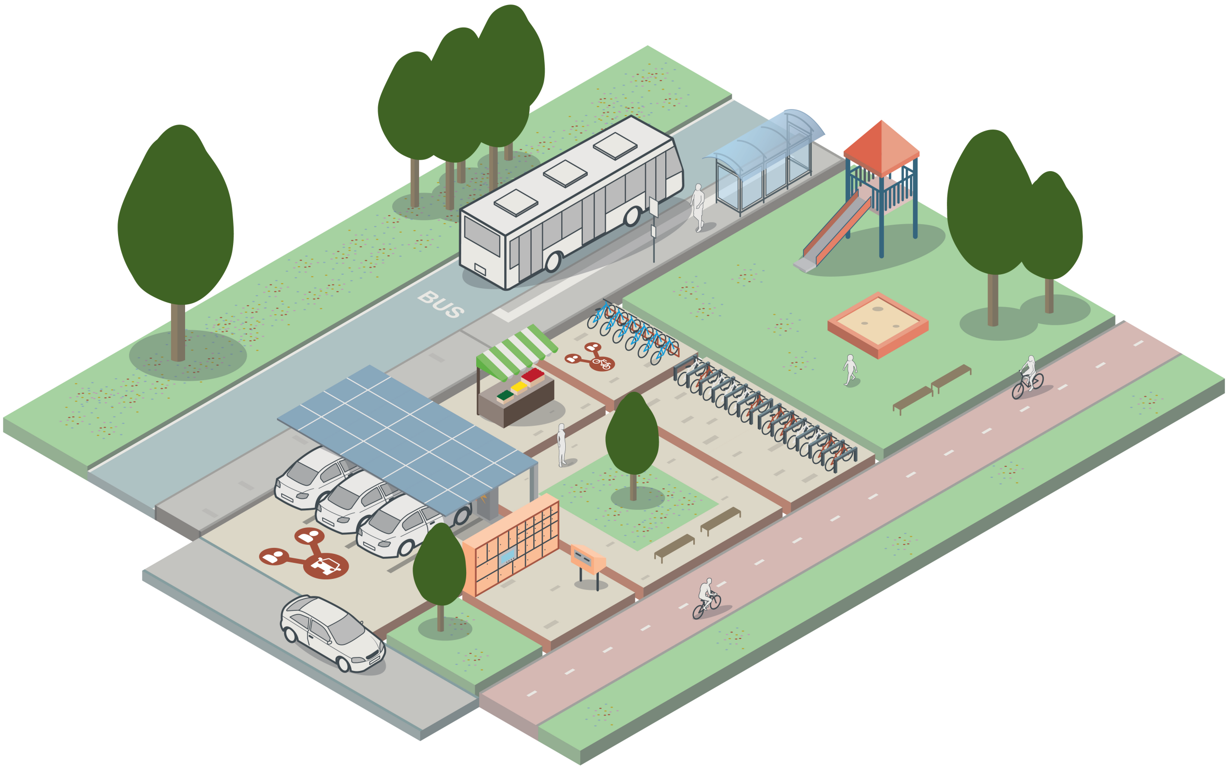
Delft University of Technology

Developing a methodology to determine the potential of areas for regional mobility hubs



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Preface

By the end of June in 2020, I started searching for an interesting company and topic for my TU Delft master's thesis, to finalize my MSc Transport, Infrastructure & Logistics. After contacting several companies, I was welcomed with great enthusiasm by Sweco and I could start my research by the end of September, leading to my first day at the office of Sweco, which unfortunately turned out to be one of the few days at the office. Despite the consequences of the coronavirus pandemic, the project progressed quite smoothly, not in the least due to the perfect supervision provided by Sweco and TU Delft.

Therefore, I would first like to thank my TU Delft supervisors, Rob van Nes, Gonçalo Homem de Almeida Correia and Jan Anne Annema, for their flexibility in planning meetings on short notice, their willingness to help me and review my documents, motivate me and keep me on the right track in my research.

In addition, a big thank you goes to Sweco, where my supervisors Ikram Akkouh and Stijn Altena were very committed to helping me in taking my thesis to a new level. Their frequent messages to check how I was doing encouraged me to stay focused on the thesis. Several other colleagues at Sweco helped me a lot in surpassing the difficulties in the process of doing a thesis research. A special thanks to Wouter Mieras, Guus Tamminga and Nino de Maat for helping me with the method application part of the thesis, this part would have been a lot more time-consuming without your help. Furthermore, I would like to thank the company Sweco in general for providing me with the tools, contacts and applications to execute this master's thesis research.

Lastly, I would like to thank all interviewed experts for their time and the interesting meetings we had. The additional tips and sent documents have been very useful in the process of writing this thesis. Furthermore, the organizations that provided the data needed for the execution of this research are acknowledged.

Enjoy reading my thesis report!

Executive summary

Introduction

In the Paris Climate agreement, 195 countries agreed on lowering greenhouse gasses in the upcoming years. A substantial part of these greenhouse gasses are emitted by passenger transportation, in particular on-road vehicles like cars. Together with the declining quality of life in city centers, the need for sustainable mobility that uses less space in the city center increases. To provide an attractive mobility option that offers a solution to these problems, the mobility hub is proposed.

The availability of scientific literature on the topic of mobility hubs is very limited. Few researches address the functions and features of a mobility hub, and the spatial integration of the hub in the existing arrangement is elaborated in one study. From one of the existing studies, it appears that there is a demand for research on potential locations for mobility hubs, as very few studies exist on this topic. A methodology to determine the potential of locations for a mobility hub is not yet developed in the current literature. From the literature review, it appears that the regional mobility hub is the most relevant mobility hub type for such a methodology.

That leads to the research question of this thesis, which is: ***How can the potential of areas for regional mobility hubs be determined, considering the end user, operator and government perspective?***

Eight sub questions will be answered to guide the research towards an answer to the main research question. The sub questions, consistent with the methodology used throughout the project, are as follows:

1. What is the definition of a mobility hub and which types of hub can be distinguished?
2. Which facilities do the different types of mobility hub include?
3. Which factors affect the potential of a regional mobility hub location?
4. What are the requirements for the methodology to determine the potential for a regional mobility hub?
5. Which elements should be included in this methodology?
6. How can the results from the methodology and its application be interpreted?
7. What can be learned from the application of the methodology to a case?
8. How can the methodology be improved?

Literature Review

The first three sub questions are answered in an extensive literature review. An overview of the relevant information available on the definition, typology and features of the mobility hub is presented. In this thesis, the adopted definition of the mobility hub is: "The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, possibly including other amenities, ranging from retail, workplaces to parcel pick-up points." A classification of mobility hubs into three types is done based on the literature, leading to the residential, city and regional mobility hub. The classification is based on the urban context, offered modalities, transportation function and target groups. For these hub classes, the possible features are investigated for every hub class, first by examining the existing literature, and then relating the features from the literature to the stakeholder groups: the end user perspective, operator perspective and government perspective. It became clear that the selection of features that should be included in a hub strongly depends on the local situation and needs.

Subsequently, on the basis of the envisaged scientific relevance and general applicability of the methodology, the choice is made to focus on the regional mobility hub. The factors influencing the potential of a location for a regional mobility hub are examined by means of an extensive literature review. The economic and mobility function of the hub are investigated in separate subsections, in which the literature on the mobility function is split up according to the three mobility functions of the hub (based on the identified target groups): a mobility hub positioned at the activity side of the trip, the home side of the trip, and in between as transfer point. All literature on factors influencing the potential of a location for a mobility hub found in these sections is combined, together with the interests of the end users, government and operators, into one comprehensive overview of influential factors. This overview of influential factors is the input for the following chapter, the development of the methodology.

Methodology

With the overview of influential factors, a methodology is developed to determine the potential of areas for a regional mobility hub. This methodology is required to spatially evaluate multiple alternatives, incorporating the interests of the defined stakeholder groups and in the application, the output should be visual, in the style of a heat map. These requirements lead to the selection of the Multi-Criteria Analysis (MCA) to evaluate the problem. Parts of the Multi-Actor MCA and GIS-MCA are combined into one methodology, that requires the following steps to be taken:

1. Define alternatives: The alternatives are defined which will be used in the analysis. These alternatives are all areas in the region that satisfy the urbanization constraint posed in the hub classification.
2. Define criteria and weights: The determination of the criteria and weights is done based on the stakeholder objectives. The used methodology for finding the weights is the Analytic Hierarchy Process (AHP). In this methodology, trade-offs between criteria are made by the stakeholders, to establish the weights that will be allocated to the criteria.
3. Criteria, attributes and measurement methods: Attributes are constructed to operationalize the criteria. These indicators should be measurable, and are often quantitative. An overview of criteria and attributes which are used in the developed methodology is presented in Figure 1, including the link to the factors from the previous chapter and the stakeholders.
4. Overall analysis and ranking: All alternatives are evaluated according to the determined weights and criteria.
5. Results: The scores of the various alternatives are given. A sensitivity analysis is performed, to see the result of changes in the weights.

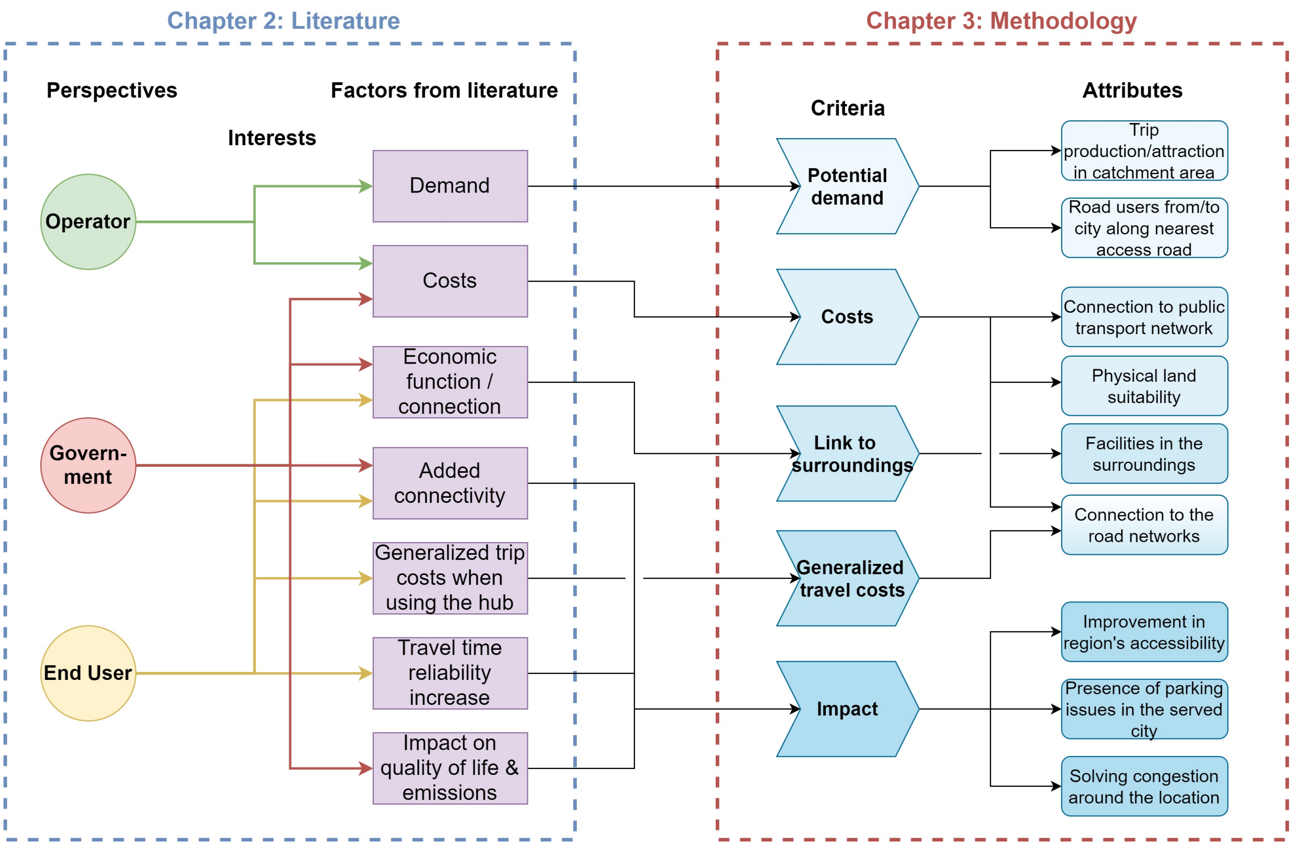

Figure 1: Connection between the stakeholders, literature and methodology

Method application

The next step in this research is the application of the methodology to a case. This step is needed to show that the methodology works as expected, so to validate the methodology, and to guide users of this methodology in the process of applying the method. In this application, the following steps are taken:

1. **Region selection**: In the application, the first step is to select a region for which the mobility hub potential will be evaluated. The region is selected on the basis of posed data requirements and current societal issues, which lead to the choice of the Rotterdam region.
2. **Expert interviews**: Experts are interviewed to gather information on the weights for the trade-offs between the criteria, and to provide additional insights in the facilities included in a mobility hub. Eight experts are interviewed at organizations in one of the perspectives plus one independent expert, and as trade-offs are not explicitly made by the experts, the trade-offs are made in this thesis on the basis of the interests of the experts.
3. **Scenario formulation**: Five scenarios with varying stakeholder configurations are developed to gain more insight in the result of uncertain influences of the perspectives. Two scenarios have the same stakeholder configuration, but differ in the weight assigned to the costs criterion, as a high level of uncertainty is present in this criterion. The weights assigned to all criteria in this thesis are presented in Table 1.
4. **GIS tool selection**: A GIS tool is selected that is able to execute the developed methodology in an application. In this research, FME is chosen out of three applications (ArcGIS, FME & QGIS), the decision is made on the basis of the user-friendliness of the tool and available expertise at Sweco.
5. **Data gathering**: The needed data to operationalize the attributes is gathered from various sources. The attributes that will be used in the method application and the corresponding data sources can be found in Table 2.
6. **Data preparation**: The data is prepared for usage in the GIS tool, which means that every attribute is assigned a value depending on the presence or quantity of the element measured by the attribute, with a correction applied for the distance from the evaluated area to the element. After this, normalization is applied, so every attribute value is scaled to a value between 0 and 1.
7. **Method execution**: The method application is executed, leading to the results.

Table 1: Weights allocated to the criteria for the scenarios used in the method application.

Criterion	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Potential demand	0.2222	0.1111	0.1111	0.4444	0.1333
Costs	0.2063	0.2460	0.1032	0.2698	0.3818
Generalized travel costs	0.0476	0.0238	0.0952	0.0238	0.0476
Link to surroundings	0.1429	0.1429	0.2143	0.0714	0.1255
Impact	0.3810	0.4762	0.4762	0.1905	0.3117

Table 2: The criteria and attributes from the methodology, with the corresponding attribute and the data source for the method application.

Criterion	Attribute (methodology)	Attribute (method application)	Data source
Potential demand	Trip production/attraction in catchment area	Production/Attraction	Traffic model (V-MRDH 2.6)
	Road users from/to city along nearest access road	Traffic along road from/to city center	Traffic model (V-MRDH 2.6)
Costs	Physical land suitability	Presence of parking area	Topographic file (TOP10NL)
	Physical land suitability	Physical land suitability	Topographic file (TOP10NL)
	Physical land suitability	Land owner	BRK Rotterdam
	Connection to public transport network	Presence of high-quality bus/tram link	Traffic model (V-MRDH 2.6)
	Connection to public transport network	Presence of light rail/metro/train station	Topographic file (TOP10NL)
	Connection to the road networks	Presence of regional cycle route	National cycle route database
	Connection to the road networks	Presence of main road	Topographic file (TOP10NL)
Generalized travel costs	Connection to the road networks	Presence of regional cycle route	National cycle route database
	Connection to the road networks	Presence of main road	Topographic file (TOP10NL)
Link to surroundings	Facilities in the surroundings	Number of retail workplaces	Traffic model (V-MRDH 2.6)
Impact	Solving congestion around the location	Maximum I/C-ratio in vicinity	Traffic model (V-MRDH 2.6)
	Improvement in region's accessibility	Reached users (SEGs)	Traffic model (V-MRDH 2.6)
	Presence of parking issues in the served city	-	-

Results

The results of the method application, which demonstrate that the methodology can be applied to a case, are given in the style of heat maps for every scenario, showing the potential for a regional mobility hub in the selected region. As an example, the result of scenario 1, with equal stakeholder influences, is given in Figure 2. The evaluated areas are colored based on their MCA score, revealing their regional mobility hub potential: a red color indicates a low potential, a yellow color a medium potential and a green color a high potential. Not all areas in the region are evaluated due to the urbanization constraint posed by the regional mobility hub: a maximum address density of 2500 addresses/km^2. The resulting highest potential area, situated just right of the city center of Rotterdam in Figure 2, has a high value on all included attributes, and combined with a favorable position in the transportation networks, this area would be a very promising location for a regional mobility hub. Further analyzes are applied to be able to make statements on the performance of the method and its application. The results of these analyzes is presented in Table 3. Overall, the method seems to perform well in finding high-potential locations for regional mobility hubs.

