossings	Route weather protection	Wait weather protection	Elevators	Escalators	Bottle neck capacity	
	0.399181167	0.058341863	0.233367451	0.03684749	0.11668373	0.155578301	Step 5
Ksi*	0.067553736						
Sum of weights	1						
Constraint 1	0	-0.067553736	-0.067553736	0.06755374	-0.0675537	-0.067553736	
	0	0.067553736	0.067553736	-0.0675537	0.06755374	0.067553736	
Constraint 2	0.067553736	-0.015353122	-0.061412487	0	-0.0675537	-0.065506653	
	-0.067553736	0.015353122	0.061412487	0	0.06755374	0.065506653	

Figure 3.2: Capture of the BWM environment

3.2.2. BWM in practice

To gather the weights needed to combine all factors in our model a questionnaire will be carried out. For this study it was chosen to do a series of expert interviews because of the low sample size needed when using experts. The interviewees are all professionals who work for operators, governments, in academics and research, or in consultancy. Field experts were handpicked. They were mostly found through the networks of myself and my supervisors next to this some authors of used literature were approached. Finally fifteen questionnaires were carried out, six in the academic field, four with employees of various PT-operators, four with government workers, and one with a consultant.

In the digital interviews, that lasted about half an hour each, a questionnaire was presented via screen share from Excel. After a short introduction from the interviewer and interviewee the questionnaire started. This consisted of two parts. First a control experiment was conducted. In this control experiment respondents were asked to order the thirteen factors by importance in determining the quality of a facilitated transfer. This was done because maintaining ordinal consistency is seen as an important feature of a well functioning weighing algorithm (Rezaei, 2015).

The main part of the interview consisted of the filling in of the BWM questionnaire. The interviewer asked all questions to the interviewee and filled in results in the spreadsheet which view was shared with the interviewee. An example of the questionnaire environment can be found in figure 3.2 above. First the four main categories were listed weighed. After this the three categories containing multiple elements were weighed. During the interview notes were taken on the respondents’ reasoning behind given answers. The respondents were asked to answer from their expert/professional point of view and not as a private person. As context was given an intermodal interchange at a medium to large station. Final results were presented and shortly compared with the previously executed control experiment. After this potential final remarks were noted and the session was ended.

Conducting this steps yielded a weights vector for every respondent. To combine the weights of all respondents the geometric mean of the weights was taken and then the resulting vector was rescaled. The complete results of the questionnaires and the averaging and rescaling process can be found in the appendix in table A.1. Factor weights are now assigned within their categories, a total weight of 1 was distributed between all factors in a category. The resulting final weights vector can be found in table 3.3 below.

Distance	1
Path Quality	
Traffic crossings	0.221
Route weather protection	0.096
Wait weather protection	0.227
Elevators	0.123
Escalators	0.110
Bottle neck capacity	0.224
Services	
Shops	0.297
Toilets	0.275
Staffed desks	0.241
Detour	0.187
Information provision	
Fixed Signs	0.618
Dynamic information	0.382

Table 3.3: Final results of the BWM questionnaires

During the interviews many respondent referred to the theories of Van Hagen (2011) either implicitly or explicitly. For all respondents except one distance was the most important factor. As one respondent put it: *’Distance is time, human’s most precious good.’* Many people mentioned factors as being part of safety and reliability on the one hand and convenience and comfort on the other. Many relating it’s perceived importance to this notion bringing the findings of the interviews in line with the theories of Peek and Van Hagen (2002), Van Hagen (2011).

An issue of the model that is developed is in it’s generic nature. Many facilities at a station are based on the level of service required at that station which is based on the usage and place in the system. This is difficult to include in our tool which is somewhat normative and generic in nature. The provision of toilets and escalators were mentioned as examples of factors that are only provided at certain stations based on the usage numbers. As one interviewee working for the national train network manager put it: *’Step free access can also be achieved by a simple ramp. An escalator is mainly a method to increase capacity and comfort.*

Many respondents also noted that certain factors are only relevant for certain target groups. This is mainly the case for elevators and staffed desks. This made it hard for respondents to valuate these criteria and some of them referred to the position of their employer on issues of inclusivity. One respondent mentioned that around sixteen to twenty percent of travellers are dependent on elevators, this can be disabled people or people with young children using a stroller.

We will conclude with some remarks on the usage of the BWM in this project. Generally it can be said that the BWM served it's purpose. It helped in gathering factor weights with the answers of fifteen expert questionnaires. Initially the BWM is not the most intuitive method, both for the researcher and for the respondents. It was noted that during the interviews the skill of the interviewer in explaining everything increased and later interviews went smoother. What it however managed to do is provide an organised framework that allowed carrying out the interviews in only half an hour whilst still collecting expert's opinions besides only the answers to the questionnaire.

3.3. Route Weights: Transfer Data Analysis

We have not yet included the literature factor of design priority. To operationalize this we will add weights to every route corresponding to the relative size of the flow of the OD-pairs. This was also done by (Bryniarska and Zakowska, 2017) who suggested that smart card data might be used for this cause. The goal here is to weigh the busy routes heavier to see if important routes actually score well. In this project smart card data collected from Dutch OV-Chip cards will be used. Through an ongoing project we have access to this data, more information about the project is given in chapter 4. From the available data we can obtain the transfers made. With this an OD-matrix for every pair of modalities can be aggregated. Practically this will mean that the found factor values will be multiplied by the route weight that is based on the relative flow of every mode pair. Per station we can use the relative flows from the OD-matrix of the station as a route weight vector:

$$R = (r_1, r_2, ..., r_{n^2-n}) \tag{3.5}$$

This vector resembles all intermodal flows, the entire OD-matrix excluding the diagonal with intramodal flows. In the next chapter we will elaborate on the practical process of the preparation of the data required to get this vector.

3.4. MCA Model Statement

Now that we have defined all elements that make up our model we can combine them into one model statement:

$$s_{ij} = f_{ij} * r_i * w_j \tag{3.6}$$

The model combines three sources of data into the final scores. The first building block is the matrix of normalised observations, the matrix F defined in paragraph 3.1. Every element in this matrix is weighed twice. The elements are weighed by the factor weight corresponding to the measured factor and the route weight corresponding to the route. These weights are the vectors W, the factor weights vector defined in paragraph 3.2, and R, the route weights vector defined in paragraph 3.3. This yields the element score s_{ij} as can be seen in equation 3.6. The factors have been divided into categories and the factor weights have been distributed accordingly. The next step will be to calculate the category scores C for all categories k of every route. G_k represents the subset of factors that make up every category k. This will be done as follows:

$$C_{ik} = \sum_j f_{ij} w_j \qquad \forall j \in G_k \tag{3.7}$$

This step does not use a route weight because it is the score of a single route. After this step there are several options to aggregate the score. This can be done for individual routes, modalities, entire stations. In the table below the process of aggregation per category is shown without the intermediate step of calculating the C_{ik}, this is not shown due to space constraints on the page. The main indicators that will be used in further analyses are the aggregated category scores for the entire station. Yielding scores for the four categories distance, path quality, services, and information provision. These are calculated as follows:

$$
\begin{aligned}
S_k &= \sum_i C_{ik} r_i \qquad or \\
S_k &= \sum_i \sum_j s_{ij} \qquad \forall j \in G_k
\end{aligned}
\tag{3.8}
$$

4

Case Study

In chapter 3 we have layed out the steps of collecting data in order to build up the model. In this chapter we will follow these steps with real world data. This has two main goals. The first goal is to test the practical feasibility of the model and its building blocks. The second is to gain insight in the explored case. We will now first introduce the case study and the individual research objects. After that the practical process of data collection and will be highlighted. The chapter will finish with the first results of this study.

4.1. Noord-Zuidlijn

This research is part of a larger research project run by multiple institutions including TU Delft. This research project investigates the effects on travel behaviour and activities after the 2018 opening of a new metro line, more on the project can be found in Brands et al. (2020). This new metro line called Noord-Zuidlijn (NZL) in Dutch connects the two main train stations of the city, Amsterdam Centraal and Zuid, and runs through the inner city, an area previously mainly served by trams. The northern terminus of the line is the newly opened station Amsterdam Noord, this station is located in the northern part of the city across the river IJ, an area that not had any rail connections until the opening of this line. At Amsterdam Noord also a new bus station was opened serving as the terminus of the regional busses connecting areas north of Amsterdam to the city. These busses previously drove to Centraal but now halt at Noord and thus skip the busy tunnel going under the river. The opening of this new line also had a major impact on the design of the stations it connects. Noord is a completely new facility, Centraal got a new tunnel with platforms that runs perpendicular to the railway tracks underneath the stations, and Zuid is in ongoing processes of renovation and capacity increases.

Via this larger project we have access to travel data collected through OV-chip cards (OVC). The OVC is the dutch system of check-in check-out PT-smart card that is used across all modalities. This large data set consists among other parts of a set of transfer data. This data includes all transfers made at stations and smaller stops in Amsterdam. We will use this data to calculate the route weights. More on this in paragraph 4.4. More on the history and working of the Dutch OVC-system and of its applications in scientific practice can be found in Van Oort et al. (2015).

The PT-system in Amsterdam consists of trains, metros, trams, busses, and ferries. Ferries are excluded from this study because they are more part of the cycle and pedestrian networks of the city than part of the PT-network. They are free and therefore there is no data available for the ferries. The organization of the system is represented in table 4.1, here we can observe the complex situation with multiple contractors and operators. The Vervoerregio Amsterdam (VRA) is a government authority where fifteen municipalities in and around Amsterdam cooperate to provide public transport. This complex situation provides a very interesting case for our model that tries to measure the integration of the system.

Mode	Operator	Contractor	Network Manager
Train	NS	Nat Gov	Prorail
Metro	GVB	Vervoerregio	Municipality
Tram			
Bus			
	EBS		
	Connexxion		

Table 4.1: Stakeholders in Amsterdam

The current network can be seen in figure 4.1. Here we can see the locations of the three aforementioned stations as either important interchanges between train and metro or as terminus (with bus connections).

Figure 4.1: Amsterdam network of metro and train with the NZL (line 52) in blue

4.2. Case Study Objects

To test the workings of our model we will deploy it on three cases. The background of our cases has been set in the previous paragraph and in this paragraph we will present some details on the individual cases. We have selected Amsterdam Centraal, Zuid, and Noord stations as the three main objects of study. They have all been heavily influenced by the construction of the NZL, have key positions in the network, and present an interesting range of size, from mid-size to very large and age Amsterdam Centraal is over 150 years old although it has been renovated many times, and Noord is a new facility.

The ongoing project that TU Delft participates in drew focus to the NZL. Within this project these three stations are the most significant intermodal nodes. The choice was made to only use stations directly connected to the NZL to look at the effects the NZL connection had on its design and usage, due to an error in the data this did not happen however, more on this in paragraph 4.4. In the table below a quick overview of the three stations. Here we can quickly see some of the complexities of the three chosen stations.

	Train	Metro	Tram	Bus
Centraal Station	x	x	x	3 ops
Zuid	x	x	x	2 ops
Noord		x		3 ops

Table 4.2: Overview of the three stations and their connections, for busses the number of connecting operators is noted

4.2.1. Centraal Station

Centraal station is the main railway station of the city of Amsterdam and connects to both the old metro and the NZL, serving as a hub for both. The station is located on the north side of the city centre on the bank of the river IJ. The station itself is erected on an artificial island which makes it very constrained space wise. The central part of the facility is the railway station. This is a fully indoor station with six platforms serving the trains. Underneath the railways run five tunnels, the first, third, and fifth provide access to all platform, the second and fourth are gate free passages connecting the inner city with the water front. The bus station is located on the north side of the railway tracks. It is located under one continuous roof from the train station and has open sightlines to the trains. The busses are served from one central island platform running parallel to the railway tracks. The bus platform can be accessed from the IJ-hal. This is the secondary main entrance hall that connects to all five tunnels and to the waterfront. Trams stops are located on the square on the city (south) side of the stations. In two clusters of parallel tracks on both sides of the central acces way. The metro has two access points. The older metro lines have their acces via a ticket hall located underneath the tram square. The NZL runs underneath the station perpendicular to the railway tracks roughly underneath the middle of the five tunnels. The NZL has entrances in the IJ-hal and the central metro hall. Recently a direct connection from the railway headhouse to the metro hall called the Cuyperstrap was opened, this eliminated the need to go outside for passengers connecting from train to metro. On the map (fig. 4.2) this connection can be seen during construction still being wrapped. Shops and other facilities are abundant and scattered throughout the entire facility, the gate free passage tunnels have a more relaxed casual shopping setting than the other three more utilitarian tunnels. More details on the layout of the station can be found in figure 4.2 and for the underground part in figure 4.3.

4.2.2. Zuid

Amsterdam Zuid is the second busiest railway station of the city and the terminus for the NZL, furthermore it connects to two other metro lines of the pre existing network, local and regional busses, and local and regional trams including the recently renovated rapid tram to Amstelveen. The station is located on the south side of the city and serves the central business district of the city called 'Zuidas' as well as living quarters and other services. The railway is located in the median of the ring road which makes it very space constrained, the metro tracks run parallel to the railway. On the north and south side of the ring road there are small access buildings forming the beginning and end of the tunnel connecting the platforms of both train and tram. Both tram and train have two island platforms with four tracks. The tram and bus station is located 200 metres north of the train station. The connection between the two is formed by an open air square that also gives access to bike parking and some shops. The tram and bus stops are located alongside a public road that also serves car traffic. This road is elevated above the square connecting it to the station. Services are located in buildings around the entrances of the tunnel, inside the tunnel and on the square. Details on the layout of the station building with train and metro can be found in figure 4.4, a map of the tram and bus station is shown in figure 4.5.