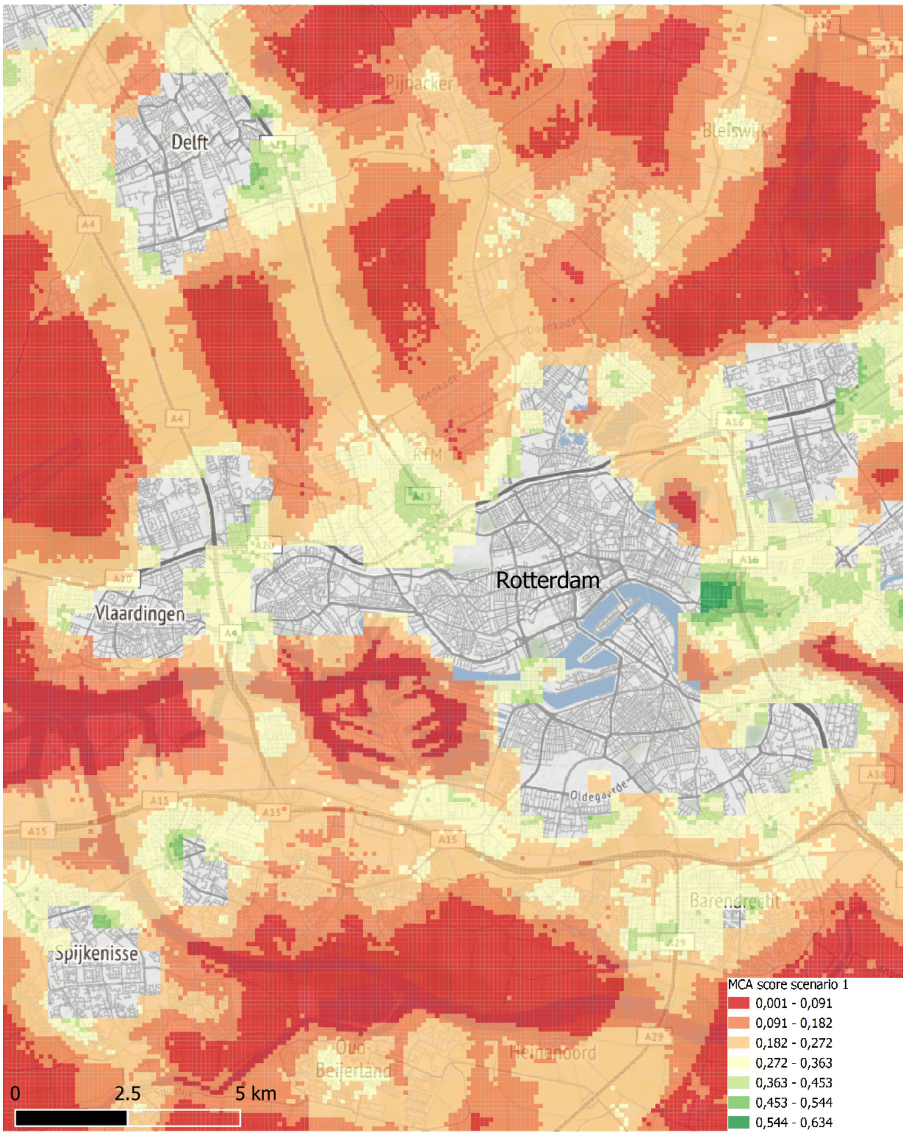

Figure 2: MCA score of the areas in the Rotterdam region in scenario 1.

Table 3: Result of the steps taken to analyze the performance of the methodology and its application.

Analysis step	Result	Description
First output analysis	Logical	Rural areas with no roads nearby and water areas have low potential, areas close to the highway have high potential.
Scenario comparison	Insensitive method	The method is relatively insensitive to a change in stakeholder group influence. The various scenarios are only slightly different.
Attribute contribution	Some irregularities	The used scaling factors in the normalization cause unwanted deviations from expected attribute contributions to the final score.
Verification	Some irregularities	Irregularities related to the input data and used GIS tool. Normalization leads to a very small number of areas that score high on certain attributes.
Sensitivity analysis	Insensitive method	This analysis results in a relatively low sensitivity of the method for both a change in perspective weight and attribute weight.
Robustness analysis	Robust method	The outcome is robust for a large part of the high scoring areas in the region, meaning that the spread in MCA scores is low for most areas that score high in one of the scenarios.
Omitting urbanization constraint	Logical	The highest scoring areas can be found in city centers. The lack of space in the centers causes this methodology to be less suitable for application to extremely dense city centers.
Analysis of high-potential locations	Logical	Regional urban centers and suburban centers are identified as high potential areas, along with areas around rail stations and congested roads.
Comparison with MRDH hub network	Logical	The proposed hub locations are an 82% match to the high-cost scenario (scenario 5), the mismatch can be substantiated by future developments and the other criteria used in that report.

Discussion

A reflection on the methodology is presented in the discussion chapter. The methodology is widely applicable to other regions in the world, as it is based on literature from various countries. The elaborated application in this thesis can be largely adopted for application to another region in The Netherlands, the only important requirement is the presence of a traffic model.

An important limitation of the methodology is caused by the normalization of the attributes. By scaling the attribute values to a value in between 0 and 1, the actual significance of the value is discarded. For example, the highest number of retail workplaces in the region is scaled to the value 1, whereas the actual importance of this value for the regional mobility hub potential is not taken into account.

The most noticeable limitation from the method application is the lack of a recalculation of the areas in the provided traffic model, which is needed to evaluate the impacts of a mobility hub at a specified location. The used input data for this application poses some additional restrictions. Future (real estate/mobility) developments are not taken into account when determining the mobility hub potential of an area using the provided application.

Conclusion & recommendations

In the conclusion, an answer to the main research question is presented, which is that the potential of areas for a regional mobility hub can be determined using a GIS-Multi-Actor Multi-Criteria Analysis, based on the GIS-MCA and Multi-Actor MCA. Criteria and attributes are defined to incorporate the factors, resulting from an extensive literature review, influencing the mobility hub potential of an area. The result is the GIS-MAMCA methodology. This methodology is applied on a region by a GIS analysis, and the outcome is analyzed. From this analysis, it is concluded that the developed methodology is suitable for determining the potential of areas for a regional mobility hub, given the assumptions and limitations posed in this thesis.

To finalize this thesis, recommendations for future research are given, which are, in short:

- Researching the sensitivity to a change in the catchment area of the mobility hub, as this can also provide useful insights into the effects of a change in catchment area on the potential demand.
- Researching the combined freight passenger mobility hub is relevant, as combining the two functions in one facility may lead to an even higher usage and potential of the hub.
- Investigating revealed preference data from current shared mobility providers might lead to improvements in the methodology. The service area of the operator should be outside of extremely urbanized areas in order for it to be useful for the regional mobility hub.
- Fundamentally researching the criteria in the methodology, instead of using approximations and simplifications for all factors based on literature. Research on the impacts of various facilities on the demand for a hub should be executed. Besides, the extent to which the modal shift to a regional mobility hub will be made by various population groups should be studied, to be able to make statements on the future usage of the hub.

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List of Abbreviations

AHP	Analytic Hierarchy Process
BRK	Key register kadaster
BRT	Key register topography
GIS	Geographic Information System
I/C-ratio	Intensity divided by capacity ratio
MaaS	Mobility as a Service
MAMCA	Multi-Actor Multi-Criteria Analysis
MCA	Multi-Criteria Analysis
MRDH	Metropolitan Region Rotterdam The Hague
NRM	Netherlands regional model
P&R	Park&Ride
PT	Public transport
SEGs	Socio-economic data
TOD	Transit-oriented development

Chapter 1

Introduction: Problem statement and research outline

The world is currently captivated by global warming, caused by increasing greenhouse gas emissions. The consequences of this high number of greenhouse gas emissions have not gone unnoticed. In the Paris Climate Agreement, signed in 2015, 195 countries from around the globe approved on measures to limit global warming, by means of cutting greenhouse gas emissions in the European Union by 55% compared to 1990 levels (Government of the Netherlands, 2019). The transportation sector accounts for 30% of the greenhouse gas emissions worldwide, of which 70% is emitted by on-road vehicles (Tanç et al., 2019). Intervening in this sector is crucial to achieve the goal posed in the Paris Climate Agreement.

From the on-road vehicles, about 25% of the emitted greenhouse gases results from heavy-duty traffic (buses and trucks), while 75% is caused by cars and light commercial vehicles (European Commission, nd). In this category, passenger transportation is highly represented. Therefore, there is a growing political interest in the impacts of passenger transportation.

A study investigating global mobility, in which 131 countries are considered (Fountas et al., 2020), shows that the average share of the car in passenger transportation is 61.2%. In countries with a high gross domestic product per capita (above $35.000), this share increases to 80.8%. The number of vehicles and the demand for mobility have been historically rising, this growth has been strongly associated with economic development (Dargay et al., 2007). The car has been an efficient modality in the previous decades. The private car has very clear advantages over other transport options, which can be related to the availability, comfort and flexibility of this modality (Viegas et al., 2016). However, there are some serious drawbacks to this modality. The majority of the transportation is executed by private cars, leading to low vehicle occupancy rates and a low efficiency of the transport network (Zhu et al., 2016). Impacts of private vehicles on air pollution and congestion have been under investigation in the past decades (Zavitsas et al., 2010).

An additional problem caused by private vehicles is the quality of life in city centers. Cities are reaching their limits in terms of space, and there is an increased attention for the attractiveness of the city. It results from previous research that an increase in traffic intensity and speed negatively influences social interaction and friendliness of the urban environment (Mullan, 2003). According to the same source, reducing traffic speeds and intensities have led to an increase in quality of life in the investigated street.

A partial solution to the posed problems has been provided by the introduction of the electric vehicle. This vehicle has the advantage of lower levels of local emissions and a reduction in noise compared to vehicles powered by fossil fuels. This change in power source, however, does not resolve the other problems: the quality of life in cities and the inefficiency of private vehicles (Harbers and Snellen, 2016).

To deal with the domination of private vehicles in highly urbanized city centers, solutions have to be found to facilitate the demand for mobility. A policy only aimed at discouraging car use, without providing alternatives, will fail and frustrate the public. Furthermore, eliminating people's movements to solve the problem would lead to a loss in the advantages of these movements (Bull, 2003, p. 84). Improved public transportation, stimulation of active modes (walking, cycling) and the introduction of shared mobility provide a solution to this problem. The mentioned solutions imply a big role for multimodal travel, introducing transfers in the travelers' trips. To provide an attractive transfer between those various modes, and to solve the issue of a lack of space in urbanized areas, the mobility hub is invented. In the mobility hub, all previously named modalities (public transport, walking, cycling, private vehicles and shared mobility) come together in one place.

The mobility hub is designed to offer the traveler, based on the available information, the optimal route and modality at the time of travel. Public transport plays a central role in these multimodal mobility hubs (Miramontes et al., 2017), supplemented by a shared mobility service, like car sharing or bike sharing. The service is integrated in mulitmodal trip planners, and integrated in terms of pricing and/or access. The convenience offered to the end user by these features aims to make multimodal travel easier for the traveler.

The transfer between modalities currently takes place at transportation nodes, such as a city's main train station. This raises the question as to what sets the mobility hub apart from the existing transportation nodes. The mobility hub can be seen as a unique facility, because of the sustainability of the transportation modes, integration of shared mobility services, inclusion of additional facilities at the hub and integrated route decision making. The integrated route decision making aims to offer the best possible route to the traveler, given current traffic and public transport conditions, whereas in the present situation, the mode choice is made by the traveler. In a future with mobility hubs, the route planner will select the modality that best suits the traveler's destination and preferences. This integrated route planning is currently under development in the Mobility as a Service concept (Giesecke et al., 2016). The modalities offered at a mobility hub use almost exclusively non-polluting power sources, like electricity. The electric bus, train, metro, tram, (shared) electric vehicle and bike can all be connected to a mobility hub. Besides, the hub contributes to sustainable transportation by providing the opportunity of making a trip (partly) by shared electric vehicles instead of a privately-owned gasoline vehicle.

1.1 Existing research and gap

1.1.1 Research on mobility hubs

Limited research has been executed on the topic of mobility hubs. For this reason, literature research is not limited to scientific articles, but grey literature, like master's theses, government documents and reports, is consulted as well. Few researches address the functions and features of a mobility hub (Aono, 2019; Bell, 2019; Groenendijk, 2015). Also, the spatial integration of the hub in the existing arrangement is elaborated in L. van Gils (2019a). The effect of the introduction of a mobility hub on the passenger's travel behavior in Munich is researched in one paper (Miramontes et al., 2017). This research uses a survey to investigate the effects for one specific hub. The authors recommend further research to generalize the results. Another recommendation for further research in the report by Aono (2019) is a focus on the integration of the mobility hub into future projects. This can help in identifying key locations for a hub. In the other chapters of that report, the difficulties in finding a suitable location for the hub are extensively described.

From the report by Aono (2019), it appears that there is a demand for studies on potential locations for mobility hubs. Very few studies exist on this topic. In a strategic study on transportation for South East of Scotland (SEStran, 2020), the opportunities for development of mobility hubs in Scotland are investigated, and the potential hub locations are identified. This study incorporates multiple data sources and factors, with a short justification of each factor, but the weighing of the factors, exact scores or literature supporting the inclusion or exclusion of certain factors are not mentioned in the report. The deliverable of this study is a set of heat maps showing the potential need and demand for mobility hubs in the Scottish region. Another research, intended to advice on fitting mobility hubs into the local situation (CoMoUK, 2019), provides some factors to examine in the site selection process. However, these factors are mainly focused on the exact physical integration instead of the actual location selection problem. Furthermore, general guidelines on mobility hub locations are introduced in a paper by Enbel-Yan and Leonard (2012). Case studies are presented in that research, and it is advised to plan mobility hubs in an interdisciplinary way, to ensure a good integration of the hub in all related disciplines, like land use planning and transit operations. Nevertheless, this research does not present a way to find a hub location in a certain region. In short, what lacks in the current literature is a general framework/methodology to find high potential mobility hub locations in a specified area.

1.1.2 Research on other transportation nodes

Inspiration for this methodology can be found in research on locating other transportation nodes. Next to the well-known Park&Ride facility, located at a public transport node to facilitate the transer between car and public transport, the so-called transferium is often researched in the literature. This transferium sets itself apart from the Park&Ride facility by a placement as close to the main road as possible, not necessarily at an existing public transport stop (Egeter et al., 1990). For transferia (the plural of transferium) and Park&Ride facilities, literature on finding a good location has been published decades ago (van Binsbergen et al., 1992) (Faghri et al., 2002). To find a suitable location for a transferium, van Binsbergen et al. (1992) provides a flow chart with the steps that should be taken, but this step-by-step guide provides a very time-consuming methodology, as the logical transferium locations should be determined manually and the process of selecting the locations is iterative. Concerning a Park&Ride location choice, a hybrid knowledge-based expert system/GIS tool is elaborated on in Faghri et al. (2002). The experts in this research are transportation planners and engineers in the United States, the weights are calculated from the scores these experts give to the various criteria. The scores given by the experts are combined into one value per criterion. GIS is used for the analysis of the criteria. This research, however, requires predetermined potential locations as input, and can not determine the most promising locations without this input. Computing the Park&Ride potential for a very large number of input locations, for example all areas within a region, is highly time-consuming using the proposed method, as some criteria, like the site expansion potential, are manually determined using intuitive knowledge from the transportation planner.

1.1.3 Gap in current literature

As the mobility hub differs from the Park&Ride facility and transferium in several ways, of which the most determining are the integration of shared mobility services and inclusion of additional facilities at the hub, the potential of a location for a mobility hub differs from the potential of a Park&Ride facility or transferium. This implies that the existing methodologies can not be adopted unreservedly. The mobility hub does not only serve as a node in the public transport and road network, facilitating the transfer between the networks, but adds mobility value by offering shared mobility, hence faster trips for passengers with no car available, or for trips to the city center where private car usage is restricted by (future) policies and high parking fares. Furthermore, it adds value for both the transfer passengers and the neighborhood by providing facilities, like a parcel pick-up point or a supermarket at the hub.

In the process of developing a mobility hub, it became clear from the literature that the location is an essential part. A generally applicable methodology that makes it possible to determine the potential of a location for a mobility hub, without having to perform multiple time-consuming iterations or determine criteria values manually, is not yet present in the literature. This literature gap will be further addressed in this thesis.

1.2 Research objective

The objective of this thesis is to present a methodology, which enables an interested company/government to scan a region for the highest potential locations for a regional mobility hub. Finding the highest potential location means that all areas in the region are evaluated for their regional mobility hub potential, to be calculated by the developed methodology, from the stakeholders' point of view. To elaborate on this, a high potential location means that a regional mobility hub at that location would satisfy the wishes of the stakeholders to a higher extent than for a low potential location. The stakeholders are grouped in three perspectives. The categorization of the stakeholders into three perspectives is inspired by a stakeholder analysis of a report, presenting an analysis framework on the success and failure factors of innovative modalities (Talen et al., 2018, p. 3). The first perspective are the end users (the travelers), the second perspective is the operator perspective (the transportation authorities, shop owners, hub operator etc.), and the third perspective is the government perspective (national, regional, provincial and local governments). The highest potential locations will be a balanced combination of the three incorporated perspectives.

The deliverable of this thesis is a methodology, intended to contribute to the emergence of innovative, environmentally friendly mobility solutions, that lead to a reduction in the negative impacts of the envisaged increase in demand for mobility. In short: the mobility hub is seen as a solution to a societal issue, and this thesis can help in simplifying the process of finding suitable locations for these hubs. In order to maximize the usefulness of this thesis, the methodology should be designed in a way such that it can be applied to any region throughout the world. To clarify the application of the methodology, a step-by-step plan of the application is included in the research.

1.3 Research questions

For a successful execution of the research, a structured way of working is crucial. A clear and comprehensive research question should be formulated, which can be referred to at any time. The main research question in this research is as follows:

How can the potential of areas for regional mobility hubs be determined, considering the end user, operator and government perspective?

To improve the structure, the main research question is divided in eight sub questions, which will be answered during the research. These sub questions, which are specified below, are consistent with the methodology used throughout the project.

1. What is the definition of a mobility hub and which types of hub can be distinguished?
2. Which facilities do the different types of mobility hub include?
3. Which factors affect the potential of a regional mobility hub location?
4. What are the requirements for the methodology to determine the potential for a regional mobility hub?
5. Which elements should be included in this methodology?
6. How can the results from the methodology and its application be interpreted?
7. What can be learned from the application of the methodology to a case?
8. How can the methodology be improved?

1.4 Scope

A first reduction of the research scope results from the problem statement in the first paragraphs of the introduction. The high share of passenger transportation in the greenhouse gases emitted by the transportation sector lead to the limitation of the scope to passenger hubs. The logistic hub, intended for freight traffic or a combination of freight and passenger traffic, is gaining extra attention over the past years, both in academic literature and in documents provided by Dutch municipalities and provinces. However, since the priorities and decision makers in the logistic hub field differ a lot from those for the passenger hub, those two hub types cannot be easily combined in one methodology. A choice is therefore made, for this research the focus is on the passenger hub.