Figure 4.2: Map of Amsterdam Centraal at groung level

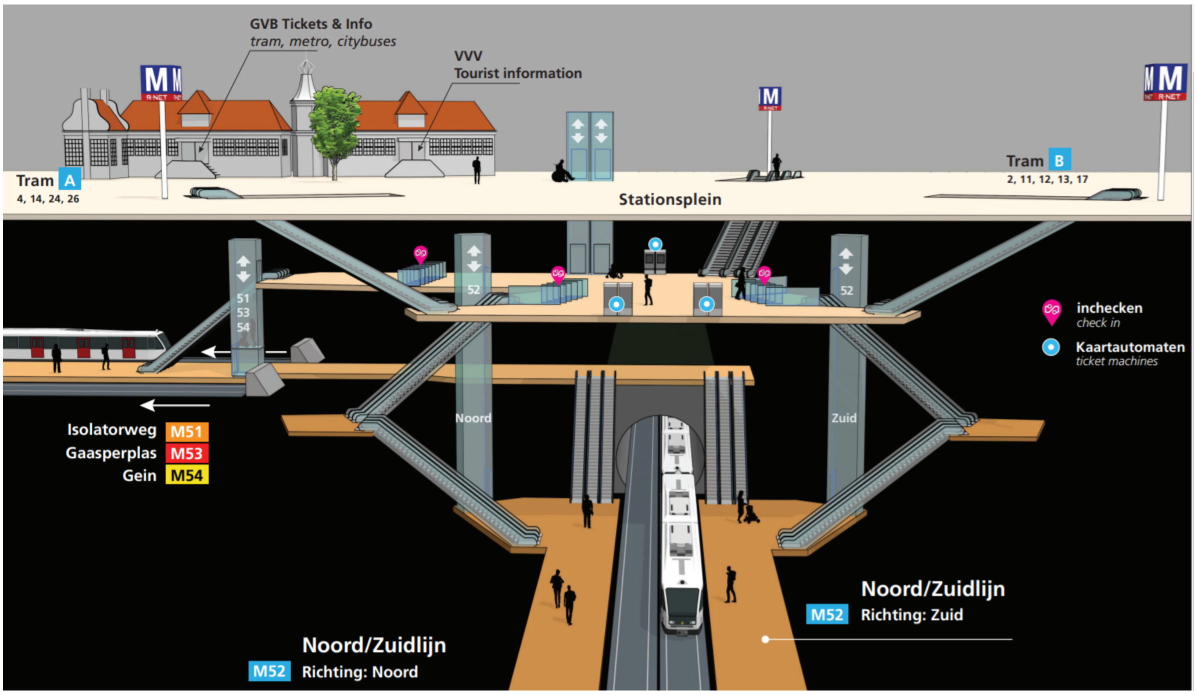


Figure 4.3: Map of the underground parts of Centraal

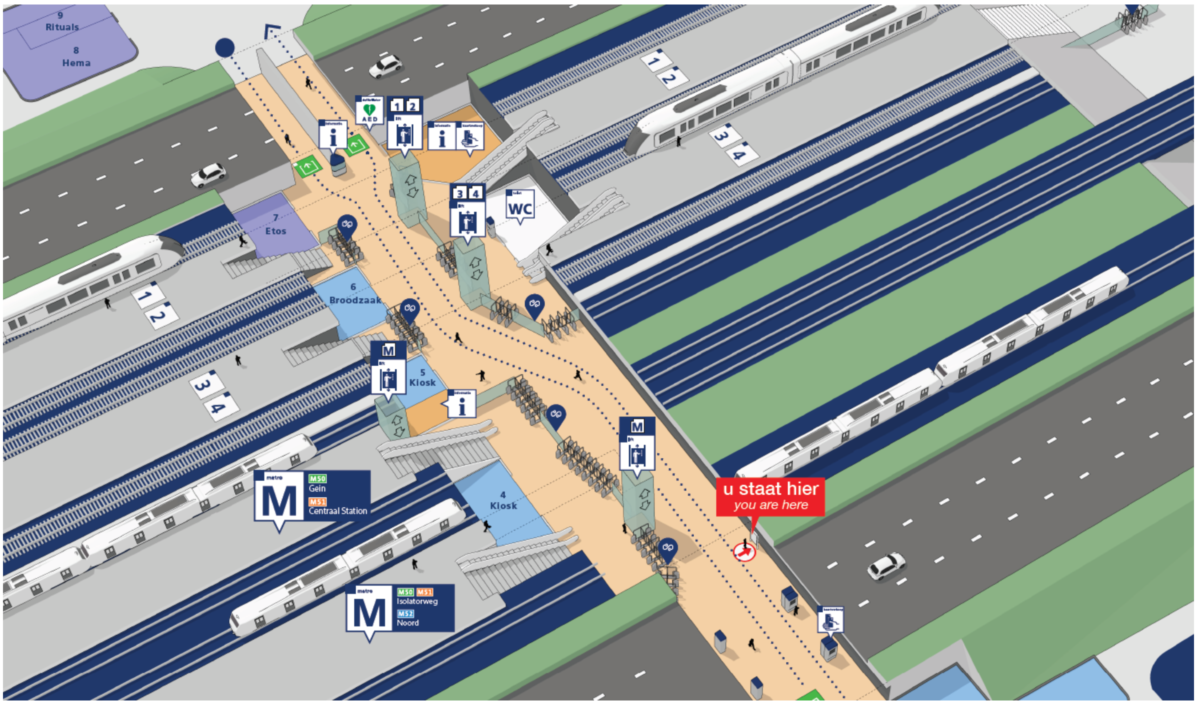


Figure 4.4: Map of the Amsterdam Zuid station building with train and metro

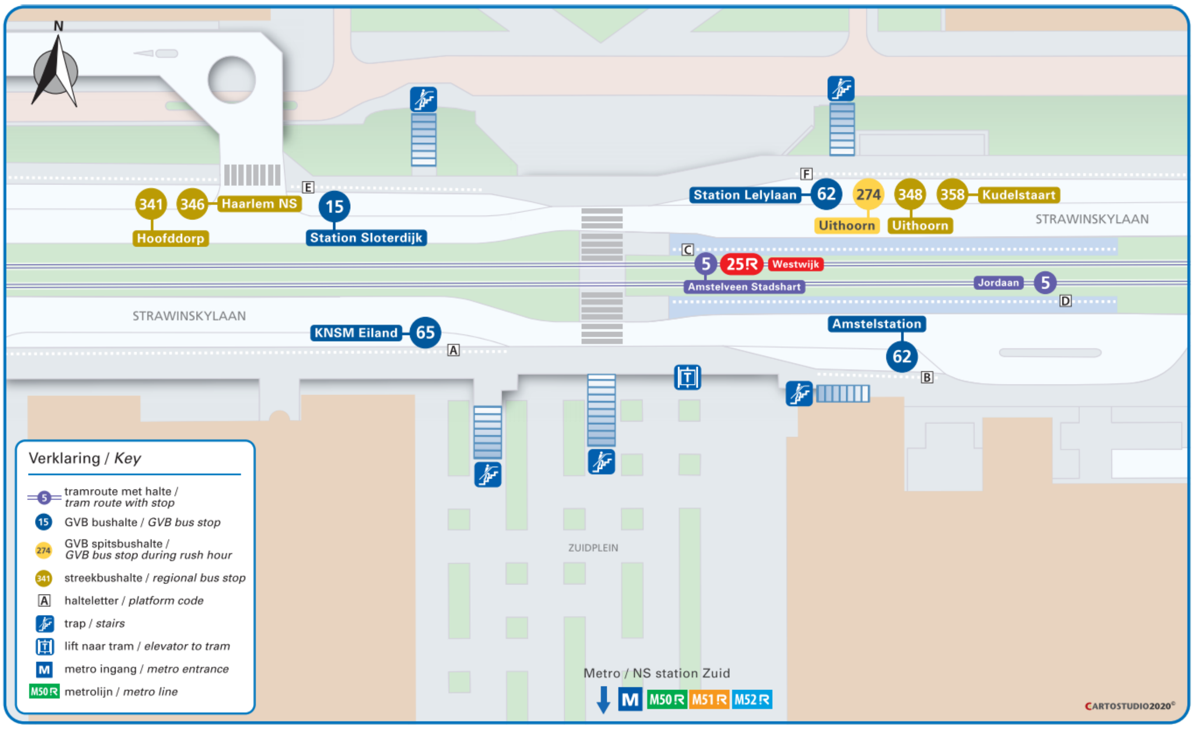


Figure 4.5: Map of the Amsterdam Zuid tram and bus station, 200 metres north of the station building

4.2.3. Noord

Noord is a new station purpose build for the NZL. It serves as the northern terminus of the NZL and as a regional bus station for busses connecting to the north, the Waterland region. Partially it took over the duties from nearby bus station Buikslotermeerplein when it opened and partially lines previously crossing the river to stop at Centraal were shortened to now stop at Noord. The central element of the station is a building underneath the metro tracks. This building has a shop, a staffed desk, and the stairs, escalators, and elevators to the metro tracks. On both sides of the metro are clusters of eight parallel bus platforms. Details on the layout of this station can be found in figure 4.6

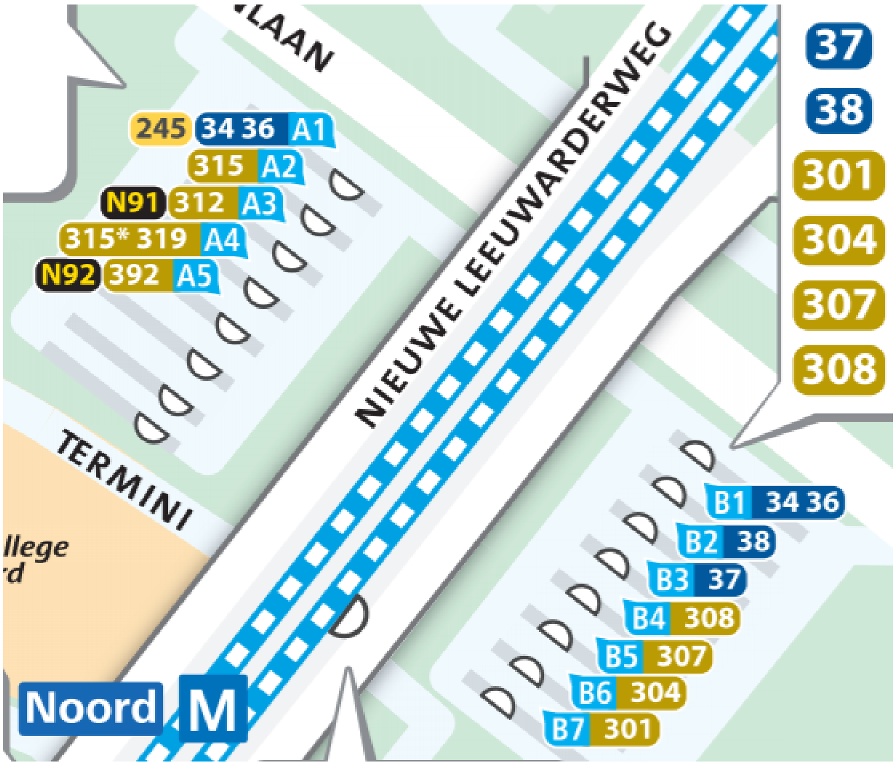


Figure 4.6: Map of Noord station, the station building is located underneath the metro tracks

4.3. Data Collection

In paragraph 3.1 we have set out the framework for our on site measurements. For all of the three stations two rounds of surveys were conducted. One in the morning peak and one in the afternoon peak on different days. This was done to observe the station under maximum stress. It is important to note however that all measurements were done under a situation of (partial) lockdown due to COVID-19. Given the situation in the world this was the only option however. Most factors however are not affected by the crowding of the station so they won't be influenced. This was also the reason to skip transfer flow as a factor. From the two rounds the worst observed performance for every factor was noted. Next to the standard checklist general notes were taken. In a survey all factors except distance and detour were filled in. These two factors were found using a distance measurement tool in Google Maps. An example of a filled in checklist can be found in table 4.3. This was the result of the first survey of Amsterdam Zuid during a morning peak. Here it was clearly visible that the main choke points of flow through the station were formed by the exits of the platforms towards the main tunnel. Both for trains and metros this situation was observed, albeit worse for the trains. Hence all OD-pairs emitting from train are marked as having bunched bottle necks.

	Dist	Cross	Routew	Waitw	Elev	Esca	Cap	Serv	Toilet	Desks	Det	Signs	Info
Train-Metro	130	0	full	part	y	y	bunch	++	1	0	+	full	ot
Metro-Train	130	0	full	full	y	y	crowd	++	1	+	+	full	ot
Train-Bus	280	car	half	part	y	n	bunch	++	1	0	+	full	ot
Bus-Train	280	car	half	full	y	n	free	++	1	+	+	ns	ot
Train-Tram	280	car	half	part	y	n	bunch	++	1	0	+	full	ot
Tram-Train	280	car	half	full	y	n	free	++	1	+	+	ns	ot
Metro-Bus	230	car	half	part	y	n	crowd	++	1	0	0	full	ot
Bus-Metro	230	car	half	part	y	n	free	++	1	0	0	ns	ot
Metro-Tram	230	car	half	part	y	n	crowd	++	1	0	0	full	ot
Tram-Metro	230	car	half	part	y	n	free	++	1	0	0	ns	ot
Bus-Tram	60	car	not	part	y	y	free	++	1	0	-	full	ot
Tram-Bus	60	car	not	part	y	y	free	++	1	0	-	full	ot

Table 4.3: Example of a filled in survey checklist

Although the number of travellers is only at about 40% of pre covid levels (Verlaan, 2021) it was clearly visible that due to social distancing measures capacity is severely limited and crowding or even bunching can still occur. On escalators for example it is advised to keep three steps headway between travellers. This is a sharp contrast to normal situations with two rows of travellers on an escalator. People also seem to keep this in mind when queueing, this leads to queues being longer and in some spaces interfering with the flow of passengers.

We will now continue with the findings of the observations at the three locations. The complete results of the surveys can be found in appendix B. The upcoming sections will highlight some interesting results from the survey checklists as well as other observations made describing the area or specific occurrences.

4.3.1. Centraal

Amsterdam Centraal has three very distinct parts. The first part is the indoor station building with trains and busses, second is the underground part where the metro is serviced, and third is the open air tram area at the front. Generally the facility is well interconnected, most measurement levels are sufficient and the service availability is very good. A notable exception on many factors is the connection to the tram. Firstly it is located out side which makes it score lower on both categories of weather protection, secondly the execution of information provision is substandard. General signage stops when one exits the station building, when connecting towards the tram this is only a small problem because one can already see the trams, in the other direction however there is no clear indication besides having the station building in sight and the high posts with the metro logo on top, no reference to the bus is visible when alighting the tram. A second issue on the information provision of the tram is the location of the dynamic information display. This screen is located between the two clusters of tram stops, this is not the location where you exit the station building when following the signed routes. This can cause people to either wait at the wrong location for their trams or at least having to walk extra to look for information. The connections between the busses located at the back of the station and the trams at the front are routed via the two tunnels that are known as passages. These are the second and fourth tunnel (from west to east) going underneath the railroad. They were specially designed to form a gate free connection between both parts of the station, the other three tunnels have check in gates for the trains controlling entrance to these parts of the station. Because they were designed separate from the core train system and because of its accessibility to non travellers this has been designed more as a place focussing on the experience value than as a node focussing on the connection value. We can see this in the available services, in the three train tunnels the services mainly include convenience stores, fast food, and other grab and go concepts. In the passages the available services mainly consist of clothing stores, cosmetics, and gifts, services for the casual shopper. This distinction is also clearly visible in the general design and experience. The passages are more dimly lit then the train tunnels, music is played here, and in one of the passages a bar is located in the middle of the walking route through the passage. This gives the feeling of a less utilitarian node focused design and a larger focus on experience and place value. A recent addition to the station is the so called Cuyperstrap. This is a set of stairs connecting the main hall of the train station directly to the ticket hall of the metro station. These stairs eliminate a large detour and the need to go outside for a connection. This is a clear example of a step made to increase the integration of the hub. Ticket desks are located in stores operated by all operators servicing the station. These ticket stores are open from 7 am to 9 pm. There are several manned information desks run by the train and regional PT operators on several locations as well.

4.3.2. Zuid

Amsterdam Zuid has two distinct parts this can also be seen in figures 4.4 and 4.5, that were provided by the different parties operating the stops. The southern part of the station consists of the station building with a passenger tunnel connecting passengers to trains and metros. Access to the trains is located on both sides of the tunnel, access to metros only on the east side. Besides the capacity of some connections other measured values for connections inside the station building (train-metro and vice versa) were good. The second part of the station is formed by the tram and bus station about a hundred metres north of the station building. This part effectively is a collection of road side bus stops with a tram stop in the median of the road. These stops are located alongside an active road that is also used by general traffic as well as by taxis that have their official stop there as well. Passengers going to or from trams and busses have to cross this road in many cases. The tram and bus station is located fully outside with some small shelters. Signage in this part of the station is substandard. There is one information screen indicating the stop platforms for all busses but its location could have been better. There are no indicators of where to go when one wants to transfer to train and metro. The distance between the tram and bus stops and the station building is just over a hundred metres so relying on sight lines here is not enough. A strong point of the tram and bus station is that it is very compact and all level, this makes navigating on sight very easy. The station has a good supply of services although they are mainly concentrated in the station building. There is one convenience store near the tram and bus stop. Some services, for example the toilets, are located behind the gate line of the train station. Ticket desks are operated separately by the train operator and the local urban PT operator. Due to the pandemic the desks of the local operator had limited opening hours. Generally one can say that both parts of the station function well on their own. The station building has all amenities and is well connected internally and the tram and bus stop is very compact and clear although it lacks some services. But the connections between both parts are lengthy and ill marked giving the feeling of two distinct parts.

4.3.3. Noord

Noord has an almost symmetrical design. The centre of the station is formed by the station building located underneath the metro viaduct. On the east and west side of the station building there are bus stations with seven parallel bus platforms each located under one canopy. The station building also houses the ticket desk of the municipal transport company (GVB) and a convenience store, both located west of the metro tracks. The area in the middle of the station hall giving access to the stairs, escalators, and escalators going to the metro platform, is guarded by ticket gates. One can go around these when connecting from bus to bus or when visiting the shop and ticket desk. The ticket desk operated by the GVB had limited opening hours due to COVID, there is no desk for the operators of the regional bus services, here purchasing tickets on the bus is possible however. In the category information provision we can observe two very opposite patterns. When connecting from the metro to the bus, on either side the fixed signage is good, but the dynamic information is lacking. Here it is difficult to know on time whether one has to go to the eastern or western part of the bus station. When coming from the outside this pattern is mirrored. Fixed signage is not present outside, most likely people will be drawn to the station building and find their way from there, but dynamic information is on point. The information screens located just outside the station building in the waiting area for the bus stations include departures for both metros and busses on both sides of the station. Next to the waiting areas on the bus platform located underneath a canopy there is a general waiting area for bus passengers against the outside of the station building. This area is partially covered and has the advantage of overlooking all bus platforms and being able to read the information screens with departure information on every platform. All connections to and from bus include the level crossing of the bus lane used by departing busses. Generally the connections are good, the station is very new and some commercial units are still vacant. No significant crowding was observed although measurements were done during (partial) lockdown.

4.4. Transfer Data Analysis

One of the goals of our model is that it should be able to address design priority. We have learned from Bertolini (1998) that heavily used areas such as public transport stations can suffer from spatial stress. In these cases good design and adequate prioritisation is important to maintain a well functioning system. The model has to be able to weigh what routes are important. This will be done by using the relative flow, the fraction of the flow on the given OD-pair of all intermodal transfers made in the hub, on every route as a weight for the route score. For this study data is available from OV-chip cards, the Dutch smart card system. The data was available through the larger NZL project. A sample of this data, with fictitious numbers, can be found in table 4.4. This table is a shortened version of the available data, headers are translated to English (from Dutch), and some fields were adjusted to fit the page. The data that was used was from the data set 2019Q4. This measurement period ran from the 25th of August till the 14th of December and included 80 working days. Just about from the end of the summer holiday until the beginning of the Christmas holiday. This means that the data is made more than a year after the opening of the NZL but before the Covid-19 pandemic hit western Europe. The table shows a number of characteristics of the modalities on both sides of a transfer. A transfer is defined as a set of a check out and a consecutive check in within 35 minutes. The transfer does not necessarily need to be between two stops in the same cluster. People can for example walk or drive between two stops and check back in within the thirty minutes and have their transfer registered. The stops all have a code from the national register of PT-stops (Dutch: Centraal Haltebestand (CHB)). There is an accompanying table with data on every stop in the data set including public name and location. Railway stations are indicated with their regular abbreviation used internally by NS. In the line data we can see that some data is not able to pinpoint the exact lines taken. Train and metro use check ins and outs on land and trams and busses use check ins and outs on board. For train and metro this means that we cannot always know what happens between a check in and out, especially when lines run parallel it is not possible to determine which line is taken. This is visible in some of the metro connections that depict multiple line numbers. For the train connections the outgoing lines are represented by one reference stop showing up as the line number. The data used in this research is from the time period rest of the day. These are working days except the rush hours. Advantage of this data is that it is mostly symmetrical and that it has the highest resolution of all available data. Due to privacy reasons transfer numbers below 300 as ranges, blocks of fifty such as ’101-150’ this can also be seen in table 4.4. For the data above 300 the actual numbers are used.

quarter	**transfer _stop _from**	**transfer _stop _to**	**time_ period**	**line# _from**	**mode_ from**	**oper-ator _from**	**line# _to**	**mode _to**	**oper-ator _to**	**number _of_ transfers**
2019Q4	30000001	30000008	Rest	22	Bus	GVB	37	Bus	GVB	51 - 100
2019Q4	30000001	30000008	Rest	3	Tram	GVB	1	Tram	GVB	151 - 200
2019Q4	30000001	asdm	Rest	1	Tram	GVB	utg	Trein	NS	9541
2019Q4	30000020	30009512	Rest	1	Tram	GVB	m5054	Metro	GVB	400

Table 4.4: Sample of transfer data with fictitious numbers

For this research first some preparation steps had to be taken. All data analysis was carried out in Spyder using Python code. A framework of the conceptual working of the code and the manual post editing can be found in figure 4.7 First the right data had to be selected from the large data set. The original data set contains about 850.000 lines of transfer data. Using the accompanying table we could identify all stop codes that together form our stations of interest. Most large stations have various stop codes for different modalities servicing the station. Transfer data was selected when both the from stop and the to stop were part of the cluster of interest. An extra step had to be taken here for train stations that were not part of the accompanying legend table, these were added to the code manually. Secondly data of the right period of the week had to be selected. As explained above this research uses data from the rest of the day period. Originally this period is called ’Werkdag (buiten schoolvakanties) restdag’ in Dutch, this can be translated to working day (outside school holidays) rest of the day. The last step of the preparation was the conversion of the data in ranges to data in numbers. The translation of the values in ranges to a single value that can be used for calculations is not straightforwrd. Especially for the lowest ranges we cannot just assume the middle value of the range as overall value. The data set originally contained a lot of very low numbers due to small errors and due to some connections not being used regularly. In his recent thesis Van Hees (2021) performed a statistical analysis to determine the most accurate values to be used instead of the ranges. The ranges to numbers conversion as suggested by Van Hees (2021) was used in this research, this can be seen in table 4.5 below. These numbers will be used in further analysis.