From the concise literature review conducted to arrive at the research gap, it became clear that mobility hubs and their characteristics strongly vary by country. Even within a city, a wide variety of mobility hub types often exists. The developed methodology in this research only considers one specific type of mobility hub: the regional hub, located in a regional urban context. The hub classification and the choice for this hub type is elaborated in chapter 2.

This thesis aims to determine the potential of locations for a regional mobility hub. The objective of the used methodology is not to find an exact location for the hub, but only to determine the potential of locations, as factors influencing the exact positioning of the hub can not be integrated in the methodology. The result of the methodology will not contain the exact size, layout and functions included in the mobility hub, as this is subject to case-specific and location-specific constraints and stakeholder wishes, which are not included in the universally applicable methodology. The result of the methodology only presents a first indication of the potential of areas for regional mobility hubs, and using the result, the location can be selected and the actual hub can be developed.

This research and the resulting methodology are not limited to usage in The Netherlands, but the method application will be based on a Dutch region. Applying the methodology in another country would make some changes necessary, in the data gathering, weight determination and perspective influence. The setting of the weights from the different perspectives differs per country, since the priorities of the national and regional government, operators and end users vary per country and region. Besides, as the objectives of the method application are to serve as a validation of the methodology and to guide users of the methodology in the application process, and not to provide an accurate evaluation of the region, the determination of the weights for the attributes will be less substantiated that the preceding parts of this research.

In some previous studies, a mobility hub network is designed for a city. In this thesis, it is assumed that only one hub is to be placed, and for this hub, a location potential determination methodology is developed. Designing a hub network requires additional research on competition effects between the hubs, and a solution tailor-made for the selected region. All in all, a generally applicable framework for a hub network is outside of the scope for this thesis.

One of the distinctive features of the mobility hub is the integration in terms of pricing, access and route planning. Integration of different shared mobility modes, public transportation and potentially more functions in one service (ticketing system and route planner) is called Mobility as a Service (MaaS). MaaS is mostly software-oriented development, relying on elements like a car sharing system, or a mobility hub network. The mobility hub requires MaaS in order to offer integrated route planning, but this concept will not be elaborated in this thesis. More information on the software-oriented integration is presented in Appendix A.

1.5 Methodology and thesis structure

To be able to tackle the research question and sub questions, and to achieve the objective, a step-by-step plan is established. The steps in this plan are performing literature research, determining and developing the methodology and elaborating an application of the methodology. In this elaboration, expert interviews are conducted to improve the analysis. The next step contains a visualization of the output of the method application, in which five scenarios are presented with varying levels of stakeholder influence. A discussion of these results and the conclusion follow, along with recommendations for further research. A concise overview of the taken steps in this research is given in Figure 1.3.

1.5.1 Literature on mobility hubs

First off, literature research is required, as the mobility hub is a recent topic, with no well-established definition and typology. In providing an answer to the main research question, this definition and typology is needed, because the answer depends on the adopted definition and typology. This literature research is carried out in chapter 2. To give an idea of what the different mobility hub types look like, literature is consulted and taking the wishes from the three stakeholder perspectives into account, a list containing the possible features of the various mobility hub types is created. This step serves as a detour on the main methodology, but is useful in the process of designing a mobility hub.

At this point, a choice is made for a specific hub type to focus on in this thesis: the regional mobility hub. From here on, the focus is on determining the potential of areas for this type of mobility hub. In the literature, the possible functions of the regional mobility hub are found, and for these functions, literature is investigated, to find out which factors may influence the potential of a location for accommodating a mobility hub. In this step, it is important to find out which stakeholders are involved in the process of locating a mobility hub, as different stakeholders may have different interests. This research into the factors determining the potential of a location, combined with the view from the various perspectives (stakeholder groups), results in a complete overview of influential factors. Out of these factors, a selection of the most relevant influential factors is made, which will be used in the next step, the methodology.

1.5.2 Developing the methodology

To be able to process these relevant factors into a regional mobility hub potential per area, simultaneously incorporating the importance of the different factors, a suitable methodology should be developed. This is elaborated into detail in chapter 3. The desired result is a determination of the potential of areas for a mobility hub in a region of choice. The results should be easy to interpret, therefore a visual representation is desired. As the results concern a geographical region, a possible representation of the result could be a heat map, as depicted in Figure 1.1

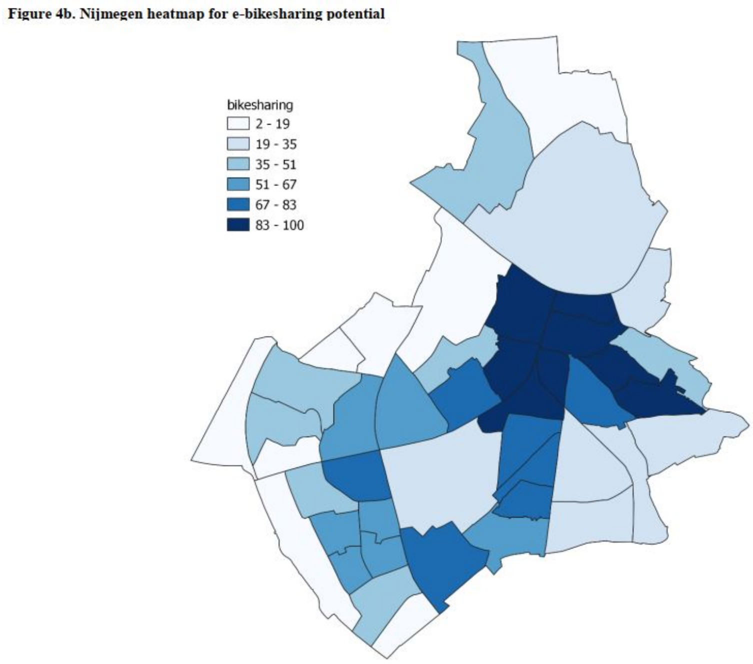

Figure 1.1: Example of a heat map for the potential of shared mobility in the Dutch city of Nijmegen, as inspiration for the desired output of the methodology (Liao and Correia, 2019a).

In order to find a suitable methodology, it should be clear what requirements are imposed for the method. There are five main requirements:

- The topic investigated in this thesis requires an approach that considers multiple alternatives, as multiple locations are studied.
- The method should give an answer to the question of which option performs best, given influential factors from the literature.
- The method should allow for spatial evaluation, as the evaluated alternatives are locations in a region.
- The stakes of various stakeholders should be incorporated explicitly in the evaluation method.
- It should be possible to produce a visual outcome of an application of the methodology.

In order to find which method is suitable for this thesis, literature is reviewed. A search with the terms "spatial", "evaluation", "alternatives" and "stakeholders" in Google Scholar results in 9 out of the top 10 articles (sorted by relevance), 8 of which are cited in more than 30 other articles, using a Multi-Criteria Decision Analysis (MCDA) method to spatially evaluate multiple alternatives. The other results in the search query do not describe a method to spatially evaluate multiple alternatives. Searching for specific literature comparing different methods, suitable for comparing multiple options in a transportation project, results in a paper by Macharis et al. (2009). According to this paper, two methods are able to include non-economical aspects in the evaluation: the mentioned Multi-Criteria Decision Analysis (MCDA), and the Social Cost-Benefit Analysis (SCBA). The advantage of the MCDA over the SCBA is the inclusion of quantitative and qualitative criteria, to be able to include all effects.

On the basis of the previous concise literature review, the Multi-Criteria (Decision) Analysis (MCA) seems to be the suitable methodology. In essence, the MCA is not specifically designed for spatial evaluations. Literature is reviewed to find out more on spatial evaluation in a MCA. A first paper on the usage of a MCA to find a potential hub location, is provided by Zhang et al. (2019). In that paper, the TOD (Transit-oriented development) index of a certain area (e.g. how extensive is the transportation system, is there a high land-use potential) is measured using a Spatial Multi-Criteria Analysis (SMCA). In this spatial MCA, indicators of each grid are calculated using ESRI ArcGIS, where after the TOD index is measured. The use of this TOD index is to find disequilibrium in the city. Part of this methodology, more specific the use of a spatial MCA, can be adopted in this thesis, to find the suitability of an area for a mobility hub.

The spatial MCA methodology is widely usable, as can be seen in a highly cited paper on wind farm site selection (Haaren and Fthenakis, 2011). In this paper, map layers from a GIS database are used to find the best locations for potential wind farms in the state of New York, United States. The location finder is developed in ESRI ArcGIS Desktop 9.3.1. Constraints were added, leading to the exclusion of certain locations in the area, where after an economic evaluation is performed. Afterwards, important bird areas are added to come to a final site map indicating the best sites to build a wind farm. The information from the spatial MCA is compared with the locations of existing wind farms as verification, where it resulted that the existing wind farms are placed in feasible areas, close to high net present value centers according to the tool. This means that the tool is able to find suitable locations for a wind farm, since the existing wind farms are built in favorable locations.

The exact name adopted for the methodology (the spatial MCA) in this thesis is the GIS-MCA, inspired by Malczewski and Rinner (2015); Al-Shalabi et al. (2006); Malczewski (1999). Next to the spatial requirement of the MCA, an additional methodology requirement is the explicit incorporation of the stakeholders' interests. An adaptation of the MCA, the Multi-Actor Multi-Criteria Analysis (MAMCA) is found to explicitly include varying stakeholders influences (Macharis et al., 2009, 2010), after a search on Google Scholar with the terms "MCA", "stakeholders" and "explicit".

After having found a methodology that meets the requirements, this methodology should be specified to be able to apply it on the calculation of the mobility hub potential across a region. The first step in this development, is creating a combination between the GIS-MCA and Multi-Actor MCA, the GIS-MAMCA (Geographic Information System-Multi Actor Multi-Criteria Analysis). In chapter 3, the exact design of this methodology is further elaborated.

Having found a methodology that might be suitable for answering the research question, the next step is to look into the methodology and insert the influential factors from the literature research. In the GIS-MAMCA methodology, the used elements are: criteria, attributes, alternatives, stakeholders and weights. Every element of the method is shortly described below, an overview is given in Figure 1.2.

- Criteria: The influential factors are classified into evaluation criteria by merging related factors in one criterion. This is done to make sure trade-offs can be made between all criteria. A high number of criteria might cause difficulties in this process, leading to more uncertainty in the result, so a low number of criteria is preferred.
- Attributes: The attributes are in place to quantify the criteria. To find out which attributes can be used for the criteria, a reflection to the literature is carried out.
- Alternatives: The alternatives which will be evaluated in the methodology. All areas in the region should be evaluated, therefore these areas represent the alternatives in the methodology.
- Stakeholders: The three perspectives in this thesis represent the stakeholder groups, which will be used in the developed methodology.
- Weights: The criteria should be given weights in order to obtain to a final score from the methodology. The weights for every criterion are determined per perspective (stakeholder group). This process is executed using the most common method for determining weights in the MAMCA and GIS-MCA, the AHP (Analytic Hierarchy Process). In the AHP, pairwise comparisons are made by the involved stakeholders to determine the relative importance of criteria. The selected method to arrive at the comparisons is conducting expert interviews among the relevant stakeholders, a way of gathering first-hand information on stakeholders' considerations with regard to a mobility hub location.

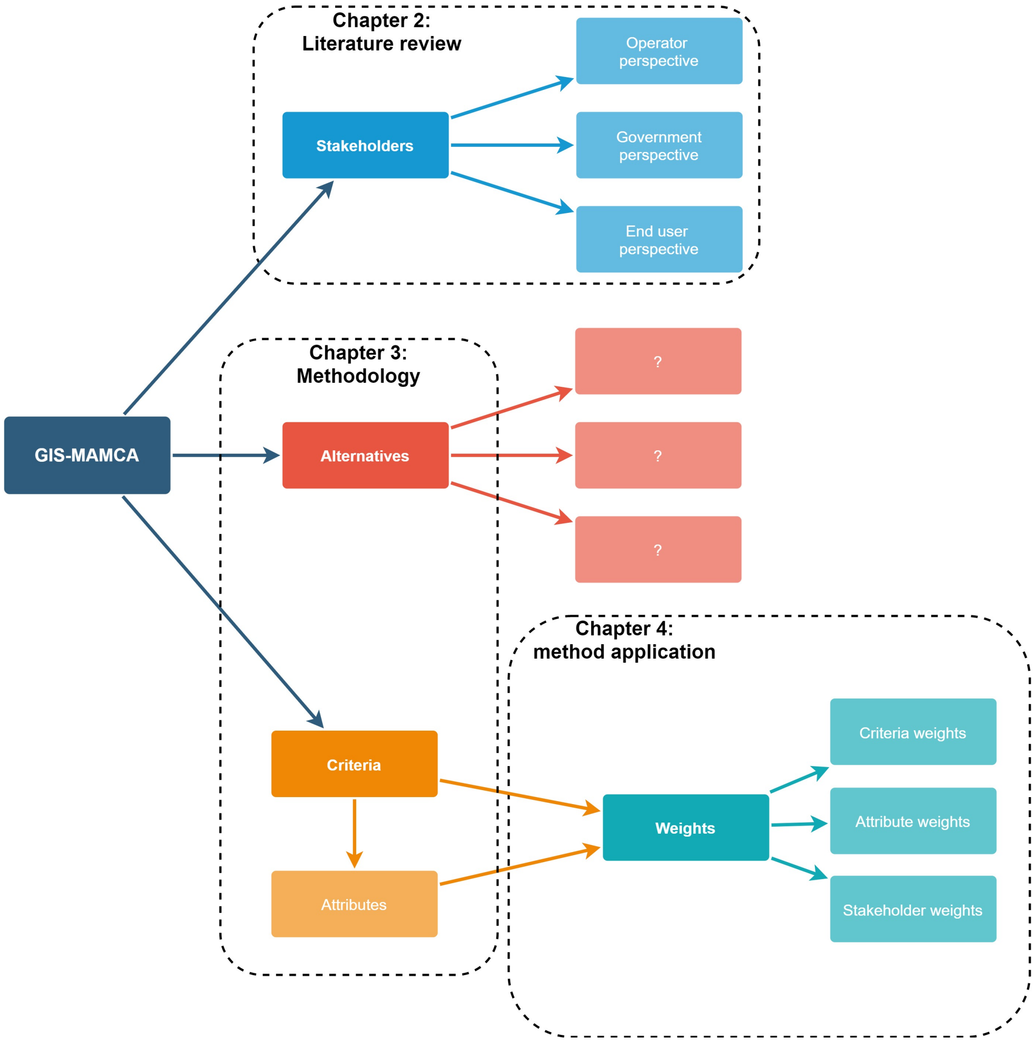

Figure 1.2: Elements of the developed methodology, along with the chapter in which the elements are addressed.

1.5.3 Method application

In order to test the usefulness of the methodology and to guide users of the methodology in the process of applying the methodology, an application to a region is elaborated in chapter 4. Per methodology element, it is described what is needed for the application in the list below.

- Criteria: The criteria are known from the literature, no adjustment is needed for the application.
- Attributes: The attributes are known and in the application, the right data is matched to the attributes. In the case of unavailable data for the selected region, simplifications or substitutions on specific attributes can be included in the application.
- Alternatives: The alternatives are all areas in the selected region.
- Stakeholders: The stakeholders are known from the previous chapters.
- Weights: Expert interviews are conducted to determine the weights, by means of the AHP method elaborated in the methodology. The weights of the individual attributes within the criterion are established by a combination of information from the interviewed experts, reflection to the literature, own insights and expert judgment of Sweco employees. The stakeholder weights are determined per scenario, explained in the following paragraph.

The first phase in the application is to select a suitable region. The suitability can be determined by considering existing congestion and quality of life issues in the region, and by identifying which data sources can be consulted to gather the needed data for the operationalization of the attributes. On the basis of these data requirements and the potential added value of a mobility hub in that region, the region of Rotterdam is selected. Subsequently, the expert interviews are performed, in which experts in the field of innovative mobility will be interviewed to obtain insights into weights for the criteria and, as an addition to better understand the future perspective of mobility hubs, the vision of relevant organizations in The Netherlands on mobility hubs. The experts should be part of one of the three chosen perspectives to provide information on the trade-offs, and are preferred to be occupied with either the mobility hub or transport in the selected region (Rotterdam). Nine expert interviews are conducted and using these interviews, the weights assigned to the criteria are calculated. The stakeholder weights are then calculated. The weighing of the three perspectives in the final score is done by developing five scenarios with varying stakeholder influences. The five scenarios will eventually lead to five separate outputs.

What follows is the selection of a GIS tool to run the model application, where a choice is made out of three suitable tools. After defining the region, weights, scenarios and the used tool, the actual data can be gathered. Important in this search is the availability, completeness and reliability of the data. The data should be available as open data, or on request from the responsible authority (e.g. the public transport operator or municipality). The data should provide a complete overview of the values of the concerned attribute in a region, and the dataset should be reliable, as errors in the data decrease the performance of the methodology. The following step is to prepare all data, by normalizing and converting to the right format, for usage in the GIS tool. After inserting all data, weights and scenarios into the GIS tool, the method application can be executed.

1.5.4 Results & Discussion

The next step in the research is presenting and analyzing the output of the GIS tool in chapter 5, as a validation of the methodology. The output consists of five heat maps, one for every scenario, that show the areas with a high potential for a regional mobility hub in the region of Rotterdam. In the five scenarios, the ability of the hub to fulfill the wishes of the different stakeholders is incorporated, one of these wishes is providing a solution to the environmental and quality of life issues in cities. Using this multi-actor scenario approach, societal issues are included in the methodology.

After presenting the output, the output of the method application is tested for its usefulness. The usefulness relates to the extent to which the methodology and its application are able to attain the research objective, so the extent to which the potential for a regional mobility hub is correctly determined by the methodology. A total of nine analysis steps are carried out to assess the usefulness, in which the output is evaluated on rationale, robustness, correctness and sensitivity. These analysis steps include a sensitivity analysis and a comparison with an existing concept of a mobility hub network in the Rotterdam region. In the following discussion, found in chapter 6, a reflection on the results is provided, along with strengths and weaknesses of the developed methodology and its application, and other points of attention discovered in this research.