Range	**Value**
1 - 50	3
51 - 100	65
101 - 150	120
151 - 200	175
201 - 250	225
251 - 300	275

Table 4.5: Ranges to values conversion (Van Hees, 2021)

The three preparation steps mentioned above were carried out for all three stations mentioned in paragraph 4.2. For Centraal and Noord an extra step was taken to split some of the modalities into different locations. For Centraal travellers using the NZL use routes that are signed differently from the other (older) metro lines, from the train station these travellers are led north instead of south. To differentiate these travellers transfers from and to the NZL (line 52) were selected and put in a separate category. The travellers using the other metrolines were categorised as Metro-City because the station of the older metro lines is located on the southern city facing side of the station complex, see for reference figure 4.2. For the Noord station busses terminating there have a static platform on one side station building, bus lines driving through the station stop on both sides of the station depending on the direction they are going, this can be seen in the map of Noord in figure 4.6. Here we can select transfer of certain bus lines and allocate these to the specific part of the bus station. We do not know the direction of busses that passengers transfer to so it was chosen to split the travellers of the through lines evenly between east and west. This can be supported by looking at the symmetrical nature of the rest of the day data. These travellers are put into the two new categories Bus-East and Bus-West.

After taking these steps for Centraal and Noord the data was ready to be aggregated into transfer OD-matrices. In spyder we aggregated all transfers that have the same pair of origin and destination modalities, or specific sub-divisions. This was done by looping over every row in the selected data set and adding it's number of transfers to the row and column in the OD-matrix matching the origin and destination modality of the transfer. This process yields an OD-matrix with absolute numbers. Dividing these numbers by the total number of transfers made gives the shares of every OD-pair in a matrix. All found OD-matrices can be found in appendix C, here one is shown as an example in table 4.7 below. Additionally we show an OD-matrix with the daily average of travellers to provide a more intuitive insight in traveller numbers. A small note for this table has to be made: the values on the diagonal of the OD-matrix are very unreliable. These values represent intermodal transfers, but for modalities with on land check-in, train and metro, this does not require checking in and out leading to a potential under representation of these transfers. The code for this part of the analysis can be found in the appendix in E.

Asd	**Bus**	**Metro_City**	**Tram**	**Train**	**Metro_NZL**
Bus	904	1475	949	2401	1129
Metro_City	2045	125	1827	5628	434
Tram	1282	1710	2287	6816	1419
Train	3026	5617	7164	613	4354
Metro_NZL	1324	212	1359	4340	155

Table 4.6: OD-matrix of transfers at Centraal with daily averages, indicating the flow of transfers from the vertical to the horizontal modes.

Asd	**Bus**	**Metro_City**	**Tram**	**Train**	**Metro_NZL**
Bus	1.5%	2.5%	1.6%	4.1%	1.9%
Metro_City	3.5%	0.2%	3.1%	9.6%	0.7%
Tram	2.2%	2.9%	3.9%	11.6%	2.4%
Train	5.2%	9.6%	12.2%	1.0%	7.4%
Metro_NZL	2.3%	0.4%	2.3%	7.4%	0.3%

Table 4.7: OD-matrix of transfers at Centraal with relative flows

As route weights an OD-vector instead of a matrix is needed. In order to be able to multiply the values in the survey matrices with their route weights we need an input in a vector. Some small steps have to be taken to convert the OD-matrix as shown above to the needed vector. Since this research focuses on intermodal transfer the values on the diagonal of the matrix will be filtered out, these values represent the intramodal interchanges. After this is done all other values have to be rescaled to make sure the total of all weights equals 1 again. We do this by dividing all values by the sum of all values outside the main diagonal of the matrix. For Centraal the transfer between Metro-City and Metro-NZL was also regarded as intramodal and thus these values were also excluded from the final OD-vector. One example vector can be found in table 4.8 below, other vectors can be found in appendix C.

Train-Metrocity	0.104
Metrocity-Train	0.104
Train-Bus	0.056
Bus-Train	0.045
Train-Tram	0.133
Tram-Train	0.127
Metrocity-Bus	0.038
Bus-Metrocity	0.027
Metrocity-Tram	0.059
Tram-Metrocity	0.058
Bus-Tram	0.018
Tram-Bus	0.024
Train-MetroNZL	0.081
MetroNZL-Train	0.081
MetroNZL-Bus	0.025
Bus-MetroNZL	0.021

Table 4.8: OD-vector of Centraal

4.5. The Model in Practice

Now that all model elements are defined we can start integrating them. This section will describe the technical steps taken to go from the original data sets to the useful model components and finally the results. In figure 4.8 below all steps taken are summarized. Squares describe data and ovals describe processes of data collection and manipulation.

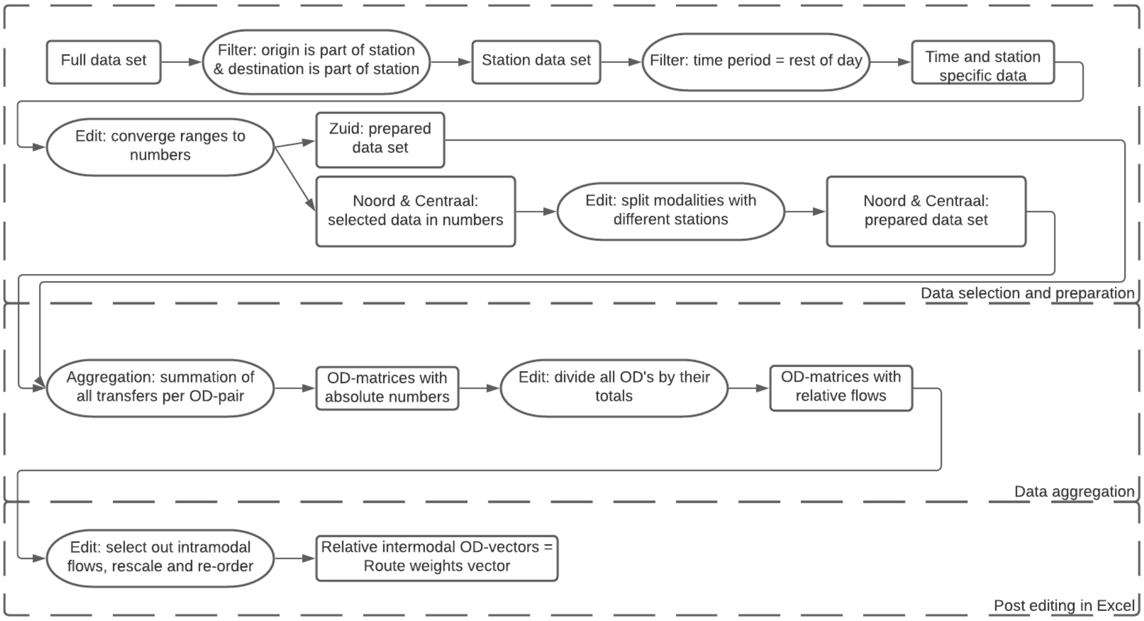


Figure 4.7: Conceptual framework of the selection and aggregation code

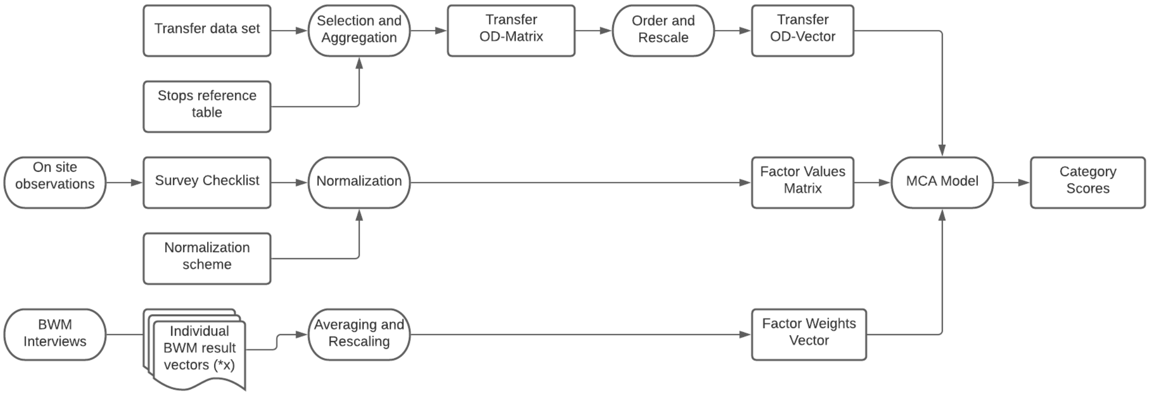


Figure 4.8: Conceptual view of all steps taken towards execution of the final model

In chapter 3 we described the three theoretical input components of the model: the normalized factor values matrix, the factor weights vector, and the route weights vector. In this chapter we have described the steps taken to obtain these components. The final model combines all three of these. All columns of the matrix are multiplied by the factor weights vector and then all rows are multiplied by the route weights vector. This process yields a matrix of weighted scores. The final step in the model is the summation of the scores within one category. In this step the scores across all factors (columns) belonging to one measurement category, distance, path quality, services, and information provision, are summated yielding four category scores. The actual used code can be found in appendix E. Not all steps of data analysis and editing were carried out by programming in Python. Some steps were done in Microsoft Excel when this was deemed faster and more intuitive. Results of these steps can for example be found in table A.1.

4.6. Results

In this paragraph the results of the run of the model with case study data will be presented. First the aggregated results at modality level for every station will be presented and compared and finally results across station will be compared coming to a conclusion. A score of one is the optimal mark for a factor, more on the build up of the points system can be found in paragraph 3.1. For every station the scores are showed in four figures. The figures depict the weighted average score for connections towards and from the modalities. Some factors such as wait weather protection only count for the 'to' mode and for example cases of crowding at platform exits count for a 'from mode'.

4.6.1. Amsterdam Centraal

Amsterdam Centraal is a large station with a high level of service. Detailed results for all modalities can be found in figure 4.9, full results can be found in the appendix in table D.1. The figures depict the weighted average score for connections towards and from the modalities. Some factors such as wait weather protection only count for the 'to' mode and for example cases of crowding at platform exits count for a 'from mode'. Due to its size many connections are longer than ideal but good design at for example the Cuyperstrap, the new connection between the station hall and the underground metro ticket hall, and the NZL with its connections on both sides of the railway tracks mitigates this. Distance wise (see first subfigure) the NZL clearly scores best due to its connections on both sides of the railway that acts as a barrier for other connections. The other modalities all score lower with the more centrally located train scoring best of the rest.

The scores in the category path quality are more differentiated (see subfigure 2). Most low results are due to the connection to the tram. The tram is located outside in front of the railway station building and scores low marks on various factors. The tram stop is located outside with only small shelters, this affects the connection towards the tram, this can be seen in the difference in scores between routes to and from the tram in the figure. The outside connection and crossing of the active tramways affect connections both ways. The only observed crowding occurred at the bus station, here several bus loads of people had to exit the platform via one escalator. This leads to a lower score for routes emitting from the bus as can be seen in the difference in the scores to and from the bus.

The service provision in the station is very high (see subfigure 3). All measured factors across all routes score full marks. Although the bulk of the services can be found in the main station building there are also some shops in the underground metro area giving a good coverage of functions.

In the category information provision (subfigure 4) the tram again scores weakly. All scores below one for the other modalities are caused by lacking information about the trams. The signage of the station stops at the front exit of the station where the tram is located and only one dynamic information screen is present at a location not serving all travellers. The lack of signage mainly affects travellers from the tram because there are no signs pointing towards train and bus, the entrances of the metro are located directly next to the tram and are indicated with high signs with the metro logo and thus score well. The lacking dynamic information affects travellers towards the tram. The one screen present is located in front of the central exit on the front side of the station. This is not the exit that is used when one follows the signs towards the tram inside the station, secondly a second screen would be needed to optimally serve both parts of the tram station.

Overall the tram scores the lowest across most categories, the rest of the facility is large and thus scores low on distance but further performs well. The tram being located outside and having level crossings automatically makes it score low on various aspects of path quality. However the lacking information provision is not a natural effect of this design choice, an easy improvement could be made here by bringing the signage and dynamic information up to standard.

Figure 4.9: Factor category scores for connections emitting from and going towards various modalities at Centraal

4.6.2. Amsterdam Zuid

Amsterdam Zuid also has a large footprint. This is however not mainly caused by the amount of supplied service but by the large transitional area in between the two core parts of the station, the station building with trains and metros, and the outdoor tram and bus station. Within the two main areas distances are relatively small, but connecting between the domains takes a lot longer. Half of all intermodal transfers go between the two areas so this has a large impact on the station's performance. In the visualisation of the outcome of the analysis in figure 4.10 tram and bus connections are shown together since they have exactly the same scores across all categories and functionally serve as one domain within the station. For distance (subfigure 1) tram and bus score low because of the large share of travellers going towards train and metro, train and metro score better because of their high share of mutual transfers.

For path quality non of the routes score full marks (subfigure 2). Routes from and to the busses and trams have to deal with an outside connection that also crosses an active car route and has stairs with no escalators. The train is the only modality with a fully covered waiting area. The trams and busses only have small shelters as does one of the metro platforms. Capacity problems occur for routes emitting from both trains and metros. Crowding was observed for passengers exiting the railway platforms and bunching for passengers coming from the metros. This is the only sub optimal score for the connection between metro and train. FOr the trains we can observe a difference between the from and to scores. Emitting routes suffer from the observed crowding and from the lesser weather protection at target modalities. For bus and tram we can observe an opposite pattern. There is free flow heading out.

For service provision scores are better (subfigure 3). Especially connections to the trains score high since some of the services such as the toilets are located within the ticket controlled area. Opening hours for the desks of the GVB are limited due to Covid which affects the scores of connections towards modalities other than trains. Most facilities are offered within the main station building away from the tram and bus. Passengers connecting between tram and bus are affected by the detour when wanting to use the services offered, however this is only about three percent of all transfers.

In the category information provision transfers emitting from the bus and tram area score very low (see subfigure 4). In the tram and bus station no signage is present indicating the direction of the train and metro station. This is especially a problem because of the one hundred metre gap between the two domains making it difficult to navigate just on sight. For connections from the train and metro towards bus and tram signage stops outside of the station building but here one only has to continue straight ahead so full marks were given for this connection.

Amsterdam Zuid scores lower than Centraal on almost all aspects. Services seem to have not grown along with the increased usage of the station. This however is a known problem and throughout the coming decade a large scale renovation and extension of the station is planned, which also includes moving bus and tram closer to the station building and increasing the capacity of stairs and escalators (NS, 2021b).

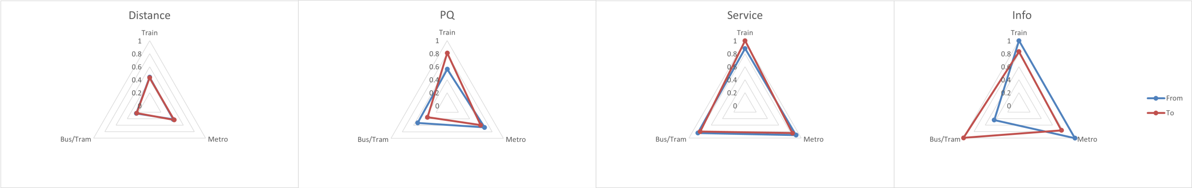


Figure 4.10: Factor category scores for connections emitting from and going towards various modalities at Zuid

4.6.3. Amsterdam Noord

Amsterdam Noord is a compact facility. It fits the archetype of a commuter transit centre as set out by Pitsiava-Latinopoulou and Iordanopoulos (2012) with connections of the regional busses to the urban metro. Amsterdam Noord has no fully indoors connections. All routes pass via the outside and cross active PT lines. Outside of these two factors all other aspects of path quality are up to standard. The facility is rather new and provides sheltered waiting, full coverage of elevators and escalators, and has no observed crowding issues.

The service level (see subfigure 3) is much lower at this station compared to the two train stations. There is only one convenience store and a staffed desk with limited opening hours due to Covid. There seemed to be vacant additional commercial units inside the station that might be used to increase the service supply and bring the services closer to the eastern bus station.

As with the two other stations connections from outside to inside score low for information provision (see subfigure 4). Although the dynamic information at the bus stations at both sides is very good, with screens indicating the departure times of busses and metros and with platform departure signs clearly visible from the general waiting area right outside the station building, there is zero signage indicating where the metros and other busses depart. For routes emitting from the metro the picture is exactly opposite. The fixed signage is complete and correct, but dynamic information is late causing a lack of information at the decision point for travellers having to go to one of the two bus stations.

The overall picture of Noord is that of a modern and compact facility aimed at commuters with a service level supporting this goal. However the supply of information is not on par with the standards for a well functioning commuter transit centre, especially given this is a very new facility.

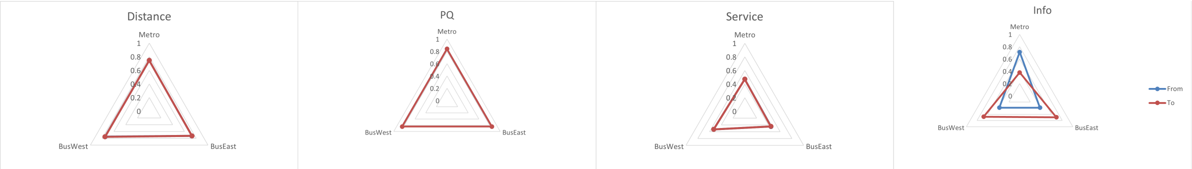


Figure 4.11: Factor category scores for connections emitting from and going towards various modalities at Noord. Note: most results are symmetric for this case so the blue line is hidden.

4.6.4. General results

	Asd	**Asdz**	**Nrd**
Distance	0.45	0.38	0.74
Path quality	0.89	0.59	0.84
Service	1	0.88	0.48
Info	0.86	0.85	0.55

Table 4.9: Aggregated model results

Now that we have highlighted the results of all three stations we can conclude this case study by comparing the aggregated results of all three stations. The results of the model run on the most aggregated scale can be found in table 4.9 above, the table gives weighted average values for all factor categories for entire stations. Although the model is generic and normative in nature it is important to recognize that not every station is the same and travellers will expect other things from different stations (Pitsiava-Latinopoulou and Iordanopoulos, 2012). That is why in the previous section already usage patterns and their relationship to design characteristics were highlighted.

Amsterdam Centraal clearly is a well scoring large station. Amsterdam Centraal combines connections to a wide variety of modes with and extensive supply of services, scoring the only full 1 in this analysis, and good internal connections. Providing full coverage of elevators and escalators and only minor signs of bunching. Amsterdam Zuid falls behind Centraal on all categories. The scores suffer from the connection between the station building and the tram and bus station to the north. This connection is long, lacks escalators, and is ill signed. Capacity wise significant crowding was observed at the trains and some bunching at the metros. Services here are concentrated towards the station building which gives lower scores for busses and trams. However plans are well underway to improve capacity and quality of this station in the upcoming ten years. Amsterdam Noord clearly serves a different function in the system which is matched by the level of certain services. This does however not mean that aspects like information provision can be neglected. The station is compact and connections are mostly good, with scores only suffering from the small outdoor connection that also crosses the bus lines. Compared to Centraal and Zuid, Noord does not have any fully indoors and traffic free connections. The outdoor parts of Centraal and Zuid also score lower but these scores are somewhat mitigated by the indoor connections that also form the largest part of the connections made (58.2% of connections at Amsterdam Centraal are fully indoors).

Across all cases we can observe a clear distinction between modes located inside the station buildings and outside. Routes connecting to modalities located outside do not only score low on factors directly covering weather protection, but also generally have a level crossing, and are often ill signed. Locating a mode outside a station building and serving it with a level crossing to connect the platform are deliberate design choices, the ill signage however is obviously not a deliberate design choice.

4.7. Model Validation

In the previous paragraph the model outputs were presented. In this paragraph these outcomes will be compared against existing data on customer experience to validate the model results or to identify weak points. The goal of the model was to operationalize the transfer quality from the perspective of the customer. This was done because transfers are currently perceived as the worst performing parts of the system. The outcome of the model should thus mirror the actual experiences of customers. This is why the model outcomes will be compared against outcomes of customer surveys carried out by operator NS.

For this research data from the stationsbelevingsmonitor (SBM, translated: station experience monitor) carried out by national railway operator NS was used. This is a data set based on customer questionnaires. This questionnaires are carried out on the platforms with waiting travellers as respondents. For more information on the SBM see NS Stations and ProRail (2021), the actual used data is not available to the public, this web page contains highly aggregated information. For large stations the data is gathered four times per year. This means however that there only is data for the train stations. That is why the outcomes of Centraal and Zuid will be compared against data from the SBM. In the questionnaire respondents were asked to grade several aspects of their experience of the station on a scale from one to ten with ten being the highest score. Unfortunately the questionnaire did not cover all aspects of our model. Some other results do not match directly but can be linked to factors in the model. The results of the relevant questions can be found in table 4.10 below.

	Unimpeded acces	Shelter	Shops	Info where	Fixed info	Travel info	BTM location	Station quality
Asd	7.70	6.79	7.98	7.78	7.75	7.75	7.77	7.50
Asdz	6.98	4.93	6.76	7.26	7.32	7.41	7.47	6.73

Table 4.10: Grades for several aspects of station experiences from SBM

Now this results can be compared with the model outcomes from the previous paragraph. The SBM used a grading system intuitive for a Dutch respondent because it uses a ten point grading system that is also used in education, hence people have a good feeling for what certain marks mean. A grade of five or lower is considered a fail. Here we will however mostly cover the relative differences between the two stations rather than their absolute scores. We will start by comparing the general picture. In the SBM respondents are asked to give a general mark for the quality of the entire (train) station. Although it was chosen to not aggregate into one score for our model it is still interesting to compare this numbers to our results. Zuid scores worse than Centraal on all four aspects of the model, this is reflected by the general mark given by the public in the SBM. It is important to note that the questions in the questionnaire can mean several things for respondents. The question: 'I can reach the train unimpeded', can cover the capacity of a station as well as step free access for disabled people. To compare these results to that of our model some assumptions will be made. The first question in the table on unimpeded access seems to match the model results. Crowding was observed at the platforms of Amsterdam Zuid and bunching on the metro platforms. For Centraal only minor bunching was observed at the bus station. The sheltering score however does not match. Both Centraal and Zuid scored full marks for the sheltering of the station platforms. This does not match the valuation in the tool where a canopy over every platform is already considered fully sheltered. This was done because the sheltering (wait weather protection) is seen as a dissatisfier scoring full marks when a satisfying level is met. Apparently people also value the more closed nature of Centraal that also offers wind protection over only a small canopy that does not protect against wind and noise blowing over the highway adjacent to the railways. Respondents even rate this factor with an unsatisfactory grade of 4.93. For the model another factor level could be added. Groenendijk (2015) for example features the factor heated waiting covering fully enclosed heated indoor waiting areas. Shops show a somewhat similar picture as shelter did. In the tool both stations score full marks on this category but in the SBM the surplus of shops at Centraal is clearly valued by travellers. To include this several factor levels could be added on top of the current three levels. Zuid features eight shops in the relevant category (convenience stores, reading materials, hot drinks, and fastfood) and Centraal has over twenty. In the model the various aspects of information provision have comparable score for both stations. In the SBM however there is a clear difference between both stations that is hard to explain from observations.

Especially for the train parts of the stations both Zuid and Centraal score full marks. Scores below one are mainly caused by lacking information provision in the domains of other modalities, the tram for Centraal, and the bus and tram for Zuid, all located outside the station building. The difference in the scores of Zuid and Centraal in the SBM could be caused by people entering the PT-system at those stations via routes that weren't included in this tool since it only covers transfers within the PT-system. The last question with values in the table is 'The bus tram/tram/metro lies in a sensible position'. Given the results in the tool lower marks were expected. Relatively however the grades in SBM seem to match the distance scores from the tools. Being in a sensible location directly connects to the concept of design priority which was the original factor where the route weights were based of.

Unfortunately not all factors from our tool were covered in the SBM questionnaires and some were not useful. The question for toilets for example asked to rate the cleanliness which does not help in determining the importance of the presence of said toilet. From the available results however we van generally say that the stated results from the SBM match the outcomes of the developed tool. The largest difference seems to be for values that go above the original upper bound of the measurements in the tool. Possibly the measurement ranges for these factors could be extended.

Overall this leads to the conclusion that most modal results effectively mirror the stated experience of the station's users. We will conclude with a small experiment that was carried out to show the usage of the tool on a smaller scale. During the pilot survey at Centraal the Cuyperstrap, the recently opened indoor connection between the station hall and the underground metro hall was closed. This provided an interesting alternative scenario that could be used to compare against the current scenario. The data collected in the pilot has been analyzed by the model and is compared to the outcome of the model with data where the connection was included. This comparison can be seen in table 4.11 below. Services and information have been left out here because these went unchanged. We can clearly see the positive changes this connection made in decreasing the connection's distance and introducing a fully roofed passage.

		Distance	Crossing	Routew	Waitw	Elevators	Escalators	Cap	PQ
Train-MetroC	With Cuyperstrap	0.267	0.221	0.048	0.227	0.123	0.110	0.224	0.952
Train-MetroC	Without Cuyperstrap	0.433	0.221	0.096	0.227	0.123	0.110	0.224	1.000

Table 4.11: Comparison of the metro train connection with and without the Cuyperstrap

5

Conclusion

The goal of this research project was to gain insight in multi modal transfer quality of public transport stations by making the quality measurable. To do this a measurement tool was developed that combines the design factors of the stations with usage numbers using a multi criteria analysis (mca). This chapter will look back on the development and usage of this tool and try to answer if this model fulfills the goals set out in the introduction of this project. After this the chapter will touch on the scientific tradition this research aims to contribute to. Furthermore the possibilities of continuing with the legacy of this research will be highlighted. The chapter will finish with a reflection on the project.

5.1. Conclusion

The main research question for this project was:

How can we measure a public transport station's ability to facilitate an efficient and comfortable multi-modal transfer?

In the upcoming paragraph first all sub research questions will be answered. After that these answers will converge in the conclusion on the main research question that was the impetus of this project.

5.1.1. Conclusions on sub question

1. What design factors influence a station's performance to facilitate multimodal transfers?

Sub question 1 was the focal point of the literature study that was part of this research and is elaborated on in chapter 2. The goal here was to find a list of factors that could then be used to build up the model. In a multi criteria analysis every design option or scenario is described by the values of a series of criteria (factors) that together make up all relevant characteristics. The factors were gathered by studying various scientific approaches at assessing station performance. Finally six scientific research fields were highlighted:

1. Public transport integration. This type of research looks into the administrative and economical organisation of the PT-system and studies its effects on performance.

2. Customer satisfaction research. This research fits in the scientific schools of psychology and marketing focusing on the effects of certain design elements on human (customer) behaviour and preferences.

3. Utility based traveller research. This type of research fits into the econometric paradigm seeing humans utility maximizers seeking the best outcome for themselves across all possibilities.

4. Simulation modelling. This is an engineering method that uses computer simulation to ex ante explore the effects of design choices on passenger flow.

5. Ex post station design analysis. With two kinds of research. Researching the performance of existing stations by studying usage patterns and stated customer satisfaction.

While studying these six scientific fields, factors stated as influencing station performance were collected. When combining all these factors many had overlap with other fields but many also showed new insights. Using criteria from Sijtsma et al. (1998) the more or less abstract factors were translated to thirteen final measurement factors that can be found in table 5.1. The factors were categorised into four groups, distance, path quality, services, and information provision. This was done because it grants a better insight in the functioning of the stations. One fully aggregated score per station would imply mutual compensation between factors. This is not the case since sub par execution of certain factors can negatively impact one's experience beyond compensation. This categorisation was based on that used by Hernandez et al. (2016).

Factor name	**Definition**
Distance	Walking distance between the platforms of two modalities.
Path Quality	
Traffic crossings	Describes whether there are crossings with other forms of traffic.
Route weather protection	How are walking passengers protected against the elements?
Wait weather protection	How are waiting passengers protected against the elements?
Presence of elevators	Do elevators cover all height changes in a route?
Presence of escalators	Do escalators cover all height changes in a route?
Services	
Shops	Are convenience stores present?
Toilets	Are public toilets present?
Staffed desks	Are staffed desks for tickets and information present?
Detour	How far is the detour from the ideal route to visit a shop?
Information	
Fixed signage	Is the presented fixed signage complete and correct?
Dynamic information	Is the presented dynamic information complete correct and on time?

Table 5.1: The thirteen model factors and their definitions.

2. How can we develop a measurement model to combine and weight the design factors into performance scores?

The second sub question was divided into three sub questions that will be answered separately:

(a) How can we measure and quantify the design factors?

This sub question mainly deals with the practical implications of measuring chosen factors. It is important to note that sometimes the type of data one wants to collect will lead to a certain methodology being chosen but sometimes also available methodologies will shape the type of data that can be collected. Fitting in within the framework of existing node place models (Caset et al., 2019, Peek, 2006) and using the criteria of Sijtsma et al. (1998) meant that we were looking for easily obtainable data on the stations. Combining the practical and theoretical limitations with the factors gathered lead to the development of a survey legend that can be found in table 5.1. This legend serves as a framework for the objective observation of all stations and forms one of the main structural components of the tool. The chosen methodology with thirteen measured factors and a clear legend defining all measurement levels made it possible to objectively and consistently observe and valuate several aspects of station design.

(b) How do we compare and weight these factors?

The first step in making the measurement data comparable was normalizing on a scale from zero to one to serve as an input for the model. This is a normative step, translating the observations to scores between one (excellent) and zero (very bad). To develop a generic tool covering the full range of potential measurement values the input for normalization was based on literature combined with the made observations to come to the final normalization table that can be found in table 3.2.

The second step of answering this question is about the weighing. To perform the multi criteria analysis (MCA) that is the core of the model all factors will be assigned a weight, with weights adding up to one within every category. To get these weights fifteen field experts were questionnaired using the best-worst method (BWM). These experts came from the academic, commercial, and governmental fields. The BWM was used because of it's proven record in comparable research, see for example Groenendijk et al. (2018), and it's low data requirements. Combining the results from all conducted questionnaires gave the results that can be seen in table 5.2 and that served as factor weights in the further analysis. To achieve a score for all of the four categories all measurement values will be multiplied by their factor weights given a weighted average value of the factors on the original measurement scale of zero to one.

Factor	Distance	Traffic crossings	Route weather protection	Wait weather protection	Elevators	Escalators	Bottle neck capacity	Shops	Toilets	Staffed desks	Detour	Fixed Signs	Dynamic information
Weight	1.000	0.221	0.096	0.227	0.123	0.110	0.224	0.297	0.275	0.241	0.187	0.618	0.382
Category	Distance	Path Quality						Service				Information Provision	

Table 5.2: The thirteen model factors and their final weights

(c) How can we integrate the importance of different modalities in a hub in the model?

One of the main goals of the model was that it should be able to address design priority. In highly used station areas a good design will allocate the scarce space to the most important goals. This idea is visualized in figure 2.2. For this research it was chosen to follow up on an idea that was part of the MCA carried out by Bryniarska and Zakowska (2017) namely weighing route quality numbers by their usage shares. Bryniarska and Zakowska (2017) suggested in their recommendations for further research to gather this transfer from smart card data and not as they did from customer surveys. In this research we had access to a data set containing smart card data for travellers in Amsterdam (Brands et al., 2020). In a more generic context several sources of travel data could be used here. Bryniarska and Zakowska (2017) for example used a marketing survey to collect their route weights. Other more traditional methods such as passenger counting and travel diaries of a sample of the population could also work here. Important is that the data contains details on the parts of a trip before and after a transfer.

3. Can we use this measurement tool to accurately determine a stations actual quality to facilitate transfers?

After conducting a case study on three stations in Amsterdam we can conclude that the tool works. However there are some notable points that have to be mentioned when using the tool. The main power of MCA lies in its ability to compare scenarios and situations using its own objective framework. This means that a single score of a station without context is somewhat meaningless. A score of one across all categories would imply a perfect design, but perfect designs do not exist, there will always be a trade off somewhere. When this tool however is used across multiple cases to for example identify weak points that should be addressed these relative scores can prove very insightful. For example in identifying the bad scores of outside stops at many stations.

A second comment lies in the generic nature of the tool and the specific situation of every station. By nature a MCA-tool is normative, the decision maker chooses how he rates certain abilities and this translates into a score. This for example shows up when comparing the availability of services across the three Amsterdam cases. Noord, as a commuter transit centre (Pitsiava-Latinopoulou and Iordanopoulos, 2012), requires a different level of services than an international intercity stop like Centraal. The lower score of Noord on the aspect of service design naturally implies a worse design but here we showed this is not always the case.

One of the goals of the research was to provide a quick scan for station design without large data requirements. To validate the results of the model these should be compared against user's opinions on their experience. To do this the outcomes of the model were compared against data obtained from customer questionnaires. Generally the results of the model matched these experience values well with the biggest shortcoming being the limited upper bound of the measurements. Most customers seem to value design beyond the measurement scale that was used in this research.

4. What design lessons, positive and negative, can be drawn from the analysis of hubs using this tool?

As stated above the power of an MCA based tool lies in its ability to compare objectively. This makes it difficult to observe weak or strong points without any context for many factors. A transfer distance of zero is nearly impossible for example. When however context is available it is relatively easy to compare across cases. Although it has to be noted that context for every station is different comparing cases, such as Zuid and Centraal, can still lead to insights in the design of both stations.

Some factors fall into the category that Van Hagen (2011) describes as dissatisfiers. Factors that when designed well will go mostly unnoticed but when executed poorly will seriously impede the travel. For this factors scores can more easily be used without comparison. A full score of one is possible for for example information provision and will indicate that the category is executed sufficiently. The same goes for most factors in the category path quality. A score lower than one on this factors thus directly indicates sub-optimal design regardless of context.

For the case study a pattern was found of outside areas that scored low on information provision, weather protection, and traffic crossings. Identifying patterns like this can improve future designs by highlighting previously overlooked aspects and also help to improve current facilities. For Amsterdam Zuid we can clearly see that in the planned designs (NS, 2021b) the observed issues will be addressed, mainly in making the station more compact.