1.5.5 Conclusion

The conclusion, in chapter 7, provides the answer to the research question and sub questions. It is elaborated how the potential of areas for regional mobility hubs can be determined, along with the reliability of the result. The scientific and societal relevance of this thesis are described, in which the incorporation of the initial problem statement in the methodology is discussed. To finalize the report, recommendations for users of the methodology and future research are given. The recommendations follow from limitations and assumptions of the methodology and its application, and possible improvements discovered throughout the thesis.

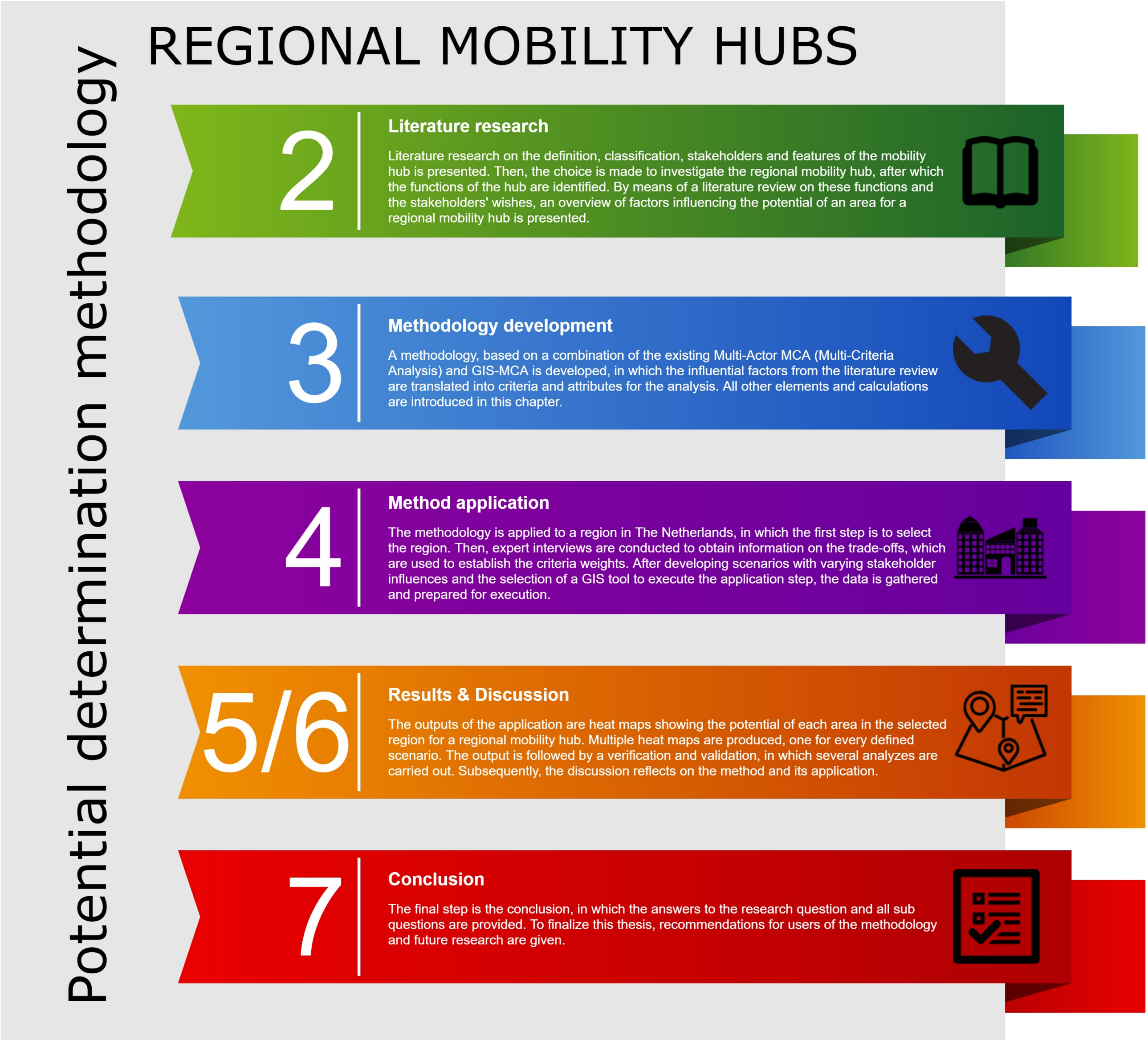

Figure 1.3: Overview of the steps taken in this thesis and the chapter in which the step is elaborated.

Chapter 2

Literature Review: Mobility hubs

This chapter is a collection of the literature research carried out for this research, and consists of literature research on the definition, typology, stakeholders, features and location of the mobility hub. At the end of each section, it is concluded what will be adopted from the literature in the continuation of this thesis.

2.1 Introduction

Three sub questions will be answered in this chapter:

- What is the definition of a mobility hub and which types of hub can be distinguished?
- Which facilities do the different types of mobility hub include?
- Which factors affect the potential of a regional mobility hub location?

The first sections will provide literature leading to an answer to the first part of the first sub question. From this point on, this definition is set and will not be changed. Within this definition, multiple hub classes can be distinguished. The classifications available in the literature are presented in the second section, followed by a division of mobility hubs in three classes, with the requirements and characteristics belonging to the different classes. This will provide the answer to the second part of the first sub question.

To guide the process of designing a mobility hub, the facilities/features that must or can be included in the hub are described, for the various mobility hub classes. To identify the facilities, the needs of the involved stakeholders should be incorporated. Firstly, these stakeholders are identified and grouped in the three perspectives. The categorization in the perspectives is of importance in this research, as the potential will be evaluated from the three perspectives. The wishes of the stakeholder groups (the perspectives) are then listed. Subsequently, literature on mobility hub design is reviewed, which leads to a list of possible features of a mobility hub. A selection is made on the essential and optional features per hub class, which forms the answer to the second sub question.

After answering this sub question, a substantiated choice for a specific mobility hub class will be made, based on the added scientific value of a location potential determination methodology. On the basis of this choice, an answer to the third sub question can be sought. In order to find out which factors influence the potential of a location for a mobility hub, literature on the different functions of the mobility hub is reviewed. To evaluate the function of the mobility hub from the mobility point of view, it is important to know which user groups will use the hub. Defining the user groups leads to multiple mobility hub functions within the investigated mobility hub type. The distinction is made between a mobility hub at the home-end of a trip, a mobility hub at the activity-end of a trip and a mobility hub at a location in between. This is relevant, as a private vehicle is often not available at the activity-end of a trip. Shared mobility provides a solution for this part of the trip.

All factors arising from the regional mobility hub functions (multiple mobility functions and the economic function) are linked to the wishes of one of the stakeholder groups, as it is important to keep in mind that the mobility hub should provide a solution to a societal problem (the government perspective), and in order for the hub to be used and operated, the end user and operator perspective are considered. This literature review leads to an overview of factors influencing the potential of a location for a regional mobility hub.

The identified influential factors affect the potential of the possible locations of a regional mobility hub. The next step is to actually determine the potential for a regional mobility hub in a region, while including the interests of the different perspectives. The complete structure of this chapter is visually presented in Figure 2.1.

For the execution of the literature research, it must be known which sources are used, and which exact keywords are inserted to perform the query. Scientific sources are complemented by grey literature (government documents, reports, Master's theses) as the mobility hub is a relatively new topic, meaning that scientific literature on mobility hubs is relatively limited. The following literature sources will be used:

- TU Delft repository, providing Master's theses, academic researches etc.
- Scopus and Google Scholar, global databases for scientific literature
- Google search for government documents and reports, technical reports, other university Master's theses etc.
- Sweco internal documents, reports and information

A search including the term "mobility hub" in Scopus results in only 19 documents. These documents are reviewed to identify the relevance in this research. Additionally, alternative keywords are used to find results on similar topics, which are "public transport node", "park ride", and the Dutch "transferium". Specifically for the definition, typology, features and location of the mobility hub, the corresponding keyword is added to the query. Furthermore, the aim is to collect literature from multiple countries, so the name of a country in which a mobility hub has been investigated is added, being North-American and Western, Southern and Northern European countries.

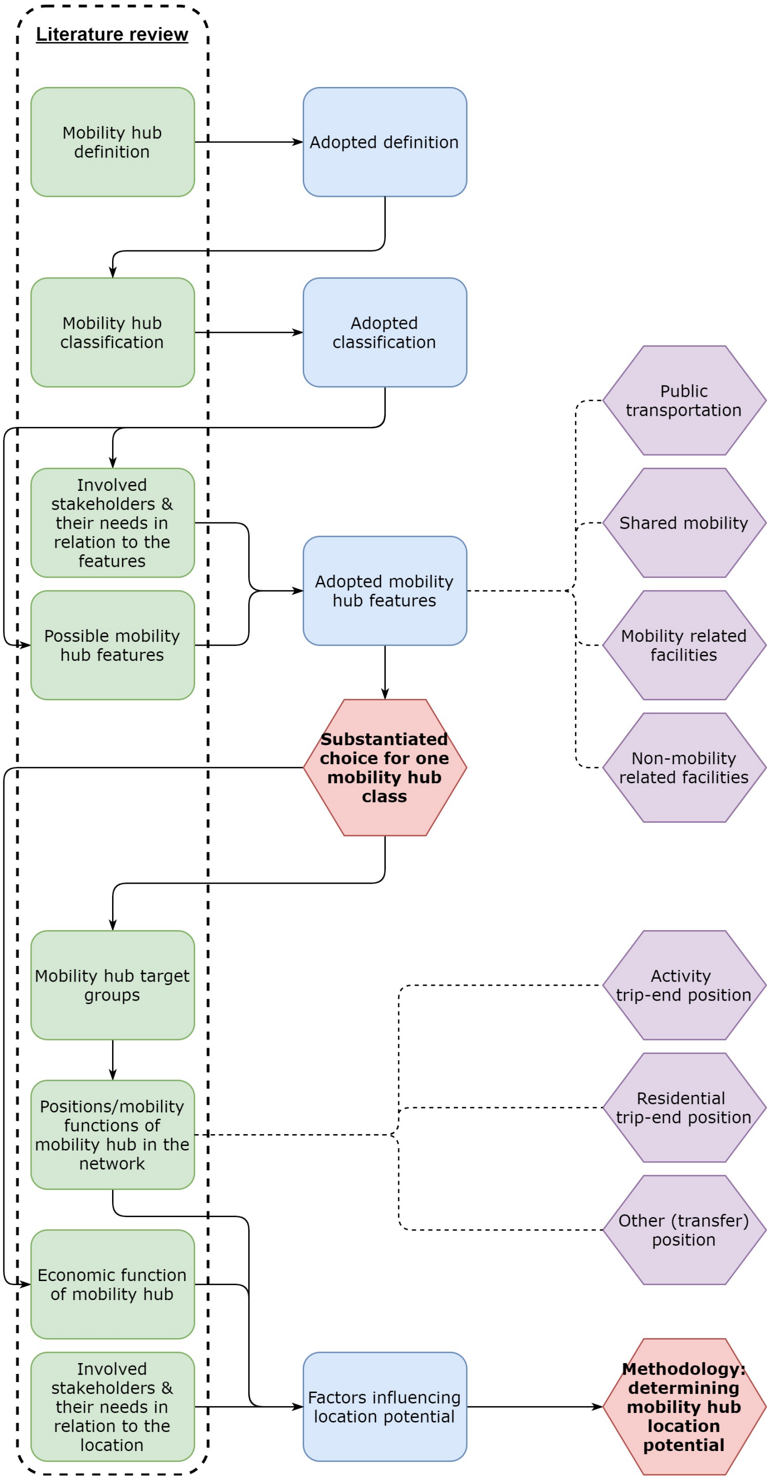

Figure 2.1: Schematic overview of the literature review carried out in this chapter. The green rectangles are the literature review steps, the blue rectangles depict subsections in which an overview is given and a choice is made, the red hexagons provide important decisions and the purple hexagons present a categorization of the respective step.

2.2 Definition

2.2.1 Literature review

In order to obtain a clear and widely supported definition for the mobility hub, literature from North-America is firstly reviewed. A paper by Enbel-Yan and Leonard (2012) presents a guideline for introducing a successful mobility hub. The paper describes mobility hubs within a city in Canada, along with their typology. Mobility hubs are described as a place of connectivity where different modes come together seamlessly, combined with a high concentration of employment, living, shopping and/or recreation. These two roles of a mobility hub (the mobility and economic role) are extensively described in this research. Additionally, this paper emphasizes the need for an integrated approach: The planning of a mobility hub must be intertwined with, among others, land use planning and transit operations. The inclusion of shared mobility services in the nodes is not discussed in this paper.

In a report by Anderson et al. (2015), in which a suitability analysis for a mobility hub in the San Francisco (United States) Bay Area is performed, a definition for the mobility hub is established. The mobility hub is a place where multiple modes or services come together in a single location, resulting in travel time or cost savings for travelers using the hub. 'Identifying Best Practices for Mobility Hubs' by Aono (2019) is another report exploring the mobility hub concept. In that report, the used definition for the mobility hub is an area where multiple sustainable transport modes seamlessly come together and connect.

In a webinar by the San Diego (US) regional public planning agency (Clementson et al., 2019), it is described that mobility hubs are placed to extend the reach of transit by leveraging shared mobility services and supporting technology. Mobility hubs should be built near high-frequency transit, with a concentration of employment, shopping, housing and recreation. In this type of areas, the potential of a mobility hub is at its maximum. The mobility hub makes it easier to travel, and is also usable for short trips in a community. This reduces the dependence on the private automobile, and therefore aims to reduce congestion.

A relevant thesis on living as a service (Li, 2020), in which a definition of mobility hubs is given, defines the mobility hub as follows: "*A mobility hub is a physical place that integrates mobility functions and other facilities that benefit the neighborhood. By providing a variety of sustainable travel options and living facilities, the mobility hub facilitates residents' travel and daily life.*" This definition is based on both North-American and European literature.

Following North-American literature on mobility hubs, the focus is shifted to European literature. In Munich, carsharing and bikesharing systems have been operating since 1992 and 2000 respectively. A paper by Miramontes et al. (2017) investigates the impacts of these mobility services on travel behavior. The mobility hubs under investigation in this paper are nodes in the transportation network providing different mobility options with a small transfer distance between the modalities. Public transport is combined with a shared mobility service at the hubs, and integrated in terms of trip planning, access, marketing and/or tariffs. The mobility hub consists of carsharing places, bikesharing docks, bike parking, EV charging, a taxi stand, information screen and a public transport stop.

A European consortium led by the city of Amsterdam introduced the eHubs project (L. van Gils, 2019a) in order to reduce emissions and reduce pressure on public space. An eHubs is a adaptation of the mobility hub, with additional focus on the zero-emission aspect of the hub. The definition of an eHubs is: "An eHub is a physical cluster of different transport modalities." Multiple zero-emission and shared modalities are offered at the eHub.

On the website of a traffic magazine (Rottier, 2020a), two mobility advisors discuss the definition of a mobility hub. Next to mobility services, facilities are offered like restaurants/cafes, parcel storage etc. The design of the hub and the included additional facilities have a big impact on the success. Accessibility to the region is important for the number of users and their travel time. A thorough location research is needed, and the biggest challenge is the regional mobility hub location. This is due to the focus on developing city hubs over the last decade.

In a workshop during the parking congress 2019 in the Netherlands (Vexpan – Platform Parkeren Nederland, 2019), the difference between a mobility hub and transferium (Dutch term for a Park&Ride at a distance of the city center) is discussed. The mobility hub distinguishes itself by offering more (shared) modalities than a transferium offers, and other facilities can be included in this hub. An example of such a facility is a parcel pick-up point, which is currently relevant because of the rise in online purchases. The mobility hub should find a balance in level of service, in four different fields: spatial (offices/residential/sport), facilities (like parcel/grocery pick-up points), new multimodal services (like bike/car sharing) and transport networks (bus/car/train/walking). van Loon (2020) states that a mobility hub at the activity side is actually a transferium, where different (sustainable) modalities can be chosen for the transportation to the city. At the residential side, the mobility hub is a parking facility for the region, with the addition that shared mobility is provided. Combining both the residential side and activity side hub into one location, close to a public transit node, leads to the most interesting location for a mobility hub.

In the so-called Deltaplan Mobiliteitsalliantie (2019), a report produced by the Dutch mobility alliance (in which mobility-related parties are represented) on mobility in 2030, the mobility hub has an important role. Hubs can serve as easy transfer point in a city or at the city edge, or as regional public transport access point to make the multimodal trip attractive. Furthermore, a mobility hub can be a smart combination of mobility, retail, parking and other facilities. Hubs are defined as a place where private, public and shared transportation connect.

In the sparsely populated Dutch provinces of Groningen and Drenthe, an extensive network of over 50 mobility hubs is already in service (Reisviahub.nl, 2020). These hubs are public transportation nodes branded as hub, where transfer between modalities is possible and additional facilities are offered. The main focus of the mobility hub is the traveler's experience and convenience. Lastly, the Dutch mobility hub operator Hely, with 19 mobility hubs in The Netherlands currently in service, identifies a place where a few shared vehicles and bikes are offered as a mobility hub (Hely.com, 2020). A public transport connection is not a prerequisite for a hub, according to Hely.

2.2.2 Adopted definition

What comes forward from all literature, is that the mobility hub connects multiple modes, ranging from public transport and private vehicles to shared bikes and cars. The sustainability of modes is stressed in some literature. Furthermore, the mobility hub has an economic function, offering additional services and facilities, in order to add value to the trips of the users. The adopted definition of the mobility hub is broad enough to encompass most defined mobility hubs from the literature and allows for the integration of additional features. This definition is as follows:

The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, possibly including other features, ranging from retail, workplaces to parcel pick-up points.