Looking at Centraal we can see that the NZL scores well on all categories compared to the other modalities present. Especially for distance with a score of 0.60 with the second modality the train scoring 0.46 we can see that connections are short. In paragraph 2.2.2 vertical stacking was described as a strategy to achieve concentration in crowded station areas. By locating the NZL-platform perpendicular to the train tracks underneath the station building and making entrances on both sides of the tracks short connections were created with all other modalities.

5.1.2. Conclusion on main research question

The main question that this research tries to answer was:

How can we measure a public transport station's ability to facilitate an efficient and comfortable multi-modal transfer?

To answer this question a measurement tool was developed. Scientifically this tool is connected to the existing tradition of explaining station performance with the node place (NP) model as first posed by Bertolini (1998). This paradigm has been the leading paradigm on station assessment in the Netherlands in the past twenty years (Groenendijk et al., 2018). Over the years this model has been used by may parties in the transport and spatial markets (Peek, 2006). This proves the model is flexible for usage from various viewpoints and makes it a good platform to base the tool on. Furthermore the usage of a family of models that has been used for over twenty years provided a good insight in the gaps still present.

NP models are mostly structured as a multi criteria analysis (MCA). Describing designs or scenarios by the value of several factors and weighing these factors to achieve final scores depicting the performance of the design. Combining this idea with using route weights lead to the structure of the model where every factor value for every connection is weighed twice, once for the weight of the connection which depends on the share of transfers using that connection, and once with a weight addressing the importance of the factor on the design in general.

Sijtsma et al. (1998) set out requirements for the factors of a mca of being a limited number, having minimal overlap, and being practically obtainable. Through a multi disciplinary literature study a list of thirteen design factors is made. This list can be found in table 5.3. Together with the legend with factor definitions and explanations of the measurement levels that can be found in table 5.1 this is the main product of this project next to of course this document.

For this study it was chosen to questionnaire fifteen field professionals to gather factor weights. To this this the best worst method was used (Rezaei, 2015), a proven method for expert based weights collection. These experts from academics, operations, governement, and consultancy provided good coverage of the PT-market as well as comments that made their answers relatable to theory such as the pyramid of customer needs of Van Hagen (2011). The final factor weights can be found in table 5.3.

Factor	Distance	Traffic crossings	Route weather protection	Wait weather protection	Elevators	Escalators	Bottle neck capacity	Shops	Toilets	Staffed desks	Detour	Fixed Signs	Dynamic information
Weight	1.000	0.221	0.096	0.227	0.123	0.110	0.224	0.297	0.275	0.241	0.187	0.618	0.382
Category	Distance	Path Quality						Service				Information Provision	

Table 5.3: The thirteen model factors and their final weights

5.2. Recommendations for further Research

Although this research has managed to answer most of the questions that were asked at the beginning of the project our understanding of the matter is never complete. Further research can be done to even better understand stations and to improve the developed tool. Recommendations for further research roughly go in two directions. Deepening research can improve the current tool, and broadening research can make the tool more useful as an integral toolbox for a better understanding of all processes going on in stations.

5.2.1. Deepening research

The currently developed tool has been build up with relatively small amounts of data. The factor weights have been gathered by interviewing only fifteen field experts. Other studies such as Groenendijk et al. (2018) have used a much larger sample (N=160) of respondents showing the ability of BWM to be used for surveys on the general public rather than only on experts. To improve the accuracy of the model the number of respondents for a re-calibration of the model could be increased, either by using more experts or by asking a sample of the general public.

In this project the model was tested on three cases. Within these three cases we already observed very different typologies of stations. In the beginning of the project the scope was set to mid-sized and larger stations. As noted in the conclusion the normative nature of the tool sometimes does not meet the practical reality of certain station types. Gathering more data on stations of the same type would increase the understanding by having more material to compare with. This is also one of the potential societal applications of the tool. Analyzing a selection of stations across a network or city to identify problems or weak points.

5.2.2. Broadening research

The tool as presented is useful as an exploratory tool or a quick scan to look at the integration of a station. There is also a possibility of combining the output of the tool with other aspects rated by NP-style models. As can be seen in table 5.4 the tool developed in this project operationalized a fourth component that was previously conceptualized by Peek (2006), Peek and Louw (2008). This gives the option of integrating the methodology of this tool into existing frameworks, such as that of Groenendijk (2015), that already operationalized the other three components. This would give an integral tool to assess the performance of a station.

	Node Values	Place Values	Model Properties
Network Properties	Classical Node Value (Bertolini, 1998)	Classical Place Value (Bertolini, 1998)	Traditional NP-model components
	Accesibility Premium (Bertolini, 2008)	Urban Centre (Peek and Louw, 2008)	Station as a geographic entity (Peek and Van Hagen, 2002)
	Transportation Node (Peek and Louw, 2008)	Transport Demand	Focus on processes and networks outside the station
	Transport Supply	Urban contextual place value	Used for land use and real estate analyses (Peek, 2006)
	Network contextual node value		Station is a black box
			Location quality
Local Properties	Connector (Peek and Louw, 2008)	Meeting Place (Peek and Louw, 2008)	Analyzing stations as micro systems
	Transfer quality (this research)	Station Experience (Groenendijk et al., 2018, Van Hagen, 2011)	Focus on processes within the hub
	Transfer Machines (Peek, 2006)	Independent Place Quality (Peek, 2006)	Station as a vital link within the PT-system
	Independent Node Quality (Peek, 2006)	Interchange Waiting	Design Quality
	Interchange Walking		

Table 5.4: Elements of the extended node place model (inspired by Peek (2006), Peek and Louw (2008))

5.2.3. Other development paths

The developed tool relies heavily on observations. The transfer numbers used as route weights are derived from observed traveller data and collected through ticketing data, and crowding is measured through observations. This makes the tool in its current state an ex post design analysis that can address the current quality of a station. The structure of an MCA also allows for an ex ante comparison of for example different design alternatives. But for that to work a source of data other than observations would be needed. Here the source of transfer data would be changed from actual observations to for example the outcome of a transport model, and the observations on crowding to the outcome of a simulation. With this new data sources as model input the tool could be used as a multi criteria decision support for comparing several design scenarios. Supporting design processes by giving an objective framework to address integration.

5.3. Reflection and Discussion

The largest scientific weakness of this work lies in the way data was collected in various steps of the research. Two main points will now be highlighted along with possibilities to overcome these challenges in the future. Furthermore some comments on the model itself will be made.

5.3.1. Challenges in collecting expert data

The weights of the factors in the MCA model are based on the opinions given by fifteen experts in interviews where a BWM questionnaire was used. These interviews were done by the researcher over a video call with the respondents. Several steps in this process should be reflected upon. First of all the selection of experts was done in a rather unstructured way. Experts known to the researcher or the supervising team were first approached. After this authors of relevant pieces of literature used in the background study were approached as well. Finally only two people did not respond or responded negatively. Although the current interviewed experts cover a wide range of functions and areas of expertise within the PT-system, this research could certainly be improved by a more systematic selection of experts and by increasing the number of interviewees. During the interviews it was noted that respondents sometimes did not completely understand questions asked. Somewhere during the process it was suggested that interviewees could be presented with some information up front. Some home work to make the interview itself more fluent. Especially during early interviews respondents did not fully understand what was covered by the model factors at the start of the interview leading to a disparity in their initial hand picked rankings and the answers in the BWM later. This problem became smaller during later interviews as the skill and experience of the interviewer increased. It was chosen not to present the interviewees with upfront reading material to not alter the methodology halfway through the process and to not claim more of their time.

5.3.2. On site observations

The factor levels for the various measured design aspects of stations were gathered through on site observations. Here efforts were made to do this in a systematic way by visiting all stations twice, once in the morning and once in the evening peak. However some observations can still be the effect of random occurrences. The factor bottle neck capacity was the hardest to establish. As we noted in chapter 3 for all factors the worst part was noted. This means that when bunching or crowding was observed after the arrival of one train or several busses this affected the scores of all routes emitting from that modality. Having to spot these relatively rare occurrences combined with the lower usage levels due to Covid make the obtained factor levels here feel a bit random. Solution here could be to do even more observations, or to work with a system that does not fully penalise a route for one bad observation.

5.3.3. Model validation

After calculating the final scores for different factor categories using the developed model no reflection step was taken to validate its results. Usually a model development contains a validation step and a potential readjustment when needed. This research lacks those steps. This was mainly due to time constraints wishing to finish this already somewhat delayed project. Preventively a control experiment with handpicked ordering of factors was carried out as part of the BWM questionnaire. This mainly covered the factor weights and not the model in its entirety. If more time would have been available an extra step of model validation with experts concerned with the chosen case study would have been a good concluding step.

Bibliography

Annema, J. A., Mouter, N., and Razaei, J. (2015). Cost-benefit analysis (CBA), or multi-criteria decision-making (MCDM) or both: Politicians' perspective in transport policy appraisal. *Transportation Research Procedia*, 10(July):788–797. `http://dx.doi.org/10.1016/j.trpro.2015.09.032`.

Bertolini, L. (1998). Station area redevelopment in five European countries : An international perspective on a complex planning challenge. *International Planning Studies*, 3(2):163–184.

Bertolini, L. (1999). Spatial development patterns and public transport: The application of an analytical model in the Netherlands. *Planning Practice and Research*, 14(2):199–210.

Bertolini, L. (2008). Station areas as nodes and places in urban networks: An analytical tool and alternative development strategies. In Bruinsma, F., Pels, E., Priemus, H., Rietveld, P., and Van Wee, B., editors, *Railway Development Impacts on Urban Dynamics*, chapter 3, pages 35–58. Physica-Verlag, Heidelberg.

Bitner, M. J. (1992). Servicescapes: The Impact of Physical Surroundings on Customers and Employees. *Journal of Marketing*, 56(2):57.

Brands, T., Dixit, M., and van Oort, N. (2020). Impact of a New Metro Line in Amsterdam on Ridership, Travel Times, Reliability and Societal Costs and Benefits. *European Journal of Transport and Infrastructure Research*, 20(4):335–353.

Bruinsma, F., Pels, E., Priemus, H., Rietveld, P., and Van Wee, B. (2008). *Railway Development: Impacts on Urban Dynamics*. Physica-Verlag, Heidelberg.

Bryniarska, Z. and Zakowska, L. (2017). Multi-criteria evaluation of public transport interchanges. *Transportation Research Procedia*, 24:25–32. `http://dx.doi.org/10.1016/j.trpro.2017.05.063`.

Caset, F., Marques Teixeira, F., Derudder, B., Boussauw, K., and Witlox, F. (2019). Planning for nodes , places , and people in Flanders and Brussels : An empirical railway station assessment tool for strategic decision-making. *Journal of Transport and Land Use*, 12(1):811–837.

Daamen, W. (2004). *Modelling Passenger Flows in Public Transport Facilities*. PhD thesis, Delft University of Technology, Delft. `http://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid:e65fb66c-1e55-4e63-8c49-5199d40f60e1`.

Delbosc, A. and Currie, G. (2011). Using Lorenz curves to assess public transport equity. *Journal of Transport Geography*, 19(6):1252–1259. `http://dx.doi.org/10.1016/j.jtrangeo.2011.02.008`.

Garcia-Martinez, A., Cascajo, R., Jara-Diaz, S. R., Chowdhury, S., and Monzon, A. (2018). Transfer penalties in multimodal public transport networks. *Transportation Research Part A: Policy and Practice*, 114(January):52–66.

Groenendijk, L. (2015). *Incorporating the traveller's experience value in assessing the quality of transit nodes: A Rotterdam case study (MSc thesis)*. `https://repository.tudelft.nl/islandora/object/uuid%3A8147787a-06f8-4ac8-a18a-ab7875b7d34b`.

Groenendijk, L., Rezaei, J., and Correia, G. (2018). Incorporating the travellers' experience value in assessing the quality of transit nodes: A Rotterdam case study. *Case Studies on Transport Policy*, 6(4):564–576. `https://doi.org/10.1016/j.cstp.2018.07.007`.

Guzman, L. A. and Oviedo, D. (2018). Accessibility, affordability and equity: Assessing 'pro-poor' public transport subsidies in Bogotá. *Transport Policy*, 68(June 2017):37–51.

Harms, L., Jorritsma, P., and Kalfs, N. (2007). Beleving en beeldvorming van mobiliteit. Technical report, Kennisinstituut voor Mobiliteitsbeleid, Den Haag.

Hernandez, S., Monzon, A., and de Oña, R. (2016). Urban transport interchanges: A methodology for evaluating perceived quality. *Transportation Research Part A: Policy and Practice*, 84:31–43. `http://dx.doi.org/10.1016/j.tra.2015.08.008`.

Hoekstra, G. (2018). *Push Back The Boundaries: The potential of multimodal concessions to make the modal boundaries in public transport disappear (MSc thesis)*. Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid%3Ae4dfc2a2-6a62-42d8-8d09-eb536690720e`.

Ibrahim, M. F. (2003). Improvements and integration of a public transport system: The case of Singapore. *Cities*, 20(3):205–216.

Lee, A., Van Oort, N., and Van Nes, R. (2014). Service reliability in a network context: Impacts of synchronizing schedules in long headway services. *Transportation Research Record*, 2417:18–26.

Li, J. P. (2000). Train Station Passenger Flow Study. In Joines, J., Barton, R., Kang, K., and Fishwick, P., editors, *Proceedings of the 2000 Winter Simulation Conference*, pages 1173–1176.

Manaugh, K. and El-Geneidy, A. (2012). Who benefits from new transportation infrastructure? Using accessibility measures to evaluate social equity in public transport provision. In Geurs, K., Krizek, K., and Reggiani, A., editors, *Accessibility Analysis and Transport Planning*, chapter 12, pages 211–227. Edward Elgar Publishing. `https://www.elgaronline.com/view/edcoll/9781781000106/9781781000106.00021.xml`.

McFadden, D. (1974). Conditional logit analysis of qualitative choice behavior. In Zarembka, P., editor, *Frontiers in Econometrics*, chapter 4, pages 105–142. Academic Press, New York.

NS (2021a). Mission Statement. `https://www.ns.nl/over-ns/wie-zijn-wij/visie.html`.

NS (2021b). Renovation Amsterdam Zuid. `https://www.ns.nl/en/travel-information/renewing-stations/amsterdam-zuid.html`.

NS Stations and ProRail (2021). StationsBelevingsMonitor.

Peek, G.-J. (2006). *Locatiesynergie, Een participatieve start van de herontwikkeling van binnenstedelijke stationslocaties*. PhD thesis, Delft University of Technology, Delft.

Peek, G.-J. and Louw, E. (2008). A multidisciplinary approach of railway station development: A case study of ‘s-Hertogenbosch. In Bruinsma, F., Pels, E., Priemus, H., Rietveld, P., and Van Wee, B., editors, *Railway Development: Impacts on Urban Dynamics*, chapter 7, pages 125–146. Physica-Verlag, Heidelberg.

Peek, G. J. and Van Hagen, M. (2002). Creating synergy in and around stations: Three strategies for adding value. *Transportation Research Record*, (1793):1–6.

Pitsiava-Latinopoulou, M. and Iordanopoulos, P. (2012). Intermodal Passengers Terminals: Design Standards for Better Level of Service. *Procedia - Social and Behavioral Sciences*, 48:3297–3306. `http://dx.doi.org/10.1016/j.sbspro.2012.06.1295`.

ProRail (2005). Basisstation 2005, deel A en B: Functionele normen en richtlijnen voor treinstations.

ProRail (2019). OV-knooppunten van de toekomst. Technical report.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, 53:49–57. `http://dx.doi.org/10.1016/j.omega.2014.11.009`.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega*, 64:126–130. `http://dx.doi.org/10.1016/j.omega.2015.12.001`.

Rezaei, J. (2021). Best Worst Method, A multi-criteria decision-making method. `https://bestworstmethod.com/`.

Rivasplata, C. (2003). Three Perspectives on the Role of Competitive Tendering in the Integration of Public Transport. In *22nd Southern African Transport Conference*, number July.

RIVM (2013). Monitoringsrapportage NSL 2013, stand van zaken nationaal samenwerkingsprogramma luchtkwaliteit. Technical report, (Netherlands) National Institute for Public Health and the Environment.

Saliara, K. (2014). Public Transport Integration: The Case Study of Thessaloniki, Greece. *Transportation Research Procedia*, 4:535–552. `http://dx.doi.org/10.1016/j.trpro.2014.11.041`.

Schakenbos, R. (2014). *Valuation of a transfer in a multimodal public transport trip (MSc thesis)*.

Schakenbos, R. and Nijënstein, S. (2014). Waardering van een overstap tussen bus / tram / metro en trein. *Colloquium Vervoersplanologisch Speurwerk*, (november).

Schakenbos, R., Paix, L. L., Nijenstein, S., and Geurs, K. T. (2016). Valuation of a transfer in a multimodal public transport trip. *Transport Policy*, 46:72–81. `http://dx.doi.org/10.1016/j.tranpol.2015.11.008`.

Sijtsma, F. J., Strijker, D., and Hoefsloot, M. L. A. W. (1998). *Duurzame ontwikkeling in het Waddengebied: een afwegingsmethodiek voor economie, natuur, milieu en landschap*. Wetenschapswinkel voor Economie, Rijksuniversiteit Groningen, Groningen.

Train, K. E. (2009). *Discrete Choice Models with Simulation, 2nd edition*. Cambridge University Press, New York.

Van Hagen, M. (2011). *Waiting experience at train stations*. PhD thesis, University of Twente, Delft.

Van Hees, S. M. H. (2021). Regional Travel Time and Transfer Impacts of the Noord/Zuidlijn using Interoperable Smart Card Data.

Van Oort, N., Brands, T., and De Romph, E. (2015). Short-term prediction of ridership on public transport with smart card data. *Transportation Research Record*, 2535:105–111.

Verlaan, J. (2021). Wat blijft er over van het openbaar vervoer na coronatijd. `https://www.nrc.nl/nieuws/2021/05/19/wat-blijft-er-over-van-het-openbaar-vervoer-na-coronatijd-a4044234`.

Vuchic, V. R. (2005). *Urban Transit, Operations, Planning and Economics*. John Wiley & Sons, Hoboken NJ.