2.3 Typology

2.3.1 Literature review

Enbel-Yan and Leonard (2012) distinguish mobility hubs based on several characteristics: The urban context of a hub is distinguished (from inner-city to car-oriented suburban location), and the transportation function, with the hub being an origin, transfer or destination hub. In this literature review on the typology, the urban context will be the main identifier for a classification, in which the **residential urban context**, **city center urban context** and **regional urban context** are distinguished. The word 'regional' is used here as being opposite to the city center, and can be anything ranging from a rural area to a mixed land-use suburb. The aim in this subsection is to find out what characterizes the three different hub classes, with regard to the function in the network and the potential users.

In an article by Bell (2019), the attributes of intermodal transport hubs are described. Four different forms of hubs are distinguished, these forms can basically be categorized in two urban contexts: the city center hub, located in a **city center urban context**, the suburban hub and regional center placed in **regional urban context**, whereas the small gateway hub can be placed in any urban context. The small gateway hub is a basic bus stop with minimal facilities. The regional center is an interface between motorized and public transport, mainly serving commuters.

Aono (2019) distinguishes multiple typologies for the mobility hub, the typology by function in the transport system, and the typology by urban context. In this report, a classification described by the LA Urban Design Studio is mentioned, in which three types of hubs are identified: the neighborhood, central and regional hub. Regional hubs are located in **city center urban context**, which is confusing because regional has a different meaning in this literature review. These hubs offer the largest number of facilities and modes. Central hubs are positioned in a lower density urban context, so a **regional urban context**, and offer amenities like bike and car sharing, whereas neighborhood hubs are small in size, in **residential urban context**. Four examples of mobility hubs are given here, one from Canada and Germany and two examples from USA. In Canada, the mobility hub has the function of being an access point for the surroundings, as well as increasing the connectivity in the area. The examples in USA present mobility hubs that are not very different from a large train station, with extra focus on cyclists and pedestrians. The German mobility hub is a typical neighborhood hub (in **residential urban context**), with bus and train stops nearby.

Li (2020) identified six hub types, based on the document by CoMoUK (2019), namely:

1. Large interchanges: Hubs in a **city center urban context**, with high passenger numbers, focused on public transport and shared mobility because of limited space for private vehicles.
2. Small interchanges: Offer a choice of modalities to people for the first or last mile. This hub is placed outside of a city center, in a **regional urban context**, to link residents to the main public transport network.
3. Suburb hubs: Hubs in a **residential urban context**, in areas with a high average private vehicle possession, built to offer shared mobility to residents. Public transportation can be added to this type of hub.
4. Village hubs: Hubs in smaller towns, so a **regional urban context**, meant to increase the transport options at public transport nodes by offering shared modalities.
5. Business hubs: Hubs in business parks, outside of a city center so in a **regional urban context**, with a high user density, serving commuting trips, possibly connecting to regional public transport.
6. Tourism hubs: Hubs, often placed in rural areas (**regional urban context**), to facilitate tourism, with a specific focus on an easy-to-use system.

In the eHubs project, three transport system functions and corresponding hub types are distinguished (L. van Gils, 2019a):

- Interregional connections hub: Facilitates travel between regions, extensive mode choice, large number of travelers. A large train station is categorized in this class. This type of hub is generally situated in a **city center urban context**.
- Regional connections hub: Public transport connections available, large parking space might be included. This type of hub is usually placed at the edge of a city (center), so in a **regional urban context**.
- Neighborhood hub: Shared mobility available for residents of the neighborhood, small in size and demand, not always served by public transportation. This hub is placed outside of the city center, in a **residential urban context**.

In a thesis provided by van den Berg (2020), a research on the added value of mobility hubs in the Dutch transport system is executed. In this thesis, some desk research on definitions and a typology of mobility hubs can be found, leading to the identification of four hub types:

1. Residential hub: reduce car possession by offering shared mobility services in a neighborhood, so placed in a **residential urban context**.
2. City hub: improving quality of life in the city, while reducing congestion, focus is on bike/car sharing in a **city center urban context**.
3. Regional hub: improving reach of public transport network, and/or facilitating park and ride intermodal transportation in a **regional urban context**.
4. National hub: increasing the choice for last mile transportation at large transit stations by offering shared mobility services, mostly in a **city center urban context**.

From the mobility vision document of the Dutch province of Gelderland Provincie Gelderland, Goudappel Coffeng, and APPM (2020), five types of hubs can be identified, being the city, outskirts, regional, rural and residential hub. The city hub is the largest one (placed in **city center urban context**), and could be represented in the form of a large central train station. The residential hub is a small hub (in a **residential urban context** or **regional urban context**, depending on the land use) in a neighborhood, industrial area or campus offering shared mobility services to the residents and visitors. The outskirts, regional and rural hub are positioned further outwards from the city center (in a **regional urban context**) and serve as transfer point in the transportation network. In the future mobility vision document of the province of Noord-Brabant, the mobility hub is an important transfer point between public transport and shared mobility. These hubs can be located at train stations, or at the outskirts of middle-sized cities and small towns, so in **regional urban context**.

A document describing the steps to be taken to introduce mobility hubs (Atkinson et al., 2020) distinguishes several possible variants of the mobility hub, for passenger, cargo and both passenger and cargo traffic. The hubs variants for passenger traffic are as follows:

- Regional hub: A hub with a large service area, connecting small flows from the service area to the main road, rail and/or high-quality public transport network. The goal of this hub is to offer a range of multimodal options, so multimodal travel can be considered by unimodal travelers. This hub is placed in a **regional urban context**.

- Transfer hub: A hub situated at a city edge, in a **regional urban context**, to facilitate trips by public transport or other modalities to the destination. The goal of this hub is to switch passenger flows from outside of the city to the optimal modality for use in the city, which are mostly sustainable modalities that use less space than the private vehicle.
- City center hub: Situated in a **city center urban context**, positioned at a node in the public transport network. The goal is to make the place around the hub more attractive, and to offer a diverse range of modalities.
- Business hub: Situated at a business park in a **regional urban context** to provide shared mobility and a limited number of parking spaces for commuter and business trips. The goal is to stimulate employees to commute with a sustainable modality (public transport, bike).
- Residential hub: A hub placed in a **residential urban context** to provide shared vehicles near people's homes. This way, parking issues can be reduced, resulting in a higher quality of life in the neighborhood.

The business and residential hub are not required to have a connection to public transport, but a public transport connection can increase the functionality of a hub. The other three hub types must be connected to the public transport network.

2.3.2 Adopted classification

A distinction was made between mobility hubs in a **city center urban context**, **residential urban context** and **regional urban context** in the literature review. An indicator of the urban context is defined by CBS (CBS, nd), in which the city center is defined as an extremely urbanized area with an address density of more than 2500 addresses per square kilometer, which qualifies areas with an address density of less than 2500 addresses per square kilometer for a regional mobility hub. As the residential mobility hub is placed in a residential area, non-urbanized areas with an address density of less than 500 addresses per square kilometer do not qualify for a residential mobility hub. Next to this classification based on the urban context, other factors are identified that characterize a hub placed in the corresponding urban context. These factors are the function in the transport system and the offered modalities, and the characteristics are described per hub class in the following paragraphs.

Residential hub A mobility hub can be placed within a neighborhood to serve as a residential hub to provide transportation to the inhabitants. In Bremen, Germany, a large system of this type of mobility hubs was implemented. Hely also uses this concept in the Netherlands. The reach of this hub is generally small, only providing shared mobility for the inhabitants in the direct surroundings of the hub. The size of these hubs and the shared vehicle fleet is small, as the demand is small. These hubs are not specifically located at a public transport stop. The motive for placing this type of hub is often a desire to reduce the private car possession in neighborhoods with a high average vehicle possession. By placing a residential hub, inhabitants are still able to drive in a vehicle without owning one. Furthermore, the residential hub can help in decreasing the parking pressure, leading to a higher quality of life in the neighborhood. This type of hub will be mostly used for unimodal trips, as there is often no connection to public transport services. These hubs should be placed in urban context, because a non-urban location is less effective, as only a small number of residents will live in the limited catchment area of this hub when placed in a non-urban context.

Regional hub A mobility hub can be placed outside of a city center, to improve the reach of the transit network and increase the number of transport options for commuters and visitors by offering shared mobility services. This stimulates the usage of shared mobility and public transport for all target groups, to decrease greenhouse gas emissions. The regional mobility hub facilitates multimodal trips by offering shared mobility, public transport and car parking, so the connecting function of the hub is important. These hubs link residents of the catchment area to the main public transport network. For the residents, shared mobility is of less importance, as this target group often has a private vehicle/bike available. This type of mobility hub should be placed at a current or future transit stop to offer the link to the network. This connection is also suggested by Talen et al. (2018), a report in which it is stated that regional and national shared mobility concepts should be linked with public transport to fulfill a connecting function in the network.

When placed at the outskirts of a big city, this hub can also serve as interface between motorized and public transport, called a Park&Ride facility, for commuters and visitors of the city. The goal of such a facility is to switch passenger flows to the optimal modality for use in the city. This way, the quality of life in the city can be increased by decreasing the number of private vehicles in the served city. Nevertheless, the facility itself requires a large parking area. The provinces of Gelderland and Noord-Brabant plan to build this type of hub in The Netherlands. A large example of such a hub is the mobility hub at De Kempen-A67, where a high-quality public transport system will provide connections to the big cities in the region (Gemeente Bergeijk, Gemeente Bladel, Gemeente Eersel, and Gemeente Reusel-De Mierden, 2020).

City hub A mobility hub can be placed at a public transportation node in a city to increase the number of transport options to reach the city center. The main goal of this hub is to improve the accessibility of the city center for residents, visitors and commuters. This can make the usage of public transport to reach the city center more attractive, resulting in less travelers (visitors/commuters) using the car to reach the city center. That way, the city hub can relieve congestion from/to the city and improve the quality of life by reducing local greenhouse gas emissions and the need for parking areas in the city center. This type of hubs connects all sorts of shared modalities, and must connect with a bus rapid transit/tram/metro or train station. Private cars play a small role in this type of hub, as space in urbanized areas is limited. Due to the high number of passengers using this hub, the activity role in this hub is important, making the hub an attractive place to stay. The hub itself can even be a destination. This is the main type of mobility hub that can be found in North-America, for example in Denver, Colorado (Aono, 2019, p. 22). Contrary to the regional mobility hub, the city mobility hub is placed in extremely urbanized areas, with a address density of over 2500 addresses per square kilometer (CBS, nd).

Table 2.1: Mobility hub classification

	Residential mobility hub	**City mobility hub**	**Regional mobility hub**
Urban context	>500 addresses/km^2	>2500 addresses/km^2	<2500 addresses/km^2
Modes offered	Shared mobility	Shared mobility, PT	Shared mobility, PT, car parking
Transportation function	Provide alternative to car possession	Improve city's accessibility	Improve reach PT, provide alternative to car usage
Target groups	Residents	Residents, visitors, commuters	Residents, visitors, commuters

2.4 Mobility hub features

2.4.1 Literature review

To assist in the mobility hub design process, the necessary and optional facilities/features of the mobility hub are gathered from the literature and linked to the involved stakeholders. The features are classified into four categories, conforming to the thesis of Li (2020). The four categories, being **public transportation, shared mobility, mobility related facilities and non-mobility related facilities**, are visualized in Figure 2.2.

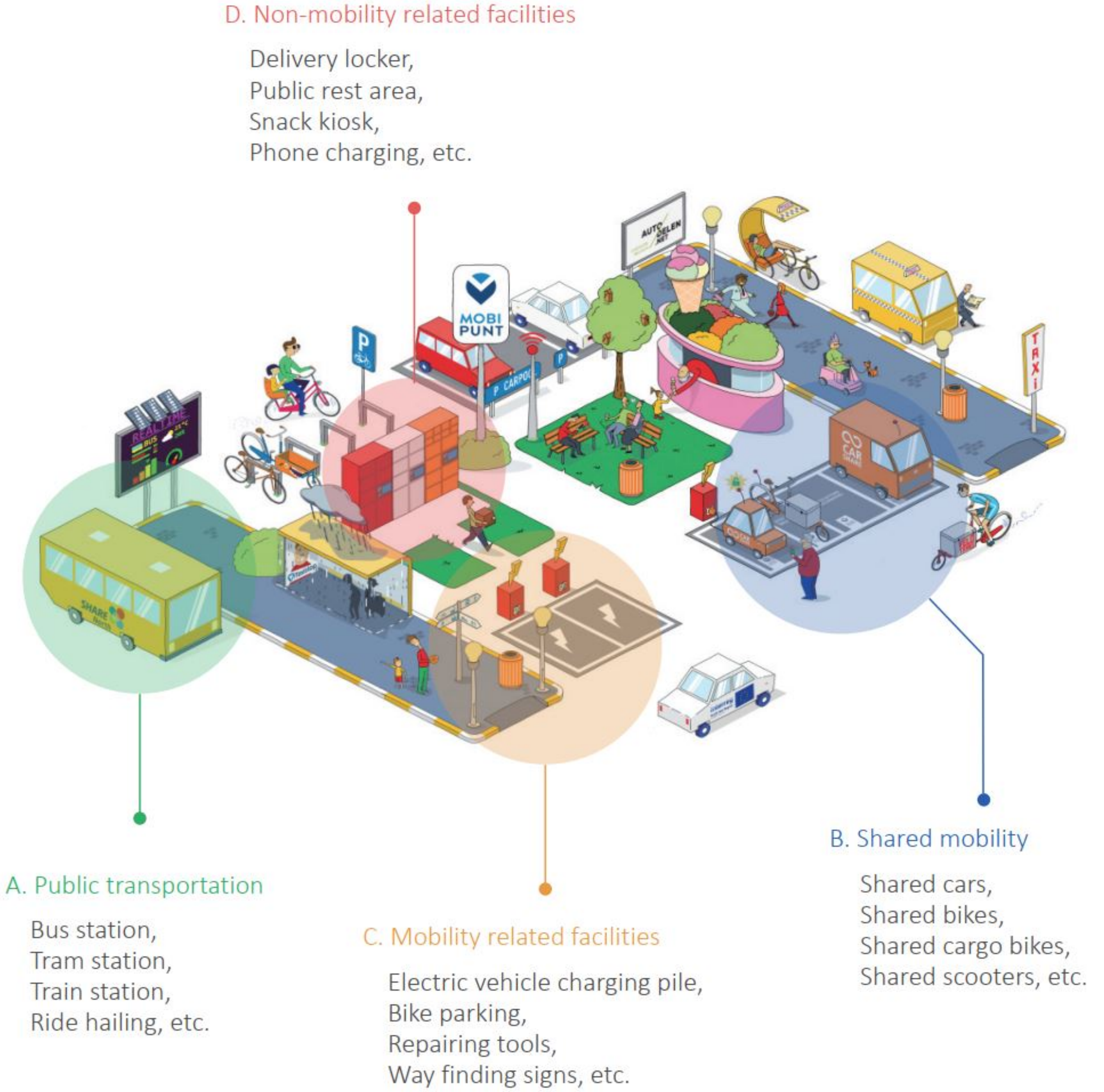

Figure 2.2: An example of a few mobility hub components, placed in the four identified categories (Li, 2020).

As named in section 2.2, Groenendijk (2015) presents a thesis in which the experience value of the traveler is researched. Weights are obtained for the importance of certain objective criteria on the experience value and these weights are visualized in Figure 2.3.

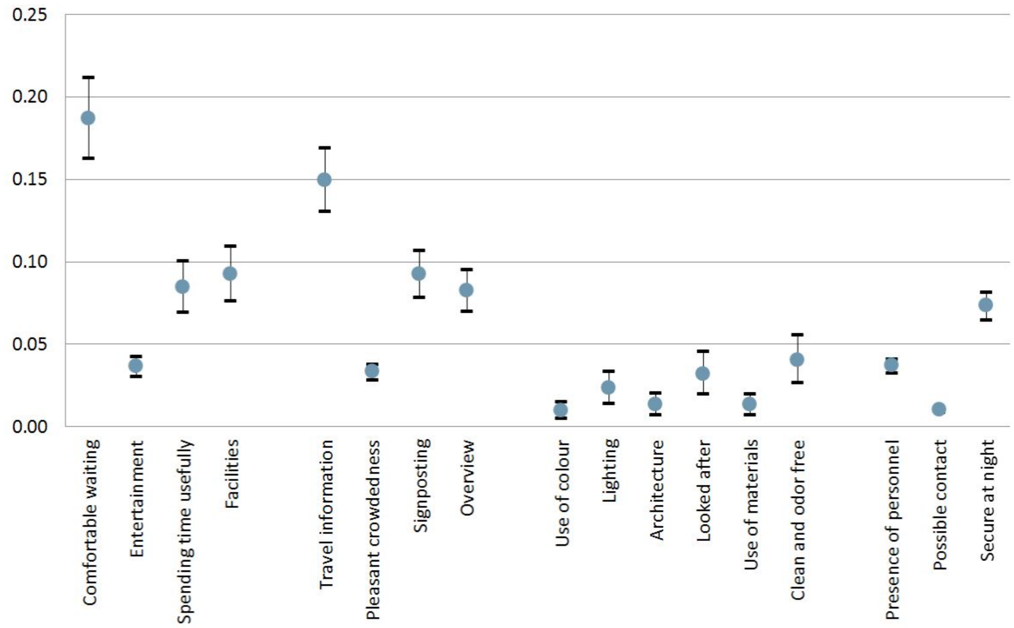

Figure 2.3: Weights criteria on experience value (Groenendijk, 2015)

The most important criterion of this experience value is the comfort criterion, found in **non-mobility related facilities**. This criterion accounts for 83% of the experience value of the traveler. Some of the used criteria are subjective, so given a certain feature of the mobility hub, the resulting experience value will differ per person. This makes it difficult to include in a model, however the criteria with larger weights will logically lead to more important features of the mobility hub. Criteria with high weights from this thesis are travel information (**mobility related facilities**) and comfortable waiting, while spending time usefully, facilities, signposting, overview and security at night (**non-mobility related facilities**) are significant as well.

In the vision of Enbel-Yan and Leonard (2012), a mobility hub is comprised of a rapid transit station (**public transportation**), serving the surrounding area reachable within a walking distance of 800 meter. This station is important in the regional transport system, as origin/destination/transfer point. Important stakeholders that are involved are named by the paper: landowners/developers, local transit agencies and municipalities. Further noticed in this paper is the high level of pedestrian priority which should be provided in a mobility hub, with connections and spaces designed for pedestrians (**mobility related facilities**). Also, seamless transfer between modalities and a vibrant and vital place (**non-mobility related facilities**) are named as important characteristics of a mobility hub. Parking facilities (**mobility related facilities**) are marked as important in North America, though the hub has to remain compact.

In a paper on user needs concerning mobility hubs (Bell, 2019), an overview of the user requirements at public transportation nodes is given. Some basic needs are identified, being accurate and reliable information on public transportation and route choice (**mobility related facilities**), which need to be provided at every mobility hub. Additionally, there is a further demand for facilities from specific user groups, including these can increase the potential of a mobility hub. These facilities are (weather) protection, safety & security, entertainment, a barrier-free hub and (food) retail facilities (**non-mobility related facilities**).

An architecture website discusses a new design for a mobility hub in Mechelen, Belgium (Polspoel, 2020). This hub is a Park+Ride facility at the city limits, in an appealing building with a public green garden, event square, offices and retail facilities (**non-mobility related facilities**). The focus of this building is on sustainability, flexibility and adjustability.

For a mobility hub in Munich, Miramontes et al. (2017) describes some mobility hub functions and how often they are used by the customers. Public transport (**public transportation**), free-floating carsharing, bikesharing, taxi service (**shared mobility**) and a bike parking (**mobility related facilities**) are the most frequently used features. The on-site information screen (**mobility related facilities**) is used rarely, which could be caused by the usage of smartphones, as all relevant information is currently provided on the smartphone as well.

For the design of a Park&Ride facility in The Netherlands, an overview of the indicators that can be improved to lift the usage of the facility is given by the Dutch knowledge platform CROW (CROW, 2020). The list of indicators is as follows:

- Travel time via the facility: Should be kept as low as possible.
- Distance to the highway, public transport travel time and frequency are important indicators.
- Costs: Parking fares should be kept as low as possible. (Operational, so excluded from the features)
- Security: Security of the visitors and cars parked at the facility should be guaranteed. Lighting, surveillance cameras or physical surveillance and the right lay-out can contribute to achieve security. (**non-mobility related facilities**)
- Parking probability: The traveler will be less prone to use this terrain if there is a chance the facility is fully occupied. (Operational, so excluded from the features)
- Walking time: The walking time to the public transportation stop should be kept as low as possible, while making this walking route attractive. (**mobility related facilities**)
- Road surface: The quality of the road surface has an impact on the attraction of the facility. (**mobility related facilities**)
- Information: Travel information should be provided by screens at the facility. (**mobility related facilities**)
- Features: Additional features like toilets and retail increase the attraction of the facility. (**non-mobility related facilities**)

A potential scan of Mobility as a Service in The Netherlands describes the significance of certain criteria for the decision to buy a MaaS subscription, based on two researches from Finland and Australia (Koopal et al., 2020). Relevant modes in this subscription are public transport (**public transport**) and car sharing (**shared mobility**), while the inclusion of taxi and bike sharing (**shared mobility**) does not have a significant effect on the adoption of a subscription among users. Bike sharing is a modality of which the adoption strongly depends on the researched region, as cycling is more important in The Netherlands compared to other European countries. Nevertheless, this modality is upcoming in other Western countries as well and might play an increasingly large role in the future mobility system. Given this fact, public transport, bike sharing and car sharing should be included in a regional/city mobility hub.

Clementson et al. (2019) describes that a mobility hub is built up of the five following feature categories:

- Shared mobility services: Transit (**public transport**), Bikeshare, Rideables, Scootershare, Carshare, On-demand rideshare, Microtransit, Neighborhood electric vehicles (**shared mobility**)
- Pedestrian amenities: Walkways, Crossings (**mobility related facilities**)
- Bike amenities: Bikeways, Bike parking (**mobility related facilities**)
- Motorized service amenities: Wireless EV charging, Smart parking, Autonomous & Connected vehicles (**mobility related facilities**)
- Support services & amenities: Real-time travel information, Electric vehicle charging (**mobility related facilities**), Wayfinding, Package delivery, Mobile retail services (**non-mobility related facilities**)

Furthermore, intelligent transportation solutions, like the introduction of a universal transportation account, can be provided to improve the potential of a mobility hub.

2.4.2 Stakeholders

The next step in the research on the mobility hub is to identify the involved stakeholders, to be able to distinguish the necessary and optional features for a mobility hub. As named in a strategic report on mobility hubs in Scotland (SEStran, 2020), stakeholder engagement is of main importance in order to successfully implement the mobility hub. Their interests should be used to design the hub. The stakeholders can be categorized relating to the three chosen perspectives, the end user, operator and government perspective. This classification is in line with the stakeholder categories in the eHubs project (L. van Gils, 2019b), with the remark that the operator represents both the public transport and shared mobility providers. Additionally, some stakeholders can be categorized as 'other' stakeholders, not associated with any of the three perspectives. All involved stakeholders are summarized in the following list. The stakeholders are obtained by consulting the literature mentioned in this chapter, an internet research and meetings with experts at Sweco.

End user perspective

- Residents within catchment area
- Tourists, visitors in the area
- Surrounding companies and their employees (commuters)

Operator perspective

- Public transport companies: Local/national rail operator, concessionaire, infrastructure manager, long distance bus companies
- Bike/car/moped sharing companies
- Ridesharing companies
- Taxi companies
- Postal services
- Retail companies
- Electric car/bike charging facility provider
- Software/Trip planning/Ticketing providers

Government perspective

- Government (province, municipality, national))
- International sustainable mobility cooperation and innovation projects

Other perspectives

- Hotels/local non-retail companies
- Land owners
- Environmental organizations
- Local artists

The stakeholders excluded from this project are the developers and possible funding providers. Including these will be important in a further stage of the hub development, but for determining the hub features, these stakeholders will not be considered yet.

2.4.3 Stakeholder wishes

End user perspective From the end user perspective, the goal is easy to define: reach the destination at the lowest cost, as quickly as possible and as comfortably as possible. Car and bike parking facilities contribute to this goal for the residents in the catchment area of the hub, as a significant part of this group owns a private vehicle/bike. Shared mobility will be less important for residents, but the presence of shared mobility can drastically reduce the travel time of visitors and commuters. On the mobility/non-mobility related facilities, a research on the traveler's experience value in public transport nodes in Rotterdam (Groenendijk, 2015) uncovers the elements that play a role in the wishes of the travelers. Four sub criteria are found to be important: comfort, ambient elements, social elements and station organization. Ambient elements describe the general look of the physical structure, social elements the security and personnel in the node, station organization the signing, information and overview, and comfort is dependent on comfort levels and facilities. A sheltered and heated waiting area improves the traveler's experience. Furthermore, entertainment elements, grocery stores, Wi-Fi, restaurants, toilets and shops are facilities that result from the user wishes. Additionally, it should be ensured that disabled people can safely use the mobility hub. Therefore, these users have additional accessibility wishes, like the presence of lifts, navigation for the visually impaired, and speakers to announce important travel information.

Operator perspective From the operator perspective, the most important feature of the hub is the inclusion of the mobility service offered by the operator. A taxi stand, bike/car/PLEV-sharing facility, parcel locker, charging facility and bus/tram/metro/train platform can therefore be included. Furthermore, the provided service should be supported to ensure a high quality of service, so transit lanes or bus priority are wishes of the public transport operators. To realize the integration of the mobility hub in terms of software, adjustments to the current trip planning and ticketing system are required. Currently, trip planning and ticketing services are provided by software companies working closely with the public transport companies, these companies can therefore be placed in the operator perspective. The provider of the smart card/ticketing system might expand their card system with the possibility to pay for car/bike sharing with this card. As these adjustment of the system lead to higher costs for the operators, this implementation is preferred to be as easy as possible. The focus in this thesis is not on the software implementation of the mobility hub, more information is provided in Appendix A.

Government perspective As for the government perspective, literature can be found in governmental documents. Mobility vision documents are widely available across the internet, like the vision of two Dutch provinces, Gelderland and Noord-Brabant (Provincie Gelderland, Goudappel Coffeng, and APPM, 2020; Provincie Noord-Brabant, 2018). In general, the government also follows the user needs, with the notion that the society in total should benefit from the mobility hub as well. Furthermore, traffic safety is very important from this perspective, so wide and safe cycle paths with priority are often named in governmental documents.

The mobility hub should contribute to the social inclusiveness from the government perspective. All user groups should profit from the introduction of a mobility hub, not only the commuters, but also elderly and disabled people with different needs. Therefore, the accessibility needs of all user groups are important from the government perspective as well.

Additionally, the government and region have to keep the climate agreements in mind. In the Paris Climate Agreement, signed in 2015, it is agreed that global warming should be limited (Government of the Netherlands, 2019). Therefore, emissions need to be reduced, so from a government perspective, sustainable transportation is a must. This leads to the facilitation of only low-emission modalities at a mobility hub. Furthermore, the integration of solar energy collectors at the mobility hub further increases the sustainability of the facility, contributing to a reduction in emissions.

Lastly, the land usage of the hub is important from the government perspective, because the municipalities are responsible for urban planning and the allocation of functions to certain land areas. Therefore, from the government perspective, integration of multiple non-mobility related functions in the mobility hub is desirable, so land use can be limited. This implies a more efficient use of space, one of the priorities of the municipalities and regions in a densely populated country like the Netherlands. In less densely populated countries, the inclusion of facilities plays a minor role for the government.

Other perspectives Surrounding hotels may benefit from the introduction of a mobility hub, and can also be involved in the process, to potentially integrate the hotel function into the mobility hub. Local artists may provide art in the hub area, which can improve the attractive force of the mobility hub, so travelers are more intended to use the hub.

Land owners should be kept satisfied, this group is only involved when land should be purchased to establish the mobility hub. Environmental organizations should be kept informed, because the construction of a mobility hub might have environmental consequences. As the mobility hub is a sustainable innovation, there will be less resistance from these organizations. No mobility hub features follow from these organizations.

2.4.4 Adopted mobility hub features

A selection from the possible mobility hub features should be made in order to have a defined hub to proceed with. For this selection, the literature in this section is used, especially the lists presented on the features in Aono (2019); Clementson et al. (2019); CoMoUK (2019); Groenendijk (2015); Li (2020); Reisviahub.nl (2020). In these lists, a variety of possible features of a mobility hub are identified, with considerations to incorporate when selecting mobility hub features of a certain category. The document by SEStran (2020) provides essential and optional components of different types of mobility hubs. Besides, the stakeholder wishes are taken into account in selecting the necessary/optional features. A complete overview of included features can be found in Table 2.2.

As explained in CoMoUK (2019), there is no 'one-size fits all' mobility hub design possible, but this should be evaluated case per case. Both the offered facilities and size of the hub depend on the location and surroundings of the hub. This also comes forward from the literature, a highly cited paper from Bertolini (1999) introduces a model that explains that the accessibility of a node and activities around a node should be in balance. There is no general hub that fits in every environment, meaning that the design of a hub should be dependent on the place. Therefore, the list does not describe exactly which elements should and should not be included in the hub, but the list serves as guideline for the necessary, optional and superfluous features of the three hub classes.

Table 2.2: Mobility hub facilities per category

Mobility hub facilities				
Category	**Attribute**	**Residential**	**City**	**Regional**
Public Transportation	Bus/tram/metro stop	Optional	Yes	Yes
	Train station	No	Yes	Optional
	Microtransit	No	Optional	Optional
Shared mobility	(Cargo) Bikesharing	Yes	Yes	Yes
	Carsharing	Yes	Optional	Yes
	Other (PLEV/scooter/e-bike) vehicle sharing	Optional	Optional	Optional
	Taxi stand	Optional	Yes	Optional
Mobility related facilities	Car wash	Optional	No	Optional
	Additional rental facility (trailer, child car/bike seat)	Optional	Optional	Optional
	Ridesharing/carpooling	No	Optional	Yes
	Kiss+Ride zone	No	Yes	Yes
	Car parking area (smart parking)	Yes	Optional	Yes
	Bike parking (secure)	Optional	Yes	Yes
	Electric vehicle charging infrastructure	Yes	Optional	Yes
	Travel information/trip planning (screen/kiosk)	No	Yes	Yes
	Bike repair tools	Optional	Yes	Yes
Non-mobility related facilities	Comfortable waiting facilities (benches, shelter)	Optional	Yes	Yes
	Lift	No	Yes	Optional
	Signposting	Optional	Yes	Yes
	Security at night (surv. cameras, lighting)	Yes	Yes	Yes
	Tactile information	No	Yes	Yes
	Office space	No	Optional	Optional
	Hotel	No	Optional	Optional
	Tap water	No	Yes	Yes
	Wi-Fi availability	Optional	Yes	Yes
	Power/USB outlets	No	Optional	Optional
	Luggage lockers	No	Optional	Optional
	Artwork, Urban realm improvements	Optional	Optional	Optional
	Catering facilities	Optional	Yes	Optional
	Toilets	Optional	Yes	Yes
	Retail facilities	Optional	Yes	Optional
	Parcel/library/pharmacy/other pick-up point	Optional	Yes	Optional
	Fitness facilities	Optional	Optional	Optional
	ATM	Optional	Optional	Optional
	Green environment (park/lawn)	Optional	Optional	Optional
	Child facilities (play area/daycare)	Optional	Optional	Optional
	Solar energy collectors	Optional	Optional	Optional

2.4.5 Focus in thesis

The mobility hub type for which the location potential determination methodology will be developed in this thesis is the regional hub. This choice is made on the basis of the following argumentation:

- Out of the three hub classes, the regional mobility hub has the broadest mobility function: improving the reach of the public transport system and providing an alternative to car usage. Therefore, the regional mobility hub is a very promising innovation. Looking into the mobility function, there is less need for a methodology to determine the potential of locations for a residential mobility hub. This type of hub is mostly intended to facilitate shared mobility for residents, without the necessity of connecting to the public transport system. Next to that, the catchment area is generally small, and the hub is small regarding its size, because the demand is typically small. All in all, much less factors will be involved in the process of finding a suitable location for a regional mobility hub. Furthermore, the residential mobility hub is usually developed in combination with neighborhood developments, so a location potential determination methodology is unnecessary, as the location of the neighborhood is known.
- A generally applicable framework to determine the potential of locations for a city mobility hub is very hard to establish, as location-dependent factors play a larger role in this type of hub than for the regional hub due to the limited space available in cities. For this reason, a combination of the city hub with existing facilities is often studied. This means that the location depends heavily on the locations of existing public transport nodes, so there is no need for a general methodology to determine the potential of all areas in

a city for a mobility hub. Instead, the choice is often made by policy makers to upgrade a current public transport node (at a predetermined location) to a city mobility hub.

- Within the consulted literature, it is named that the biggest challenge in mobility hub location research is the determination of a regional mobility hub location. Very little is known on possible locations for a regional mobility hub, so a location potential determination methodology is of high relevance. However, the limited amount of available information increases the difficulty of establishing this methodology. Using the knowledge available at Sweco and the consultation of additional government documents, this difficulty is handled.

2.5 Mobility hub location

The previous sections are mostly related to the attraction of the hub itself. Using the overview of necessary and optional functions, the potential of the hub can be maximized from the functional point of view. All other factors determining the potential of the location of the mobility hub are elaborated on in this section. The following sub question will be answered: "Which factors affect the potential of a regional mobility hub location?".

In order to find the answer to this question, literature will be reviewed, where after the influential factors are identified and categorized. The dependent variable in this research is the potential for a mobility hub placed in an investigated area. Both the economic and mobility function of the mobility hub can alter the potential of a location for the introduction of a mobility hub, so these functions will both be researched. As the developed methodology should take the three (end user, operator, government) perspectives into account, the stakeholder interests with regard to the regional mobility hub location are identified. Using information on the economic function, the mobility function and the stakeholder interests, a complete overview of factors influencing the location potential for a regional mobility hub is developed. Lastly, a justified elaboration of the excluded factors is given.

2.5.1 Economic function

Not only is the mobility hub a place at which multiple modalities come together, but a hub also offers additional facilities attracting people to use the facility. This economic function of the hub might have an impact on the potential of a location, as the presence of facilities might indicate a higher demand for those facilities, and ease the integration of the mobility hub at a selected location.

More than 20 years ago, Bertolini (1999) published an article on the development of public transport nodes. In this article, the node-place model is introduced, in which the accessibility and intensity of activities are visualized in a plot, as pictured in Figure 2.4. Dependent, accessible and under stress nodes are in balance, meaning that the accessibility and intensity of activities at the node are proportional. Two unbalanced situations can be identified, the unsustained node and unsustained place. In the unsustained node, transportation activities are more developed than activities around the node. In an unsustained place, the transportation activities are less developed than activities around the node, in other words: the accessibility of the node is disproportional, not developed enough. For both the place and node value of a public transport node, an index is developed, in which intensity and diversity of transport supply measure the node index, and intensity and diversity of activities in the walking distance (700 meters) of the node determine the place index. The goal is to keep those two indices in equilibrium, to achieve the most favorable mobility effects.