Wardman, M., Hine, J., and Stradling, S. (2001). Interchange and Travel Choice. Technical Report January 2001, Institute for Transport Studies at the University of Leeds and the Transport Research Institute at Napier University for the Central Research Unit of the Scottish Executive, Leeds. `http://www.gov.scot/Publications/2001/04/8886/File-1`.

Wegener, M. and Fürst, F. (1999). Land-Use Transport Interaction: State of the Art. Technical report, Institut für Raumplanung, Universität Dortmund, Dortmund. `ssrn.com/abstract=1434678`.

Xu, X.-y., Liu, J., Li, H.-y., and Hu, J.-Q. (2014). Analysis of subway station capacity with the use of queueing theory. *Transportation Research Part C: Emerging Technologies*, 38:28–43. `http://dx.doi.org/10.1016/j.trc.2013.10.010`.

A

Results of the BWM Questionnaires

Respondent	Distance	Traffic crossings	Route weather protection	Wait weather protection	Elev-ators	Esca-lators	Bottle neck capacity	Shops	Toilets	Staffed desks	Detour	Fixed signs	Dynamic info
University Researcher 1	1.000	0.170	0.102	0.128	0.061	0.102	0.437	0.552	0.207	0.172	0.069	0.125	0.875
University Teacher 1	1.000	0.337	0.104	0.209	0.104	0.037	0.209	0.266	0.114	0.571	0.049	0.750	0.250
University Teacher 2	1.000	0.336	0.045	0.135	0.081	0.202	0.202	0.250	0.167	0.083	0.500	0.750	0.250
Regional PT-Operator	1.000	0.155	0.078	0.116	0.233	0.034	0.384	0.094	0.516	0.234	0.156	0.750	0.250
PT-Consultant	1.000	0.077	0.154	0.385	0.038	0.231	0.115	0.596	0.145	0.078	0.181	0.250	0.750
Network Manager 1	1.000	0.119	0.068	0.159	0.238	0.036	0.381	0.353	0.391	0.038	0.217	0.667	0.333
Network Manager 2	1.000	0.319	0.043	0.128	0.191	0.128	0.191	0.500	0.200	0.200	0.100	0.500	0.500
University Teacher 3	1.000	0.387	0.097	0.121	0.242	0.032	0.121	0.112	0.619	0.188	0.081	0.667	0.333
University Teacher 4	1.000	0.047	0.342	0.199	0.080	0.199	0.133	0.682	0.082	0.071	0.165	0.750	0.250
National PT -Operator 1	1.000	0.410	0.040	0.250	0.071	0.166	0.062	0.139	0.065	0.152	0.644	0.833	0.167
National PT -Operator 2	1.000	0.107	0.036	0.214	0.357	0.143	0.143	0.063	0.265	0.617	0.055	0.750	0.250
Local PT -Operator	1.000	0.144	0.072	0.216	0.144	0.052	0.371	0.667	0.067	0.133	0.133	0.250	0.750
Regional Government	1.000	0.188	0.125	0.313	0.063	0.125	0.188	0.069	0.236	0.597	0.097	0.750	0.250
Local Government	1.000	0.188	0.125	0.313	0.063	0.125	0.188	0.069	0.236	0.597	0.097	0.750	0.250
University Researcher 2	1.000	0.399	0.058	0.233	0.037	0.117	0.156	0.167	0.542	0.083	0.208	0.667	0.333
Geomean	1.000	0.189	0.082	0.194	0.105	0.094	0.192	0.219	0.203	0.178	0.138	0.550	0.340
Category Sum		0.856						0.738				0.890	
Rescale	1.000	0.221	0.096	0.227	0.123	0.110	0.224	0.297	0.275	0.241	0.187	0.618	0.382

Table A.1: Results of the BWM questionnaires

B

Case study results

	Distance	Crossings	Route weather	Wait weather	Elevators	Escalators	Capacity	Service	Toilet	Desks	Detour	Signs	Info
Train-MetroCity	170	0	full	full	y	y	free	++	1	+	+	full	ot
MetroCity-Train	170	0	full	full	y	y	free	++	1	+	+	full	ot
Train-Bus	130	0	full	full	y	y	free	++	1	+	+	full	ot
Bus-Train	130	0	full	full	y	y	crowd	++	1	+	+	full	ot
Train-Tram	190	PT	half	part	y	y	free	++	1	+	+	full	late
Tram-Train	190	PT	half	full	y	y	free	++	1	+	+	ns	ot
MetroCity-Bus	290	0	full	full	y	y	free	++	1	+	+	full	ot
Bus-MetroCity	290	0	full	full	y	y	crowd	++	1	+	+	full	ot
MetroCity-Tram	120	PT	half	part	y	y	free	++	1	+	+	full	ot
Tram-MetroCity	120	PT	half	full	y	y	free	++	1	+	+	full	ot
Bus-Tram	260	PT	half	part	y	y	crowd	++	1	+	+	full	late
Tram-Bus	260	PT	half	full	y	y	free	++	1	+	+	ns	ot
Train-MetroNZL	130	0	full	full	y	y	free	++	1	+	+	full	ot
MetroNZL-Train	130	0	full	full	y	y	free	++	1	+	+	full	ot
MetroNZL-Bus	80	0	full	full	y	y	free	++	1	+	+	full	ot
Bus-MetroNZL	80	0	full	full	y	y	crowd	++	1	+	+	full	ot

Table B.1: Measurements of Centraal

	Distance	Crossings	Route weather	Wait weather	Elevators	Escalators	Capacity	Service	Toilet	Desks	Detour	Signs	Info
Train-Metro	130	0	full	part	y	y	bunch	++	1	0	+	full	ot
Metro-Train	130	0	full	full	y	y	crowd	++	1	+	+	full	ot
Train-Bus	280	car	half	part	y	n	bunch	++	1	0	+	full	ot
Bus-Train	280	car	half	full	y	n	free	++	1	+	+	ns	ot
Train-Tram	280	car	half	part	y	n	bunch	++	1	0	+	full	ot
Tram-Train	280	car	half	full	y	n	free	++	1	+	+	ns	ot
Metro-Bus	230	car	half	part	y	n	crowd	++	1	0	+	full	ot
Bus-Metro	230	car	half	part	y	n	free	++	1	0	+	ns	ot
Metro-Tram	230	car	half	part	y	n	crowd	++	1	0	+	full	ot
Tram-Metro	230	car	half	part	y	n	free	++	1	0	+	ns	ot
Bus-Tram	60	car	not	part	y	y	free	++	1	0	0	full	ot
Tram-Bus	60	car	not	part	y	y	free	++	1	0	0	full	ot

Table B.2: Measurements of Zuid

	Distance	Crossings	Route weather	Wait weather	Elevators	Escalators	Capacity	Service	Toilet	Desks	Detour	Signs	Info
Metro-BusEast	80	PT	gapped	full	y	y	free	+	0	0	0	full	late
BusEast-Metro	80	PT	gapped	full	y	y	free	+	0	0	0	ns	ot
Metro-BusWest	70	PT	gapped	full	y	y	free	+	0	0	+	full	late
BusWest-Metro	70	PT	gapped	full	y	y	free	+	0	0	+	ns	ot
BusEast-BusWest	110	PT	gapped	full	y	y	free	+	0	0	+	ns	ot
BusWest-BusEast	110	PT	gapped	full	y	y	free	+	0	0	+	ns	ot

Table B.3: Measurements of Noord

C

OD-matrices

Asd	**Bus**	**Metro_City**	**Tram**	**Train**	**Metro_NZL**
Bus	x	2.7%	1.8%	4.5%	2.1%
Metro_City	3.8%	x	3.4%	10.4%	x
Tram	2.4%	3.2%	x	12.7%	2.6%
Train	5.6%	10.4%	13.3%	x	8.1%
Metro_NZL	2.5%	x	2.5%	8.1%	x

Table C.1: Intermodal OD-matrix for Centraal

Asdz	**Bus**	**Metro**	**Tram**	**Train**
Bus	x	9.1%	1.2%	4.0%
Metro	9.3%	x	7.2%	21.4%
Tram	1.4%	7.5%	x	4.0%
Train	4.5%	26.0%	4.4%	x

Table C.2: Intermodal OD-matrix for Zuid

Asdz	**Bus**	**Metro**	**Tram**	**Train**
Bus	x	9.1%	1.2%	4.0%
Metro	9.3%	x	7.2%	21.4%
Tram	1.4%	7.5%	x	4.0%
Train	4.5%	26.0%	4.4%	x

Table C.3: Intermodal OD-matrix for Noord

D

Model results

	Dist	Cross	Routew	Waitw	Elevators	Escalators	Capacity	PQ	Shop	Toilet	Desk	Detour	Services	Signs	Dyna info	Info	Route Weight
Train-MetroC	**0.433**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.104**
MetroC-Train	**0.433**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.104**
Train-Bus	**0.567**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.056**
Bus-Train	**0.567**	0.221	0.096	0.227	0.123	0.110	0.112	**0.888**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.045**
Train-Tram	**0.367**	0.111	0.024	0.113	0.123	0.110	0.224	**0.704**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.095	**0.714**	**0.133**
Tram-Train	**0.367**	0.111	0.024	0.227	0.123	0.110	0.224	**0.818**	0.297	0.275	0.241	0.187	**1.000**	0.000	0.382	**0.382**	**0.127**
MetroC-Bus	**0.033**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.038**
Bus-MetroC	**0.033**	0.221	0.096	0.227	0.123	0.110	0.112	**0.888**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.027**
MetroC-Tram	**0.600**	0.111	0.024	0.113	0.123	0.110	0.224	**0.704**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.059**
Tram-MetroC	**0.600**	0.111	0.024	0.227	0.123	0.110	0.224	**0.818**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.058**
Bus-Tram	**0.133**	0.111	0.024	0.113	0.123	0.110	0.112	**0.592**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.095	**0.714**	**0.018**
Tram-Bus	**0.133**	0.111	0.024	0.227	0.123	0.110	0.224	**0.818**	0.297	0.275	0.241	0.187	**1.000**	0.000	0.382	**0.382**	**0.024**
Train-NZL	**0.567**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.081**
NZL-Train	**0.567**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.081**
NZL-Bus	**0.733**	0.221	0.096	0.227	0.123	0.110	0.224	**1.000**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.025**
Bus-NZL	**0.733**	0.221	0.096	0.227	0.123	0.110	0.112	**0.888**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.021**

Table D.1: Model results of Centraal

	Dist	Cross	Routew	Waitw	Elevators	Escalators	Capacity	PQ	Shop	Toilet	Desk	Detour	Services	Signs	Dyna info	Info	Route Weight
Train-Metro	**0.567**	0.221	0.096	0.113	0.123	0.110	0.000	**0.663**	0.297	0.275	0.120	0.187	**0.880**	0.618	0.382	**1.000**	**0.260**
Metro-Train	**0.567**	0.221	0.096	0.227	0.123	0.110	0.112	**0.888**	0.297	0.275	0.241	0.187	**1.000**	0.618	0.382	**1.000**	**0.214**
Train-Bus	**0.067**	0.000	0.024	0.113	0.123	0.000	0.000	**0.260**	0.297	0.275	0.120	0.187	**0.880**	0.618	0.382	**1.000**	**0.045**
Bus-Train	**0.067**	0.000	0.024	0.227	0.123	0.000	0.224	**0.597**	0.297	0.275	0.241	0.187	**1.000**	0.000	0.382	**0.382**	**0.040**
Train-Tram	**0.067**	0.000	0.024	0.113	0.123	0.000	0.000	**0.260**	0.297	0.275	0.120	0.187	**0.880**	0.618	0.382	**1.000**	**0.044**
Tram-Train	**0.067**	0.000	0.024	0.227	0.123	0.000	0.224	**0.597**	0.297	0.275	0.241	0.187	**1.000**	0.000	0.382	**0.382**	**0.040**
Metro-Bus	**0.233**	0.000	0.024	0.113	0.123	0.000	0.112	**0.372**	0.297	0.275	0.120	0.094	**0.786**	0.618	0.382	**1.000**	**0.093**
Bus-Metro	**0.233**	0.000	0.024	0.113	0.123	0.000	0.224	**0.484**	0.297	0.275	0.120	0.094	**0.786**	0.000	0.382	**0.382**	**0.091**
Metro-Tram	**0.233**	0.000	0.024	0.113	0.123	0.000	0.112	**0.372**	0.297	0.275	0.120	0.094	**0.786**	0.618	0.382	**1.000**	**0.072**
Tram-Metro	**0.233**	0.000	0.024	0.113	0.123	0.000	0.224	**0.484**	0.297	0.275	0.120	0.094	**0.786**	0.000	0.382	**0.382**	**0.075**
Bus-Tram	**0.800**	0.000	0.000	0.113	0.123	0.110	0.224	**0.570**	0.297	0.275	0.120	0.000	**0.692**	0.618	0.382	**1.000**	**0.012**
Tram-Bus	**0.800**	0.000	0.000	0.113	0.123	0.110	0.224	**0.570**	0.297	0.275	0.120	0.000	**0.692**	0.618	0.382	**1.000**	**0.014**

Table D.2: Model results of Zuid

	Dist	Cross	Routew	Waitw	Elev-ators	Esca-lators	Capa-city	PQ	Shop	Toilet	Desk	Detour	Ser-vices	Signs	Dyna info	Info	Route Weight
Metro-BusE	**0.733**	0.111	0.048	0.227	0.123	0.110	0.224	**0.842**	0.223	0.000	0.120	0.094	**0.437**	0.618	0.095	**0.714**	**0.324**
BusE-Metro	**0.733**	0.111	0.048	0.227	0.123	0.110	0.224	**0.842**	0.223	0.000	0.120	0.094	**0.437**	0.000	0.382	**0.382**	**0.267**
Metro-BusW	**0.767**	0.111	0.048	0.227	0.123	0.110	0.224	**0.842**	0.223	0.000	0.120	0.187	**0.530**	0.618	0.095	**0.714**	**0.196**
BusW-Metro	**0.767**	0.111	0.048	0.227	0.123	0.110	0.224	**0.842**	0.223	0.000	0.120	0.187	**0.530**	0.000	0.382	**0.382**	**0.166**
BusE-BusW	**0.633**	0.111	0.048	0.227	0.123	0.110	0.224	**0.842**	0.223	0.000	0.120	0.187	**0.530**	0.000	0.382	**0.382**	**0.025**
BusW-BusE	**0.633**	0.111	0.048	0.227	0.123	0.110	0.224	**0.842**	0.223	0.000	0.120	0.187	**0.530**	0.000	0.382	**0.382**	**0.023**

Table D.3: Model results of Noord

E

Code

In this appendix examples of all used code are given. For all three documents the version concerning Amsterdam Centraal is given. Versions for the other two stations are similar.

```python
import numpy as np
import pandas as pd

#load data
data = pd.read_csv('2019Q4_OverstapstromenLijnLijn_v2.csv')
stops = pd.read_excel('stops.xlsx', index_col=0)

#clean data
s = stops.index[stops.GEBIEDSNAA == 'Centraal Station'].values

select_data = data[((data.overstaphalte_van.isin(s)) | (data.overstaphalte_van == 'NL:S:asd'))  & ((data.overstaphalte_naar.isin(s)) | (data.overstaphalte_naar == 'NL:S:asd'))]
select_data = select_data[select_data.tijdsperiode == 'Werkdag (buiten schoolvakanties) restdag']

#change ranges to values
select_data.aantal_overstappers[select_data.aantal_overstappers=='1 - 50' ] = 3
select_data.aantal_overstappers[select_data.aantal_overstappers=='51 - 100'] = 65
select_data.aantal_overstappers[select_data.aantal_overstappers=='101 - 150'] = 120
select_data.aantal_overstappers[select_data.aantal_overstappers=='151 - 200'] = 175
select_data.aantal_overstappers[select_data.aantal_overstappers=='201 - 250'] = 225
select_data.aantal_overstappers[select_data.aantal_overstappers=='251 - 300'] = 275

select_data['aantal_overstappers'] = pd.to_numeric(select_data['aantal_overstappers'])

select_data.modaliteit_van[select_data.lijnnr_van=='m52'] = 'Metro_NZL'
select_data.modaliteit_naar[select_data.lijnnr_naar=='m52'] = 'Metro_NZL'

#create OD Matrix
OD_Asd = pd.DataFrame(np.zeros((5, 5),  dtype=int), columns=['Bus', 'Metro', 'Tram', 'Trein', 'Metro_NZL'], index=['Bus', 'Metro', 'Tram', 'Trein', 'Metro_NZL'])
for a in range(len(select_data)):
    b = select_data.iloc[a, 5]
    c = select_data.iloc[a, 8]
    d = select_data.iloc[a, 10]
    OD_Asd.loc[b, c] += d
print(OD_Asd)

#create relative OD Matrix
z = select_data['aantal_overstappers'].sum()
print(z)

OD_Asd_rel = OD_Asd / z
print(OD_Asd_rel)
```