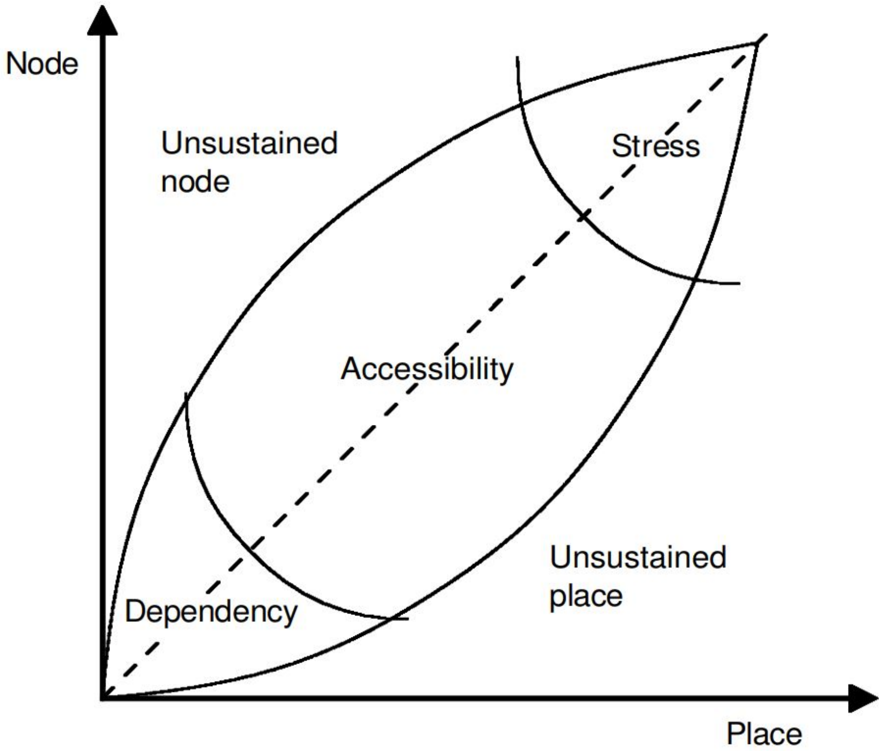

Figure 2.4: The node-place model by Bertolini (1999). Points close to the dashed line are in balance.

In an analysis of public transport nodes in the Dutch province of Utrecht (Gerretsen et al., 2018), the node-place model is converted into the so-called butterfly model. In this butterfly model, six indicators are important: Slow traffic, Public Transport, Roads, Intensities (visitors, employees, residents), Facilities and Neighborhood (quality, functions close to node). The first three indicators are related to the node (mobility) value, while the last three indicators relate to the place value of the node. This model explains that both values have to be in balance, meaning that a large place value requires a large node value, and the other way around. This is related to the supply and demand, as a large node value leads to a high demand for transportation, and a large place value means a high supply of transportation.

In this research, the recommendation is given to implement regional facilities around PT nodes, to increase the place value of a node with a high node value. The other way around provides more useful insights for the location choice of a mobility hub, as regional important facilities are sometimes linked to the road network only. Linking these facilities to the public transport network can provide the desired gain in the node value of these nodes. The importance of a regional facility is measured in number of visitors, jobs and places. These facilities can be for example a cinema, shopping mall or museum. A national park/landscape highlight is a point of interest attracting travelers as well. In the appendix of the document, an approximation of the number of visitors of several points of interest (regional facilities) is given. From the node-place and butterfly model, it can be learned that the economic function is strongly correlated to the mobility function of a node, so it should definitely be taken into account in the developed methodology.

In an interview with a program manager for the Dutch hub concept in the provinces of Groningen and Drenthe (Taxistop, 2020), it is named that social and economic facilities can give a location a higher potential for a regional mobility hub. The linking to facilities, like shops, retail or a library, should be incorporated early in the process to create a successful hub. Not only the transportation, the mobility function should be taken into account, but the socio-economic function as well. Therefore, this will be added as a criterion determining the potential of a location.

A case study on node upgrades carried out by the government for the vision of the future concerning public transport (OV-Toekomstbeeld), described in an internal document, elaborates the case of Druten, a town with a low to medium level of urbanization, located approximately 20 km west of Nijmegen, a large Dutch city. The node can possibly be combined with surrounding facilities, and shared mobility can strongly improve the catchment area of the node. A high quality node is created in this way, giving a boost to the direct surroundings.

The economic function is stressed once again in that document, and the potential added value of regional mobility hubs is pointed out.

2.5.2 Mobility function

The second function of the mobility hub is the (regional) mobility function. Before investigating this function, two aspects of the regional mobility hub are important to note. Firstly, the regional mobility hub is situated outside of the city center, in less urbanized regions, so literature concerning inner-city mobility patterns will be of less use. Besides, the regional mobility hub focuses on multimodal trips, as described in subsection 2.3.2, so research on unimodal trips is less relevant for this thesis. The literature on the mobility function of the mobility hub is therefore required to concern multimodal trips outside of the city center. Next to the limited research on mobility hubs, literature on Park&Ride locations can be taken into account as well, as multimodal trips are considered when looking at Park&Ride locations, and Park&Ride is a well-known concept, with lots of available literature related to the concept. As not enough literature might be available to obtain a complete overview of factors, the literature review is supplemented by literature on inner-city mobility and unimodal trips. In using that literature, the relevance for this thesis is analyzed.

2.5.3 Target groups

The distinction in mobility hub type is important as the target groups and therefore the demand differ for the different functions in the transport network. In the hub classification presented in subsection 2.3.2, the target groups for a regional mobility hub are shortly described: residents, visitors and commuters. As the mobility hub focuses on multimodal trips, literature on multimodal transfer points should be consulted for the potential target groups. This literature is found in the form of a Master's theses on transferia (Breedveld, 2010). In this thesis, the user groups involved when looking at a transferium are explained. These user groups are as follows, including their motivation for using the transferium:

- Inhabitants in the direct surroundings: The transferium is used as parking place and access point to the public transport network.
- Commuters to the city: The transferium will be the transfer point in the multimodal trip, as the car is parked at the transferium, and public transport is used to reach the city.
- Commuters from the city: This group leaves the city in the morning with their car, and uses the transferium to switch to public transport to continue their trip to another city center. This group is only relevant when the transferium is connected to the long-distance public transport system. The commuters in this group live at a large distance from a train station, probably outside of the city center, as the car is used to reach a station.
- Visitors of the catchment area: The transferium is used as parking place, from that point on the trip will be continued by foot or public transport to the destination.
- Business visitors: This group uses the transferium to reach their destination (office) in the catchment area of the transferium.
- Service visitors: Visitors of services/facilities close to the transferium, like a hospital, dentist or theater, use the transferium to park their car or arrive by public transport and continue their trip by foot.
- City visitors: Tourists and city visitors, for example for shopping purposes, use the transferium to park their car and continue their journey by public transport.

For the transferium, the most important target groups are commuters and visitors from/to the nearby city, as the transferium offers a mobility solution to bypass congestion on the road to the city and parking issues in the city. For the mobility hub, all target groups are equally taken into account. The comprehensive overview of the target groups potentially using the transferium is translated to three different functions of the mobility hub in the multimodal trip:

- The mobility hub as access/egress point close to the home end of multimodal trips. This mobility hub function is applicable to the resident target group, the inhabitants in the catchment area. This group generally owns a private vehicle/bike and uses this modality to arrive at the hub. In case the resident does not own a vehicle, a shared vehicle can be used, or the hub can be accessed by foot. The trip from/to the activity is covered by public transport.
- The mobility hub as access/egress point close to the activity end of multimodal trips. This mobility hub function is applicable to the following target groups: visitors of the catchment area, business visitors and service visitors. These groups arrive at the mobility hub by public transport and either shift to a shared modality in order to reach the activity, or the trip is continued by foot.

- The mobility hub has another function in the multimodal trip, and is typically being used as a transfer point. This mobility hub function is applicable to the following target groups: commuters to the city, commuters from the city and city visitors. The distance between the hub and the home trip end is typically covered by car or public transport. The private vehicle (if available) is usually not located at the activity end of the traveler's trip, so private transportation is in most cases not an option for this part of the trip. Therefore, the distance between the hub and the activity trip end is covered by public transport or a shared vehicle.

A graphical representation of the different trip end positions is given in Figure 2.5. Literature on all three functions needs to be considered to find out how the potential of areas for a regional mobility hub can be determined, so factors influencing the potential of a regional mobility hub situated at the home end of the trip, activity end of the trip and anywhere in between as a transfer location will all be studied in separate subsections.

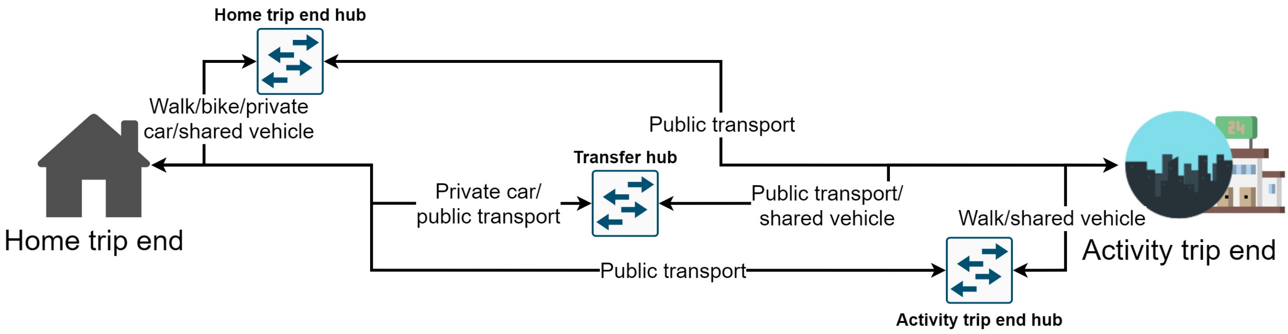

Figure 2.5: The possible hub trip end positions.

2.5.4 Home trip end position

In finding literature with regard to a mobility hub positioned at the home end of the trip, population characteristics are mainly pointed out. The challenge in this thesis is to convert the disaggregated way of investigating the potential for a regional mobility hub to aggregated factors. This translation is needed, because in evaluating the suitability of a location, the used point of view is not the passenger, but a broader point of view incorporating all stakeholder groups. This is necessary to fulfil the objective of this thesis, which is to incorporate all points of view.

In the state-of-the-art report from the eHubs project (Liao and Correia, 2019b), factors influencing preferences for shared e-mobility services are investigated. The scientific gap of the quantification of potential shared mobility demand at mobility hubs is mentioned, therefore academic literature on this topic is reviewed in the deliverable. The disaggregated and aggregated approach can be distinguished in literature, in which the choices of the individual, respectively system data are analyzed. Most studies in this report focus on the impacts of a single (shared) mode, whereas the effects of the integration of multiple modes in a hub is more relevant. Demand analyzes lead to a division of the influential factors in seven categories: system operational attributes, individual/household characteristics, psychological variables, transport connectivity, land-use variables, travel patterns and time varying factors.

The first category, system operational attributes, represents indicators related to the operation of the system. A certain system operation will be assumed before applying the location potential determination methodology, so this aspect will not be a variable in the method, and not further researched for the method. Additionally, time varying factors will be of less relevance for an aggregated calculation, since these factors are specific for every trip. The remaining five categories will be further discussed. This categorization is adopted in this subsection, to maintain a clear overview.

Individual/household characteristics

This category consists of socio-demographic and socio-economic variables, related to the individuals/households in the area, like income or household size. This indicator group is found to have a significant influence on the demand. Age, household size and income are the factors that influence this demand.

Psychological variables

This category relates to factors like the adoption of shared mobility by people, which strongly influences the demand. Multiple researches confirm this statement, finding egoistic beliefs, perceived control (Collins and Chambers, 2005) and the subjective norm (Kaewkluengklom et al., 2017) to be influencing the preference for public transport.

Transport connectivity

Factors included in this category are the service level and current infrastructure in the researched area. The presence of (public transport/road/parking) facilities generally reduce the cost of integrating a mobility hub at that location. Therefore, a well-connected location will imply a higher potential for a mobility hub.

Land-use variables

In this category, influential factors like the proximity of an office area or shopping mall are covered. This can be expressed in terms of land use in the specified area, or the distance to a point-of-interest like a shopping mall.

Travel patterns

This includes all factors related to the travel patterns of the inhabitants, like public transport usage, bike and car ownership. The most relevant factors that can be measured are car ownership and public transport card ownership per household.

A further deliverable from the eHubs project (Liao and Correia, 2019a) describes the results of a quick scan performed to find the shared mobility potential score of every zone in a designated city. These results are visualized in a heat map. The methodology to execute this analysis is first selecting the relevant variables, calculating the potential score for carsharing and e-bikesharing of every zone, deriving the relative indicator to be able to compare zones, and visualizing the result. Factors taken into account in this research are found in the following list, taking the adopted categorization into account.

- **Individual/household characteristics**: Socio-demographics, i.e. population density, gender, age and income.
- **Psychological variables**: Not used in the method.
- **Transport connectivity**: Bus/tram/metro stop, train station, PT passenger density, level of accessibility, road density, bike path network density.
- **Land-use variables**: Percentage of residential area & office area and POI data, i.e. workplace, restaurant, university, shopping center and recreational center density. Not used are the mixed land use, parking difficulty and parking price factors, because data on these factors lacks.
- **Travel patterns**: These factors are not included in the calculation, however, vehicle ownership, bike ownership, shared mobility membership and lifestyle are identified as possible influential factors.

The data sources used for determining the variables for this deliverable are two papers, one of which is on station-based carsharing and the other one concerns free-floating bikesharing. There might be differences between factors influencing demand between station-based and free-floating shared mobility. Because the research in the thesis focuses on mobility hubs, the station-based shared mobility factors are more relevant in this thesis.

The free-floating bikesharing data source (Guidon et al., 2019) analyzes transaction data from a system in Zürich, Switzerland, to find out what drives people to use shared e-bikes, and what effects the shared mobility system has on travel behavior. This study focuses on the effects in a city, whereas the bikesharing system is mostly used for unimodal trips. This research, and thereby the previously described factors, can therefore only be used with caution to come to factors influencing the mobility hub potential, since regional mobility hubs are based on the concept of multimodal, mostly regional trips.

The station-based carsharing data source (Hu et al., 2018) uses a year of transaction data from a carsharing program in Shanghai, China, to uncover factors related to the use of carsharing and the relationship between transit and carsharing. Independent variables from six categories were used as input, while the number of booking requests and turnover rate for shared cars are used as dependent variable. Named variables that have a significant influence are the number of parking spaces of a station, operation hours and number of car stations nearby (**transport connectivity**). A higher number of car stations nearby causes a lower usage of the selected station. This effect will not be present in the thesis research on regional mobility hubs, as the placement of only one hub is researched, the interaction effects between multiple hubs are not in the scope of this research because of the complexity.

In the strategic plan for the implementation of mobility hubs in Scotland by SEStran (2020), the potential locations for a mobility hub are identified. The locations with the highest potential demand for mobility hubs, thus the most viable to commercially operate, are assessed. The following indicators are distinguished and classified in the adopted categorization:

- **Individual/household characteristics**: Population, since the potential increases with a higher residential population.
- **Psychological variables**: Not used as a factor.
- **Transport connectivity**: Access to services (in drive time and public transport), since areas with a shorter drive time to services and areas with good existing public transportation are more suitable for mobility hubs.
- **Land-use variables**: Workplace population, a higher workplace population leads to a higher demand.
- **Travel patterns**: Target mosaic population, as some population groups are more intended to use a mobility hub than others.
- Other factors: Current bike/carsharing locations, these can be integrated in the mobility hub when present, and proposed locations by the stakeholders.

A study in which the potential of MaaS for every neighborhood in The Netherlands is calculated (Koopal et al., 2020) provides interesting insights in the influential factors for a location potential determination. This research has been executed on the potential of MaaS, which is the software integration of all modalities. The indicators can be partially used to determine the mobility hub potential, but information on the location should be added, since the model from the literature does not provide a location choice. This research is on the usage of MaaS based on the price, where the current thesis is on the usage of a mobility hub based on the location. The indicator groups used are Population data (**Individual/household characteristics**), mobility behavior (**Travel patterns**), the used MaaS proposition and a behavior model (containing behavior parameters) (**Psychological variables**).

One further study which provides factors influencing the potential of a mobility hub with regard to the home trip end position, is a study executed by the KiM (knowledge institute mobility), examining multimodal trips in The Netherlands (Hamersma and de Haas, 2020). Factors influencing the potential of multimodal trips in general can be classified into the adopted categories. Some notes need to be placed at this list. The gender of the traveler has been found to have an ambiguous influence, so it is very hard to reliably include that factor in a generally applicable method.

- **Individual/household characteristics**: Gender, age, education, income
- **Psychological variables**: Attitude with respect to train
- **Transport connectivity**: Closeness of departure & destination to station
- **Land-use variables**: Urbanization level at destination, urbanization level at origin
- **Travel patterns**: Car possession, driver license, student public transport card possession
- Other factors: Day of week, number of trips on a day, trip motive

To conclude this section, all factors named in the literature are listed here.

- **Individual/household characteristics**: Socio-demographics, i.e. gender, age, education, income, household size, population density and population (number of inhabitants).
- **Psychological variables**: This category relates to human factors like the adoption of shared mobility by people, the attitude with respect to the train, egoistic beliefs, perceived control and the subjective norm.
- **Transport connectivity**: Public transport service level and passenger density, current public transport infrastructure (bus/tram/metro stop, train station), current road and cycle path density and the presence and number of parking facilities.
- **Land-use variables**: Urbanization level, workplace population, residential/office area, point-of-interest data (shopping mall, restaurant, university, shopping center and recreational center density), parking difficulty and parking price.
- **Travel patterns**: Factors related to the travel patterns, i.e. car and bike possession, driver license, student public transport card possession, public transport usage, shared mobility membership and lifestyle/population groups.
- Other factors: Day of week, number of trips on a day, trip motive, current bike/carsharing locations and proposed locations by the stakeholders.

2.5.5 Activity trip end position

For the activity trip end position of the regional mobility hub, less literature is available. Current literature on this mobility function can mostly be found at hubs close to a business park or industrial area, but by locating the hub near that area, the location is already determined. In these hubs, shared mobility plays a major role, as passengers using the mobility hub at the activity trip end arrive by public transportation, so the private vehicle is not one their transport options.

Interesting information on the indicators can be found in a document describing the public transport nodes in the province of Utrecht (Gerretsen et al., 2018). The node impact/catchment area is defined as 800m walking distance/3km cycling distance (both 10 minutes) from the node. For residential side transportation, cycling is normative, while walking is normative looking at the office/activity side of the trip. One of the recommendations is to offer enough cycle parking, car parking, shared bikes and shared cars at a station. The transfer should be seamless.