Listing E.1: Data selection and aggregation code. OD generation.

```
import pandas as pd

survey = pd.read_excel('surveychecklist_Asd.xlsx', index_col=0)

surveynorm = survey

surveynorm.Distance = 1 -  (surveynorm.Distance / 300)

surveynorm.Crossing[surveynorm.Crossing==0] = 1
surveynorm.Crossing[surveynorm.Crossing=="PT"] = 0.5
surveynorm.Crossing[surveynorm.Crossing=="car"] = 0

surveynorm.Routew[surveynorm.Routew=="full"] = 1
surveynorm.Routew[surveynorm.Routew=="gapped"] = 0.5
surveynorm.Routew[surveynorm.Routew=="half"] = 0.25
surveynorm.Routew[surveynorm.Routew=="not"] = 0

surveynorm.Waitw[surveynorm.Waitw=="full"] = 1
surveynorm.Waitw[surveynorm.Waitw=="part"] = 0.5
surveynorm.Waitw[surveynorm.Waitw=="not"] = 0

surveynorm.Elevators[surveynorm.Elevators=="y"] = 1
surveynorm.Elevators[surveynorm.Elevators=="n"] = 0

surveynorm.Escalators[surveynorm.Escalators=="y"] = 1
surveynorm.Escalators[surveynorm.Escalators=="n"] = 0

surveynorm.Cap[surveynorm.Cap=="free"] = 1
surveynorm.Cap[surveynorm.Cap=="crowd"] = 0.5
surveynorm.Cap[surveynorm.Cap=="bunch"] = 0

surveynorm.Signs[surveynorm.Signs=="full"] = 1
surveynorm.Signs[surveynorm.Signs=="ns"] = 0

surveynorm.Info[surveynorm.Info=="ot"] = 1
surveynorm.Info[surveynorm.Info=="late"] = 0.25
surveynorm.Info[surveynorm.Info=="np"] = 0

surveynorm.Service[surveynorm.Service=="++"] = 1
surveynorm.Service[surveynorm.Service=="+"] = 0.75

surveynorm.Detour[surveynorm.Detour=="+"] = 1
surveynorm.Detour[surveynorm.Detour==0] = 0.5
surveynorm.Detour[surveynorm.Detour=="-"] = 0

surveynorm.Desks[surveynorm.Desks=="+"] = 1
surveynorm.Desks[surveynorm.Desks==0] = 0.5
surveynorm.Desks[surveynorm.Desks=="-"] = 0

surveynorm.to_excel("surveynorm_Asd.xlsx")
```

Listing E.2: Normalization code

```
import pandas as pd

surveynorm = pd.read_excel(’surveynorm_Asd.xlsx’, index_col=0)
weights = pd.read_excel(’BWM_results.xlsx’, index_col=0)
OD = pd.read_excel(’OD_Asd.xlsx’, index_col=0)

survey_factorweighted = surveynorm

for a in range(13):
    survey_factorweighted.iloc[:,a] = survey_factorweighted.iloc[:,a] * weights.iloc [1+a,-1]

survey_factorweighted.to_excel(”factorweighted_Asd.xlsx”)

survey_routeweighted = survey_factorweighted

for b in range(len(OD)):
    survey_routeweighted.iloc[b,:] = survey_routeweighted.iloc[b,:] * OD.iloc[b,0]


i = sum(survey_routeweighted[’Distance’])
j = (sum(survey_routeweighted[’Crossing’]) + sum(survey_routeweighted[’Routew’]) + sum(survey_routeweighted[’Waitw’]) + sum(survey_routeweighted[’Elevators’]) + sum(survey_routeweighted[’Escalators’]) + sum(survey_routeweighted[’Cap’]))
k = (sum(survey_routeweighted[’Service’]) + sum(survey_routeweighted[’Presence of a toilet’]) + sum(survey_routeweighted[’Desks’]) + sum(survey_routeweighted[’Detour’]))
l = (sum(survey_routeweighted[’Signs’]) + sum(survey_routeweighted[’Info’]))

print(’Distance score’, i)
print(’Path quality score’, j)
print(’Service score’, k)
print(’Info score’, l)

scores = pd.DataFrame({’’: [’Distance score’, ’Path quality score’, ’Service score’, ’Info score’], ’Score’:[i,j,k,l]})
```

Listing E.3: Final model

F

Scientific Summary; Research Paper

The Integrated Station, a transfer quality assessment model for multi-modal stations

Jan M. Siblesz

Abstract

Stations form the main bottle neck in a public transport journey. Efficient PT-systems depend on the optimal cooperation of modalities which makes transferring essential. For years the node place model has been the main paradigm of looking at stations in the Netherlands. This study aims to add a component to the model by developing a score for the intermodal transfer quality. This is achieved by developing a measurement model based on a multi criteria analysis. Case study measurements are weighed by the weight of their attribute and by the share of the transfer flow they represent.

1. Introduction

A good transportation network is key to a well functioning city (Vuchic, 2005). Public transport (PT) plays a key role in this system. It offers an alternative for private cars that is better for the environment (RIVM, 2013), allows for denser urban development (Bertolini, 1999), and is available to everyone regardless of age, physical ability, or other reasons preventing one from driving a car (Delbosc and Currie, 2011; Guzman and Oviedo, 2018; Manaugh and El-Geneidy, 2012). This makes PT a a key part of sustainable urban development both environmentally and socially.

Because of these properties many efforts have been made over the years to promote the usage of PT over that of private cars. This has proven rather difficult because of the strong connection many people feel to their cars (Harms et al., 2007). Many people are worried by single bad experiences with PT, people often only remember bad experiences and often shy away from PT since (Van Hagen, 2011).

Within a PT journey transfers are the worst experienced part (Peek and Van Hagen, 2002). Many efforts have gone into improving the quality, frequency, and capacity of the rides themselves (Saliara, 2014) but transfers remain a weak point. PT integration aims to take away the barriers between transfers by addressing the differences that exist between different modalities and operators (Saliara, 2014). PT integration can be divided into three main fields: organizational integration, operational integration, and physical integration. Physical integration, the aspects concerning the design of PT-facilities will be the focal point of this project.

To be able to address the issue of the bad experience that transfers offer a good insight in the problem is needed. This project aims to provide a better insight by developing a standardised measurement method to perform exploratory analyses of the transfer quality of stations. The main research question that will be answered in this project is:

How can we measure a public transport station's ability to facilitate an efficient and comfortable multi-modal transfer?

2. Scientific background

The quality of station has been the topic of scientific research for a long time. In the last twenty years the node-place model (NP-model) as first developed by Bertolini (1998) has been the leading paradigm for describing station performance (Groenendijk et al., 2018) in the Netherlands. The core idea of the NP-model is that a well functioning station combines the transport demand of an (urban) area, the place value, with the transport supply of the networks the station connnects to, the node value. A station is supposed to function well when these are balanced. Any unbalance in this situation is thought of to correct itself over time following the land use transport feedback cycle from (Wegener and Fürst, 1999). The NP-model has proven a vary versatile framework to serve as foundation for various more specified models focusing on real estate or government policy (Peek, 2006). An overview of models in the NP-model family can be found in Peek (2006); Caset et al. (2019).

These type of models however have assumed the station itself to be a black box, a dot on a map, a *station as a geographical entity* (Peek and Van Hagen, 2002), ignoring the processes going on inside the station. Recently efforts have been made to incorporate the processes taking place within the station into the model. (Groenendijk et al., 2018) have added the experience value of a station to the model. This experience value can be seen as the place value of the station itself. This leaves the node value of the station, the transfer quality, to be added to the model. A representation of the current model can be seen in table 1.

Methodologically NP-models use multi criteria analysis (MCA) as a framework for the valuation of stations. In a MCA the performance of a scenario or design option is represented by the weighted average of all relevant factors (criteria). This will be done in this study as well. The next section will focus on the gathering of these factors by studying several fields of literature that study the performance of PT-systems and stations.

	Node Values	**Place Values**	**Model Properties**
Network Properties	Classical Node Value	Classical Place Value	Traditional NP-model components
	Transport supply	Transport demand	Station is a black box
	Network contextual node value	Urban contextual place value	Location quality
Local Properties	**Transfer quality**	Station Experience (Groenendijk et al., 2018)	Analyzing stations as micro systems
	Independent Node Quality	Independent Place Quality	Focus on processes within the hub
	Interchange Walking	Interchange Waiting	Design Quality

Table 1: Elements of the extended node place model (inspired by Peek and Louw (2008); Peek (2006))

3. Literature review

To gain insight in the performance of stations and gather the factor that will build up the model a broad literature review was conducted. During this review several specific fields were identified that were all united by shared theory or methodology. These scientific fields with their main theories and methodologies will be highlighted before converging back to the list of factors obtained from this literature review.

The research field of **PT-integration** as studied by (Saliara, 2014; Ibrahim, 2003) investigates the effects of the organization of the PT-system on the systems performance and develops strategies to improve the organization by taking away barriers between operators and modalities. This study fields are rooted in macro economical and public administration research with a focus on the relationship between government and market parties. From this research field we are mainly interested on physical integration, studying the locations where multiple facets of the PT-system interact.

Customer satisfaction research study the effects of station design on user experience and behaviour. Rooted in psychology this theory describes the functional elements of a station and their individual effects on customer satisfaction. One of the main theories in this field is visualised in figure 1. In this scheme some aspects are known as dissatisfiers, factors that when executed well go mostly unnoticed but when executed poorly have a very negative effect on one's experience, mostly beyond what can be compensated for by other factors. These are factors you need to have. Satisfiers are nice to have, extra elements that when executed well will improve the experience but are not necessary to achieve a basic satisfactory experience. This theory can also be translated into design principles as is done in the right part of figure 1 by Dutch railway infrastructure manager ProRail. The dissatisfiers are most important for a successful system thus they deserve the most valuable spots nearest to the stops. Platform areas are dedicated for the circulation of people and only when there is space left can be assigned space for other facilities such as a small shop.

Utility based traveller research investigates customer behaviour by looking at the effort in time, money, and hassle of a travel opportunity presented to the user. In this field that is rooted in econometry humans are seen as utility maximizers trying to optimize their experience by carefully weighing all alternatives and choosing the best (McFadden, 1974; Train, 2009). For the PT-system the effect transfers have on overall utility of a trip is investigated by Wardman et al. (2001); Schakenbos et al. (2016). These researchers separately define the effects of waiting and walking during the transfer. Where Groenendijk et al. (2018) focused on waiting this research will focus on the walking parts of the transfer. Schakenbos (2014) looked at the effects of station layout on transfer experience and found that close connections such as a cross platform connection between metro and train are highly valued.

Simulation modeling uses mathematical models of pedestrian flows through a station to study the effects of station design on transfers. This field can be put in two groups. Micro simulation describes the position of every single person in the system and calculates the interactions between individual people and the environment (Daamen, 2004). Queueing models model the station as a network of activities and locations where queueing can occur with free flow in between, these models only count the marginal effects of individual users (Li, 2000; Xu et al., 2014). This research field mainly focuses on the effect of capacity and flow on the transfer experience (Daamen, 2004) and on the position this has in a design process.

Case studies can be used to investigate the performance of existing stations. Existing case studies provide a good insight in the methodological possibilities of collecting data. Pitsiava-Latinopoulou and Iordanopoulos (2012) studied several PT-stations in Athens Greece and compared actual usage numbers to station typologies that were assumed because of the position of the stations within the system, this showed that it is hard to develop a generic model giving normative statements on a wide range of cases. Bryniarska and Zakowska (2017) combined usage numbers with data on the layout off several on street tram and bus stations in Krakow Poland. Although the design challenges for on street stops are somewhat different than that of purpose built facilities the methodology of MCA used here was very useful, especially the usage of averages weighted by usage numbers. The third studied case study was carried out by Hernandez et al. (2016) on the Moncloa train and metro station in Madrid Spain. This study used a thirty question questionnaire to ask users of the station about their experiences. Many of these questions and especially the used categorisation of individual questions were useful for our research.

From the five research fields explained above factors were gathered. Many overlapped and were condensed. The outcome of the literature study can be found in table 2. In this table all factors are listed together with the original source of the factor.

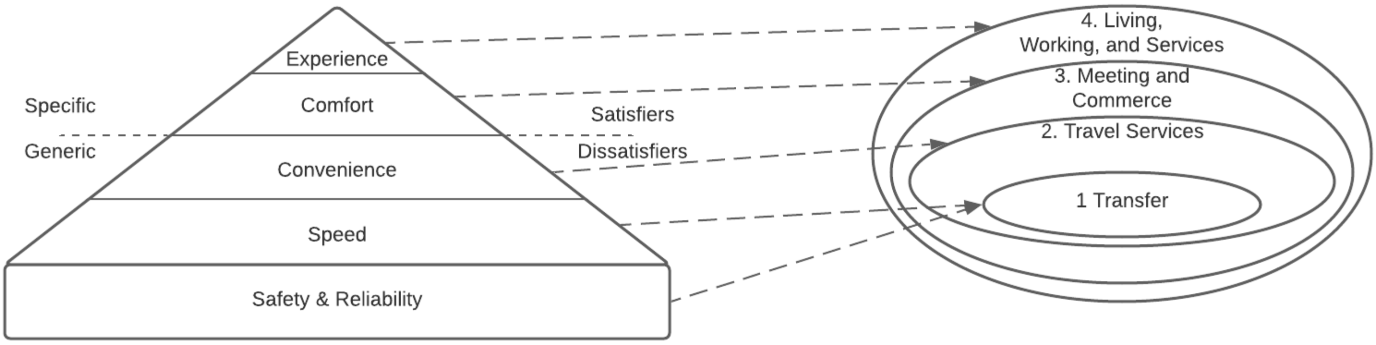


Figure 1: Pyramid of customer needs and its design implications (Peek and Van Hagen, 2002)(left) & (ProRail, 2005) (right)

	PT integration	Customer satisfaction	Utility	Simulation	Transfer numbers	Case studies
Transfer distance	x[1]	x[2]	x[3]	x[4]	x[5]	x[6,7]
Transfer flow	x[1]	x[2]		x[4,8,9]		x
Traffic crossings	x[1]				x[5]	x[6]
Route weather protection	x[10]	x[2]	x[12]			
Wait weather protection		x[2,11]	x[12]			
Elevators and escalators		x[2]				x[7]
Bottleneck capacity				x[4,8,9]	x[5]	
Signage	x[1]		x[12]			x[6,7]
Real time information	x[10]		x[12]			x[6,7]
Service availability	x[1]	x[2,11]	x[3,12]		x[5]	[6,7]
Location of services		x[13]		x[4]		
Design priority		x[13]		x[4]		x[6]

Table 2: List of all relevant factors and their source field. 1: Saliara (2014); 2: Peek and Van Hagen (2002); 3: Schakenbos et al. (2016); 4: Daamen (2004); 5: Pitsiava-Latinopoulou and Iordanopoulos (2012); 6: Bryniarska and Zakowska (2017); 7: Hernandez et al. (2016); 8: Li (2000); 9: Xu et al. (2014); 10: Ibrahim (2003); 11: Groenendijk et al. (2018); 12: Wardman et al. (2001);13: ProRail (2005)

4. Model Design

To set up a MCA factors need to adhere to three requirements set out by Sijtsma et al. (1998). They need to be limited in number and have minimal overlap, both of these requirements have already been used when converging the findings of the literature review into the final list of table 2. A third requirement however does influence the research design. Factors need to be practically obtainable. Because of this some factors were split to create clear individually measurable criteria. Elevators and escalators will be separate factors and services are split into shops, toilets, and staffed desks. To give a detailed picture of station performance the outcomes of the model will be aggregated in to four categories. Using a categorization based of the questionnaire conducted by Hernandez et al. (2016) the factor categories are shown in table 4.

To be able to observe all factors in an objective and standardized manner a clear framework is needed. The operationalization of the thirteen factors can be found in table 4. For usage in a MCA all factors have to be comparable. To achieve this the scoring system had to be normalized to score all factors on a scale from 0 to 1. This normalization can be found in table 5

Transfer Quality			
Distance	**Path Quality**	**Services**	**Information**
	Traffic crossings	Shops	Fixed signage
	Route weather protection	Toilets	Dynamic information
	Wait weather protection	Desks	
	Escalators	Detour	
	Elevators		
	Bottleneck capacity		

Table 3: Categorization of factors

For every study object data can be gathered using this methodology. After normalization this yields the measurement matrix F_{ij}.

$$F_{ij} = \begin{pmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,13} \\ f_{2,1} & f_{2,2} & \cdots & f_{2,13} \\ \cdots & \cdots & \cdots & \cdots \\ f_{16,1} & f_{16,2} & \cdots & f_{16,13} \end{pmatrix} \tag{1}$$

Factor name	**Definition**	**Measurement levels**
Transfer distance	Average walking distance in metres between the platforms of two modalities. Measured over ground.	Interval variable (metres)
Traffic crossings	This factor describes the presence of level crossings of transferring passengers with other forms of traffic.	Crossings with bicycles (**bike**), Public Transport (**pt**) and **cars** are noted. When multiple crossings are present only one with the lowest score is noted. Routes without crossings are noted as **0**.
Route weather protection	This factor describes whether parts of the connection between two modalities are covered or not	A connection can be completely inside (**full**), covering can be interrupted by a short outside connection (**gapped**), connections from a modality located inside towards a modality located outside are noted as **half**, lastly connections taking place completely outside are noted as **not**.
Wait weather protection	This factor describes the level of shelter of the waiting area of the destination modality of a transfer.	Three levels are observed: **full** is used for completely covered platforms, platforms with shelters are noted as **part**, areas without any cover are noted as **not**.
Presence of elevators	This factor describes whether or not elevators are present for all required height changes.	Complete elevator coverage is noted as **y**, incomplete coverage as **n**. Since this measure describes the inclusivity of a connection there is no in between option.
Presence of escalators	This factor describes whether or not escalators are present for all required height changes.	Complete escalator coverage is noted as **y**, incomplete coverage as **n**.
Bottleneck capacity	This factor describes the negative influence of bottlenecks on passenger flow. Bottlenecks can include but are not limited to doorways, stairwells, and ticket gates. Boarding and alighting processes are seen as part of the operational process and are mainly dependant on material type, this research focuses on infrastructure and hence does not include this processes. This is a directional measure so it can differ between two directions of the OD-pairs.	In a **free** flow situation the bottlenecks en route are no recognizable hindrance for the passengers. When a connection is **crowd**ed people have to negotiate the passage of certain choke points without having to come to a full stop. The final level is **bunch**ing here people have to come to a full stop or queue before being able to pass a choke point.
Fixed signage	This factor describes the level of fixed signage of a connection. Fixed signage includes all static information in a station, this includes signs, maps and departure time listings. Good signage has to be clear, correct, covering, and consistent.	Signage is noted as **full** when it guides travellers along the optimal route between two modes. Signage is marked as not sufficient (**ns**) when at least one of the four of the mentioned criteria is not met.
Real time information	Real time information serves two main purposes for travellers. It guides travellers to the correct platform once they have entered the domain of a certain modality and it comforts passengers by giving them exact information on when rides exactly depart.	Real time information can be on time (**ot**) when good information avoids additional detours or **late** when screens are located after decision points within the domain of a destination mode. A third level covers situations where real time information is **not** present.
Shops	This factor describes the presence of convenience stores in a station. Convenience stores sell drinks (hot and cold), food (packaged and fresh) and maybe other products such as reading materials and tobacco products. This factor is measured for the entire facility at once. Whether or not shops are located in a good place for certain mode pairs is addressed in the detour factor.	For practical purposes the measurements in this category will be aggregated into three categories: no shops (**0**), one to three shops (**+**), and four or more shops (**++**).
Toilets	This factor describes whether a public toilet is present somewhere in the facility or not.	The presence of at least one toilet is noted as **1** and **0** is used when none are available.
Staffed desks	This factor describes the presence and availability of staffed desks for information and tickets. We have noticed that in this time of pandemic many of the desks have limited opening hours compared to the normal situation. This is a directional factor that describes the state of the destination mode of an OD-pair.	When staffed desks are not present the situation is noted as **-**, limited opening hours are noted with **0**, and full opening hours covering all periods of the day where transport is offered are noted as **+**.
Detour	The detour factor describes the location of shops relative to the ideal path of an OD-pair.	The detour is measured in metres deviated from the ideal path.

Table 4: The thirteen final model factors, with definitons and measurement levels

Transfer distance	0 meters = 1	>300 meters = 0	linear in between	
Traffic crossings	zero = 1	bike = 0.75	PT = 0.5	Car = 0
Route weather protection	full = 1	gapped = 0.5	half = 0.25	not = 0
Wait weather protection	full = 1	part = 0.5	not = 0	
Presence of elevators	yes = 1	no = 0		
Presence of escalators	yes = 1	no = 0		
Bottleneck capacity	free = 1	crowd = 0.5	bunch = 0	
Fixed signage	full = 1	ns = 0		
Real time information	ot = 1	late = 0.25	not = 0	
Shops	>=4 = 1	1-3 = 0.5	0 = 0	
Toilets	>=1 = 1	0 = 0		
Staffed desks	+ = 1	0 = 0.5	- = 0	
Detour	<20m = 1	20-100m = 0.5	>100m = 0	

Table 5: Full scoring table

The second building block of a MCA is formed by the factor weights. When scoring options and scenarios not all factors have to be weighed the same. The pyramid of customer needs (Peek and Van Hagen, 2002) shows that some factors are more important than others. To accurately determine the weights of factors interviews were held with field experts from operations, academics, government, and consultancy. During these interviews a questionnaire was filled in based on the best worst method (BWM). The BWM was developed by Rezaei (2015). It provides an efficient way of using expert opinions to obtain weights to use in a MCA by asking the respondents to do pairwise comparisons of every factor and a reference factor, the best (most important) and worst (least important) factor in a category. This was done for all factors in the four categories. An example of the usage of BWM in a case study can be found in Groenendijk et al. (2018). Using the BWM a total of one point was divided over all factors within every category. By doing this the weighted average of the scores within a category stay within the original measurement range of 0 to 1. During the interviews respondents were asked to explain their answers. Many referred back to the difference between satisfiers and dissatisfiers when giving their answers. The results of all questionnaires are aggregated into the weights vector w_j that can be found in table 6. The factor weights are a structural component of the model regardless of the chosen case. The weights are calibrated for the assessment of mid-sized and larger stations.

In this project values are not only weighed by the factor values found using the BWM but are also weighed for the routes. For every pair of modalities in a station the route is surveyed and results are noted in the measurement matrix. This weighting is done to address the importance of various routes within a station knowing from Bertolini (1998) that highly used stations can experience spatial stress and that good design can counteract this. Bryniarska and Zakowska (2017) used revealed preference data as route weights in their MCA on urban PT-stops but already advised on using smart card data for this purpose. Using smart card data we can obtain a transfer OD-matrix for a station and use the shares of every connection as the route weights vector R.

$$R = (r_1, r_2, ..., r_{n^2-n}) \tag{2}$$

Distance	1
Path Quality	
Traffic crossings	0.221
Route weather protection	0.096
Wait weather protection	0.227
Elevators	0.123
Escalators	0.110
Bottle neck capacity	0.224
Services	
Shops	0.297
Toilets	0.275
Staffed desks	0.241
Detour	0.187
Information provision	
Fixed Signs	0.618
Dynamic information	0.382

Table 6: Final results of the BWM questionnaires

The main MCA model combines the three sets of data into scores for the different categories. The values of the measurement matrix multiplied by their respective factor and route weights coming to the scores of a single element. From here several choices can be made regarding the aggregation depending on the type outcome wanted for the analysis. The first option is having the results be the least aggregated, this will give results similar to that shown in table 7. These can be used to identify weak points within stations. These are results for all factor categories k for every route i individually, they are calculated as follows:

$$C_{ik} = \sum_j f_{ij} w_j \qquad \forall j \in G_k \tag{3}$$

To compare stations against each other the scores can be aggregated on a station level. This is done by taking the category scores and weighing them by the route weights R. This step yields results like that shown in table 8. They are calculated as follows:

$$S_k = \sum_i C_{ik} r_i \tag{4}$$

5. Case Study

To test the working of the model on a real life three stations in Amsterdam were studied using the developed measurement tool. Through an ongoing research project focused on the effects of the recently constructed metro line called Noord-Zuidlijn (NZL) that TU Delft is participating in we have access to traveller data from the city to serve as route weights. More on the background of this project can be found in Brands et al. (2020).

Three stations have been chosen as objects of the case study: Amsterdam Centraal is the city's main railway station. An international hub connecting (intercity) trains to all regional and local modalities serving commuters as well as tourists. Amsterdam Zuid is the second busiest railway station in Amsterdam. The station serves the Zuidas financial district as well as universities and other educational facilities. The station connects (intercity) trains to local and regional modalities. Amsterdam Noord is a station that was newly built as the northern terminus of the NZL. Along with it a large bus station connecting regional busses was erected. From these three stations all relevant information regarding design factors and usage patterns will be gathered to serve as inputs for the model.

The data set on transfers contains information for the entire city. The data was gathered in the fourth quarter of 2019, over a year after the opening of the metro line and well before the Covid-19 pandemic hit western Europe. From this large data set the relevant data for every station was selected. An example of this data can be found in the last column of table 7.

To provide an example of the working of the model the results of the model run for Amsterdam Noord are shown in table 7. The results are given on the level of single connections. We can see the scores of the elements in a category adding up to the category score that lies on a scale from 0 (very bad) to 1 (excellent).

In table 8 the results on the highest aggregation level, the station level can be found. These results can be used to compare stations against each other or to perform a quick scan looking for weak points across an entire system.

	Asd	**Asdz**	**Nrd**
Distance	0.45	0.38	0.74
Path quality	0.89	0.59	0.84
Service	1	0.88	0.48
Info	0.86	0.85	0.55

Table 8: Aggregated model results

Amsterdam Centraal (Asd) stands out as a well functioning large station. Having a high score on most quality aspects but a lower score on transfer distance. Amsterdam Zuid (Asdz) scores lower across the board. Indicating the station has not kept up with increasing usage and its current status as the city's second main station. Plans are however on their way to address these problems (NS, 2021). Noord (Nrd) is a more compact station that scores lower than the other stations on some categories. Noord is however a very different station from the two train stations with users that expect different levels of service. This also indicates the limitations of a model such as this that is normative in nature.

6. Model Validation

To be able to actual use the model in practice it is important to see if the found results hold up against the actual perceived experience of system users. To do this model outcomes are compared against data from the stationsbelevingsmonitor, a questionnaire taken out by train operator NS. Here data is used for the railway stations Centraal and Zuid.

	Unimpeded acces	Shelter	Shops	Info where	Fixed info	Travel info	BTM location	Station quality
Asd	7.70	6.79	7.98	7.78	7.75	7.75	7.77	7.50
Asdz	6.98	4.93	6.76	7.26	7.32	7.41	7.47	6.73

Table 9: Grades for several aspects of station experiences from SBM

When comparing this data to the outcome of the model we can see the same general picture. Some things stand out however. The largest difference between the lies in the shelter category. In the tool both stations scored full marks here but apparently users value execution of this factor outside of the current measurement range. Amsterdam Centraal also provides wind protection from most sides where Zuid only has a small canopy. The same goes for shops. In the tool both stations score full marks but the large shopping centre at Centraal that was not accounted for in the model is valued highly by users.

7. Conclusion

In this project a measurement model was developed to provide better insight in the role station design has on transfer quality. In the existing framework of node-place models a scientific gap was found that could be filled by this model. By methodologically connecting to existing models a clear framework was set up for the model. This framework was based on a multi criteria analysis combined with an additional weighing to take actual usage numbers into account.

A MCA compares cases or scenarios by comparing their values on several criteria (factors). To gather these factors a literature review on station and PT-system performance was conducted. During this literature study several fields of methodology and theory were found:

- PT-integration
- Customer satisfaction
- Utility
- Simulation modeling
- Case studies

	Distance	Cross	Route	Wait	Elevators	Escalators	Cap	**PQ**	Shop	Toilet	Desk	Detour	**Service**	Signs	Dyna Info	**Info**	**Route Weight**
Metro-BusE	**0.73**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.09	**0.44**	0.62	0.10	**0.71**	**0.32**
BusE-Metro	**0.73**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.09	**0.44**	0.00	0.38	**0.38**	**0.27**
Metro-BusW	**0.77**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.62	0.10	**0.71**	**0.20**
BusW-Metro	**0.77**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.00	0.38	**0.38**	**0.17**
BusE-BusW	**0.63**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.00	0.38	**0.38**	**0.02**
BusW-BusE	**0.63**	0.11	0.05	0.23	0.12	0.11	0.22	**0.84**	0.22	0.00	0.12	0.19	**0.53**	0.00	0.38	**0.38**	**0.02**

Table 7: Overview of the model results for Amsterdam Noord

The model was found to be performing well when trying to find good and bad performing stations. Especially when comparing against ongoing plans to improve the quality it shows that most found weak points are already being addressed. Some new results were also found however. Mainly in the weak position of stops located outside of station buildings.

Appendix A. Sample Appendix Section

References

Bertolini, L., 1998. Station area redevelopment in five European countries : An international perspective on a complex planning challenge. International Planning Studies 3, 163–184. doi:10.1080/13563479808721707.

Bertolini, L., 1999. Spatial development patterns and public transport: The application of an analytical model in the Netherlands. Planning Practice and Research 14, 199–210. doi:10.1080/02697459915724.

Brands, T., Dixit, M., van Oort, N., 2020. Impact of a New Metro Line in Amsterdam on Ridership, Travel Times, Reliability and Societal Costs and Benefits. European Journal of Transport and Infrastructure Research 20, 335–353. doi:https://doi.org/10.18757/ejtir.2020.20.4.4084.

Bryniarska, Z., Zakowska, L., 2017. Multi-criteria evaluation of public transport interchanges. Transportation Research Procedia 24, 25–32. doi:10.1016/j.trpro.2017.05.063. http://dx.doi.org/10.1016/j.trpro.2017.05.063.

Caset, F., Marques Teixeira, F., Derudder, B., Boussauw, K., Witlox, F., 2019. Planning for nodes , places , and people in Flanders and Brussels : An empirical railway station assessment tool for strategic decision-making. Journal of Transport and Land Use 12, 811–837.

Daamen, W., 2004. Modelling Passenger Flows in Public Transport Facilities. Ph.D. thesis. Delft University of Technology. Delft. doi:90-407-2521-7.

Delbosc, A., Currie, G., 2011. Using Lorenz curves to assess public transport equity. Journal of Transport Geography 19, 1252–1259. doi:10.1016/j.jtrangeo.2011.02.008. http://dx.doi.org/10.1016/j.jtrangeo.2011.02.008.

Groenendijk, L., Rezaei, J., Correia, G., 2018. Incorporating the travellers' experience value in assessing the quality of transit nodes: A Rotterdam case study. Case Studies on Transport Policy 6, 564–576. doi:10.1016/j.cstp.2018.07.007. https://doi.org/10.1016/j.cstp.2018.07.007.

Guzman, L.A., Oviedo, D., 2018. Accessibility, affordability and equity: Assessing 'pro-poor' public transport subsidies in Bogotá. Transport Policy 68, 37–51. doi:10.1016/j.tranpol.2018.04.012.

Harms, L., Jorritsma, P., Kalfs, N., 2007. Beleving en beeldvorming van mobiliteit. Technical Report. Kennisinstituut voor Mobiliteitsbeleid. Den Haag.

Hernandez, S., Monzon, A., de Oña, R., 2016. Urban transport interchanges: A methodology for evaluating perceived quality. Transportation Research Part A: Policy and Practice 84, 31–43. doi:10.1016/j.tra.2015.08.008. http://dx.doi.org/10.1016/j.tra.2015.08.008.

Ibrahim, M.F., 2003. Improvements and integration of a public transport system: The case of Singapore. Cities 20, 205–216. doi:10.1016/S0264-2751(03)00014-3.

Li, J.P., 2000. Train Station Passenger Flow Study, in: Joines, J., Barton, R., Kang, K., Fishwick, P. (Eds.), Proceedings of the 2000 Winter Simulation Conference, pp. 1173–1176.

Manaugh, K., El-Geneidy, A., 2012. Who benefits from new transportation infrastructure? Using accessibility measures to evaluate social equity in public transport provision, in: Geurs, K., Krizek, K., Reggiani, A. (Eds.), Accessibility Analysis and Transport Planning. Edward Elgar Publishing. chapter 12, pp. 211–227. doi:https://doi.org/10.4337/9781781000113.

McFadden, D., 1974. Conditional logit analysis of qualitative choice behavior, in: Zarembka, P. (Ed.), Frontiers in Econometrics. Academic Press, New York. chapter 4, pp. 105–142.

NS, 2021. Renovation Amsterdam Zuid. www.ns.nl/en/travel-information/renewing-stations/amsterdam-zuid.

Peek, G.J., 2006. Locatiesynergie, Een participatieve start van de herontwikkeling van binnenstedelijke stationslocaties. Ph.D. thesis. Delft University of Technology. Delft.

Peek, G.J., Louw, E., 2008. A multidisciplinary approach of railway station development: A case study of 's-Hertogenbosch, in: Bruinsma, F., Pels, E., Priemus, H., Rietveld, P., Van Wee, B. (Eds.), Railway Development: Impacts on Urban Dynamics. Physica-Verlag, Heidelberg. chapter 7, pp. 125–146. doi:10.1007/978-3-7908-1972-4.

Peek, G.J., Van Hagen, M., 2002. Creating synergy in and around stations: Three strategies for adding value. Transportation Research Record , 1–6doi:10.3141/1793-01.

Pitsiava-Latinopoulou, M., Iordanopoulos, P., 2012. Intermodal Passengers Terminals: Design Standards for Better Level of Service. Procedia - Social and Behavioral Sciences 48, 3297–3306. doi:10.1016/j.sbspro.2012.06.1295. http://dx.doi.org/10.1016/j.sbspro.2012.06.1295.

ProRail, 2005. Basisstation 2005, deel A en B: Functionele normen en richtlijnen voor treinstations.

Rezaei, J., 2015. Best-worst multi-criteria decision-making method. Omega 53, 49–57. doi:10.1016/j.omega.2014.11.009. http://dx.doi.org/10.1016/j.omega.2014.11.009.

RIVM, 2013. Monitoringsrapportage NSL 2013, stand van zaken nationaal samenwerkingsprogramma luchtkwaliteit. Technical Report. (Netherlands) National Institute for Public Health and the Environment.

Saliara, K., 2014. Public Transport Integration: The Case Study of Thessaloniki, Greece. Transportation Research Procedia 4, 535–552. doi:10.1016/j.trpro.2014.11.041. http://dx.doi.org/10.1016/j.trpro.2014.11.041.

Schakenbos, R., 2014. Valuation of a transfer in a multimodal public transport trip (MSc thesis).

Schakenbos, R., Paix, L.L., Nijenstein, S., Geurs, K.T., 2016. Valuation of a transfer in a multimodal public transport trip. Transport Policy 46, 72–81. doi:10.1016/j.tranpol.2015.11.008. http://dx.doi.org/10.1016/j.tranpol.2015.11.008.

Sijtsma, F.J., Strijker, D., Hoefsloot, M.L.A.W., 1998. Duurzame ontwikkeling in het Waddengebied: een afwegingsmethodiek voor economie, natuur, milieu en landschap. Wetenschapswinkel voor Economie, Rijksuniversiteit Groningen, Groningen.

Train, K.E., 2009. Discrete Choice Models with Simulation, 2nd edition. Cambridge University Press, New York.

Van Hagen, M., 2011. Waiting experience at train stations. Ph.D. thesis. University of Twente. Delft.

Vuchic, V.R., 2005. Urban Transit, Operations, Planning and Economics. John Wiley & Sons, Hoboken NJ.

Wardman, M., Hine, J., Stradling, S., 2001. Interchange and Travel Choice. Technical Report January 2001. Institute for Transport Studies at the University of Leeds and the Transport Research Institute at Napier University for the Central Research Unit of the Scottish Executive. Leeds. `http://www.gov.scot/Publications/2001/04/8886/File-1`.

Wegener, M., Fürst, F., 1999. Land-Use Transport Interaction: State of the Art. Technical Report. Institut für Raumplanung, Universität Dortmund. Dortmund. `ssrn.com/abstract=1434678`.

Xu, X.y., Liu, J., Li, H.y., Hu, J.Q., 2014. Analysis of subway station capacity with the use of queueing theory. Transportation Research Part C: Emerging Technologies 38, 28–43. doi:10.1016/j.trc.2013.10.010. `http://dx.doi.org/10.1016/j.trc.2013.10.010`.