In the earlier mentioned eHubs project (eHUBS Partnership, nd), an important statement influencing the location choice of a mobility hub, is that regardless of the size and urban context, the mobility hub should always be placed at a location where supply and demand meet. This implies that the potential demand is an important factor in determining a mobility hub location. Another deliverable of the eHubs project (Liao and Correia, 2019a) states a positive coefficient for the demand for shared mobility hubs when a shopping center, university, recreational center or office space is present near a hub location.

The eHubs project also provides a deliverable (L. van Gils, 2019b) in which the location selection procedure is addressed. Factors to take into account in this location selection are existing transportation currents, towards the activity centers in the morning and from these activity centers in the afternoon/evening, and the existing transport infrastructure for all modalities, i.e. public transport, cycling, road as well as barriers like railway crossings. Current parking facilities, locations with current traffic problems and important activity nodes can further influence the location choice. For the defined type of mobility hub, the hub outside of highly urbanized areas with a public transport connection, the mobility hub can be placed at a large public transport node, as the demand is high at that location, and the radius of the users' potential destinations can be increased by offering shared mobility. This effect is visualized in Figure 2.6.

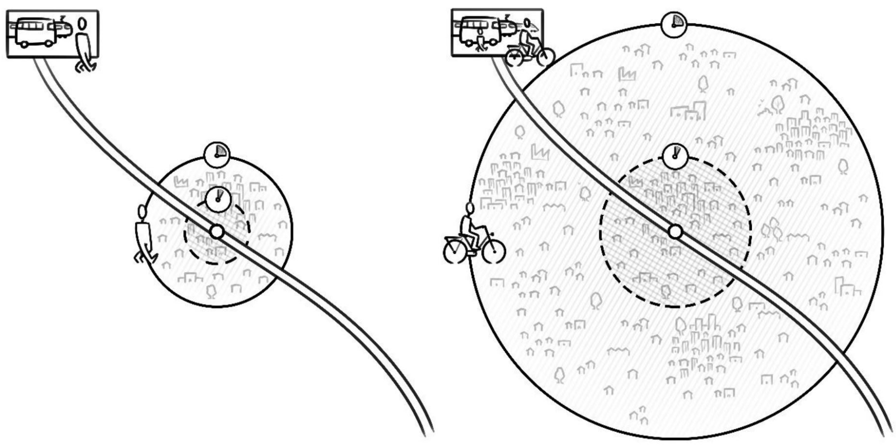

Figure 2.6: Increase in catchment area of Public Transport nodes due to shared mobility (Kager and Harms, 2017).

A transit development plan for the northwestern part of Arkansas, a state centrally located in the United States, involves the placement of mobility hubs (Alliance Transportation Group, 2020). According to the plan, the hubs should be located near in-demand destinations with a high-density mix of land uses, meaning that the planned hubs are predominantly located at the activity trip end. In this plan, a quantitative GIS analysis was performed to check areas for their mobility hub suitability. The following factors determined the suitability of an area in this research:

- Future trip productions
- Future trip attractions
- Future population & employment density

- Density of sidewalks and cycle paths
- Daily transit ridership at stop level
- Existence of Park&Ride infrastructure

Summarizing, the following factors result from literature on mobility hubs at the activity trip end position:

- Existing/Future transportation currents or productions/attractions, linked to the presence of important activity nodes like a shopping center, university, recreational center or office space
- Future population & employment density
- Existing cycle/walk infrastructure/density of sidewalks and cycle paths
- Daily transit ridership at stop level/placement at large public transport node
- Existing public transport and road infrastructure
- Existing parking or Park&Ride infrastructure
- Locations with current traffic problems

2.5.6 Other (transfer) trip position

The other possible functions of the mobility hub in the transportation system, not being an access point at the home or activity trip end, is the mobility hub as a transfer point in the trip. The most common existing transfer point between modalities is the Park&Ride facility, therefore this is the main researched topic in the literature of this subsection. It can even be stated that a regional mobility hub with only a transfer mobility function in the network (and no economic function) is a Park&Ride facility. A categorization of the influential factors is suggested in an existing research on Park&Ride location choice (Faghri et al., 2002), grouping the factors in three categories, namely:

- Factors influencing the **demand** for the facility
- Factors influencing the **ease of integration** of the facility
- Factors influencing the **cost** of the facility

The factors found in the literature on the other (transfer) mobility function of the mobility hub can be placed in one of these categories, a category 'other' is added to include factors not fitting in one of the three categories.

The Dutch CROW (knowledge institute for transport, infrastructure and public space) published a document in which guidelines for the implementation of a Park&Ride facility (Graumans, 2015) are introduced. Two target groups are identified in this document: commuter traffic and city visitors. For commuter traffic, the network value of such a facility is determined by the number of inhabitants within a 15 minute driving time of the transit stop (**demand**), and the number of jobs with a competitive travel time by public transport (compared to car travel time), within 10 minutes walking/cycling of the (city) arrival stop (**demand**). The value for city visitors is present when there is a direct connection to a city center with at least 50.000 square meters of shopping area, at a maximum travel time of 30 minutes (**demand**).

The most important criteria when deciding on a location for a Park&Ride facility have been examined by means of expert interviews in a study in the United States (Faghri et al., 2002). The most important criteria, sorted from highest to lowest importance, are as follows:

1. Location relative to transit (**ease of integration**)
2. Site access convenience (**ease of integration**)
3. Location relative to users (**demand**)
4. Traffic volume to central business district (**demand**)
5. Location upstream of congestion (**other**)
6. Transit service headway (**demand**)
7. Multimodal design (**other**)
8. Site visibility (**demand**)
9. Intrusion on existing structures (**ease of integration**)
10. Compatible land uses (**ease of integration**)
11. Cost minimization (**cost**)
12. Proximity to central business district (**other**)
13. Site expansion potential (**other**)

As mentioned in the mobility hub definition, the Dutch transferium, a Park&Ride at a distance of the city center, is in some ways equal to the regional mobility hub, especially with respect to the transfer mobility function of the hub. Therefore, literature on transferia can be used to discover influential factors for the hub location.

In a document in which the transferium concept is explored, it is stated that to improve the attractiveness of the transferium, the perspective of the car users (travelers) is of the highest importance (Egeter et al., 1990). This means that the highway connectivity of the transferium facility should be as high as possible (**demand**), to reduce the resistance of using the facility. According to Egeter et al. (1990), the different perspective leads to the difference between a Park&Ride facility and a transferium. The importance of the right location for the facility is emphasized, since this influences the extent of solving the traffic problems by the transferium. Furthermore, the transferium should be situated before the congestion appears on the route of the travelers (**other**). Therefore, a position at a larger distance of the city is preferred (**other**). This is also preferred from the environmental perspective, since a larger part of the trip is replaced by sustainable, public transport kilometers instead of car kilometers when placing a transferium more distant from the city. However, the catchment area and hence the demand of a transferium at a larger distance from the city is smaller. Summarizing, the influence of the distance to the city is ambiguous. In Egeter et al. (1990), a method to find high-potential locations for a transferium is described. The starting point are the 13 most important city clusters. Thereafter, the corridors from every city cluster are researched, and potential transferium locations are found close to the trip origins.

An unwanted effect caused by the establishment of transferia is the replacement of a public transport trip by a trip by car from the origin to the transferium, where the switch is made to public transport. The idea is to reduce the number of car kilometers traveled when introducing a transferium, which is partially canceled out by the extra car kilometers to the transferium, but a significant travel time reduction (**other**) may be achieved when using the car to enter a high-quality public transport network, instead of using only public transport for a trip (van Binsbergen et al., 1992).

A Master's thesis on transferia in the Dutch municipality of Utrecht (van Roijen, 2003) provides an overview of the success factors for a transferium. For the location choice, the success factors on the accessibility, location and supporting policies are important. The relevant factors are listed and explained underneath.

- Accessibility from the road network: Extra travel time has to be taken into account (**demand**)
- Congestion from the road network: Access to the transferium should be free of congestion (**other**)
- Accessibility from the bike network: Not taken into account in the model, but a connection to the bike network can be advantageous. (**demand**)
- Spatial integration: The facility needs to fit in the space. (**ease of integration**)
- Logical position in trip: Usage of the transferium should be logical, looking at the route from origin to destination. This can be translated to the absolute distance from the transferium to the used road. (**demand**)
- Parking policy at the destination: High parking costs at the destination cause a higher potential for a possible transferium. (**demand**)
- Parking availability at the destination: A low availability of parking spaces at the destination causes a higher potential for a transferium serving the destination. (**demand**)

A location choice in a Master's thesis on transferia (Breedveld, 2010) in Haaglanden (the region around the Dutch city of The Hague) was made based on four criteria. These are the distance to a main road (preferably highway) (**demand**), location at high-quality transit node (**ease of integration**), before the congestion to the city (**other**), and at a current Park&Ride facility (**ease of integration**).

Sweco has executed several quick-scans to find potential locations for a regional mobility hub. A pre-selection of locations is usually made, looking at the current problems and bottlenecks in the region. Afterwards, the locations are evaluated on several aspects, which can be categorized as follows:

- Position (closeness to highway, closeness to city, location compared to bottleneck) (**demand/other**)
- Current facilities/services (car park, carpool place, public transit, cycle highway) (**ease of integration/demand**)
- Integration (current land use/space, ability to build and connect to city, environmental constraints) (**ease of integration**)
- Effect (ability to solve bottlenecks, quality of life improvement) (**other**)

An additional recent development of interest is the establishment of Park&Bike facilities at current Park&Ride places. The addition of a covered bicycle parking, and shared mobility in the future, provides an extra travel option from the Park&Ride facility to the destination, adopted by multiple organizations in the Groningen region upon first introduction (Samenwerkingsorganisatie Groningen Bereikbaar, 2016). Sweco also noticed the potential of Park&Bike facilities in their white paper on sustainable accessibility of cities (Quee, 2019). The combination of car and bike is identified as a golden combination, as the bike can serve as extension of a car trip to the city center. Important to note for this combination is the importance of the distance to the city (**other**). As the top speed of the bike is much lower than car or public transport top speeds, the bike is mostly interesting for the last few kilometers. The range of the e-bike or moped is slightly higher, but travelers are not easily tempted to use a mode which does not provide protection from the elements over longer distances, especially in rainy or windy weather. Note that for Park&Bike facilities, a public transport connection is not a prerequisite.

To finalize this subsection, a summary of the factors gathered from the literature is given, categorized in the three categories adopted at the start of this subsection, complemented by the category other to integrate the factors not fitting in one of the categories.

Ease of integration

- Spatial integration: fitting of the mobility hub in the space and existing structures.
- Integration into the public transport network: the connection to public transport links/nodes.
- Current parking facilities: the presence of parking/carpool/Park&Ride facilities at a location.
- Site access convenience: The convenience of accessing the hub from the road or bike network. The convenience (comfort) relates to the ease of integration, whereas the distance to the networks relates to the demand.
- Environmental constraints: the integration with regard to protected natural sites.

Cost

- Cost: Costs of building and operating the hub.

Demand

- Inhabitants: Number of inhabitants within the catchment area.
- Workplaces: Number of jobs within the catchment area of the arrival stop with a competitive travel time compared to the car.
- City visitors: Shopping area within 30 minutes travel time.
- Highway connectivity: Closeness to the highway, extra travel time due to usage of the hub.
- Bicycle connectivity: Closeness to the bicycle network.
- Traffic volume: Traffic volume at the served highway.
- Quality of transit service: The headway of the transit service has an impact on the usage of the hub.
- Position in the trip: The facility should be close to the route from origin to destination for users.
- Destination parking policy/availability: High parking costs and low availability at the destination increase the potential for a hub.
- Site visibility: Signposting for the visibility of the site from the highway, including a display showing the number of open spaces.

Other

- Distance to the city center: The distance between the location and the central business district/city center, especially important for cyclists.
- Solving bottlenecks: The effect of the hub at a selected location on the existing bottlenecks.
- Location with respect to bottlenecks/congestion: The location can be upstream or downstream of the bottlenecks. Hub access should be free of congestion.
- Travel time reduction: The travel time reduction offered by using the mobility hub instead of the car.
- Improving city's quality of life: The effect of the mobility hub at a selected location on the quality of life in the served city.
- Expansion potential: Sites should be able to expand along with an increasing demand and/or the location should allow for the integration of future modalities.
- Multimodal design: The hub should be accessible by bicycle, foot and for disabled users.

2.5.7 Stakeholder interests

After finding factors influencing the potential of an area for a regional mobility hub, the stakeholder perspectives should be incorporated to be able to make a selection of important factors to include in the methodology. The stakeholder incorporation is essential, as the methodology should be able to determine the hub potential from the identified perspectives. Therefore, all factors from the literature are linked to one or more perspectives. For the end user perspective, the user needs have to be determined, these needs are often studied in the current literature. Grey literature (Master's theses and reports) is consulted to find information on factors from the operator perspective. For the government perspective, factors can be determined by thoroughly investigating governmental (vision) documents.

End user perspective For the end user, the reason for using a mobility hub is a decrease in travel costs and/or travel time, and/or an increase in comfort and/or travel time reliability (Atkinson et al., 2020). A mobility hub can help in reaching their destination quicker, cheaper or easier. What helps in making the mobility hub attractive, is an existing unattractive situation, for example the presence of a traffic problem on the route or high parking fares in the city. An unreliable travel time by car makes the regional mobility hub using public transportation an attractive alternative, just as a high public transport quality and reliability on the route to the city.

In short, the travel time/costs, comfort and travel time reliability are key factors for the individual in determining the attractiveness of a mobility hub for the end user. The comfort is addressed in the elaboration of the features of a mobility hub in section 2.2, so this is not related to the location choice of the mobility hub.

Operator perspective From the operator perspective, factors are less complex to determine. The operator would like to see the usage of their services as high as possible (van den Berg, 2020), and the benefits should outweigh the costs of implementing and exploiting the mobility hub in order for the operator to make a profit (Talen et al., 2018). This can be achieved by keeping the costs down to a minimal investment in infrastructure, so the implementation of a mobility hub at a current bus/train stop is preferred from this perspective. This also minimizes the adjustments in the existing routes of bus lines that have to be made. Summarizing, the connection to the present network of the operator is important.

To achieve the highest possible usage, the demand is important. Therefore, the attractiveness for the end user of the regional mobility hub should be taken into account. Next to the attractiveness for the possible users, the number of potential users in the impact area of the hub is important to determine the potential demand.

Government perspective The report in which a strategic study on mobility hubs in Scotland is carried out (SEStran, 2020) provides a list of themes and governmental policies that can be addressed by a mobility hub. For the location choice, it is important that the methodology leads to a location which addresses the policies as much as possible.

- Mobility hubs should be aligned with land use and transport planning
- Mobility hubs should be used to reduce the emissions in a region
- Mobility hubs can be placed in locations with low car ownership enhancing connectivity and covering gaps in the transport network
- Mobility hubs provide the potential to integrate shared mobility and public transport in spatial planning, to reduce parking pressure and the need for additional parking areas.

For the government, it is important that the motive for the introduction of a mobility hub is clear, in other words: accessibility, traffic safety or quality of life might be too low in the region, or bottlenecks are existent. Big cities are growing, with more and more commuters arriving in the morning and leaving in the afternoon, leading to an increasing pressure on the transport system. As municipalities aim to reduce emissions in the city center, a sustainable solution should be found. The issue of a low quality of life in a city is usually caused by, among others, an overflow of private vehicles in the city center. The mobility hub can solve this problem, by providing an attractive alternative to driving across and parking in the city center. Summarizing, the government is especially interested in the impact of the mobility hub on the environment and quality of life, a location with a higher positive impact would result in a higher hub potential than a location with a low impact.

As named in the previous chapter, land usage is important from the government perspective. This relates to the integration of a mobility hub, as the availability of space influences the costs of integrating the hub. Locations with more available space will have a higher hub potential from the government perspective. The difficulty to acquire this land is also a factor leading to a higher/lower potential for the hub location, since land owned by a private organization comes with higher costs and made effort in acquiring than using land owned by the government for a hub.

2.5.8 Adopted influential factors

The literature review and view from the three perspectives lead to factors influencing the potential of a location for a regional mobility hub. All adopted factors are listed in this subsection, with the corresponding stakeholders for which the factor is important. These factors, including the influence on the potential, are listed in Table 2.3. The excluded factors from the previous sections are listed in a subsequent subsection.

Because of the profit-making nature of the operating companies, the demand for the mobility hub is an influential factor which is relevant for the operator. Factors leading to the demand are integrated in this factor, i.e. an area's population, workplace population, the presence of activity nodes and the current traffic volume.

The costs of the placement of a mobility hub are highly relevant for both the operator and the government. A convincing business case is nearly always needed to execute a transportation project. For the operator, this translates to costs for the infrastructure and operation of the services at the mobility hub. The integration in the existing public transport infrastructure is a measure for these costs. For the government, the costs depend on the spatial integration with regard to land use, the integration in current road, cycle and pedestrian infrastructure and the presence of current parking facilities. As the mobility hub can provide a solution to societal issues, the costs for the construction of the mobility hub have to be covered by the government. In the Deltaplan (Mobiliteitsalliantie, 2019), it is assumed that investments for sustainable transportation projects are made by the government. Therefore, it is in the best interests of the government to prefer a location for which the investment costs for a mobility hub are low.

The connection between the mobility hub and the surroundings is of importance for the government. A government prefers a mobility hub which is well-integrated in the surroundings, a combination with local available facilities in therefore preferred. This limits the additional space usage necessary for the mobility hub. This relates to the economic function of the mobility hub and the connection to regional facilities, described in the literature review. For the end user, this criterion is relevant as well, as an integration of the trip with other activities (picking up parcels, doing groceries etc.) can make the mobility hub more attractive.

A further governmental interest is the level of connectivity offered by the mobility hub, compared to the current situation. This is partially location dependent, as the mobility hub offers extra connectivity in any case, but in mobility deprived areas, this additional connectivity offered can be higher than in well-connected areas. This measure is also used in SEStran (2020) to come to the potential for a mobility hub. The additional connectivity also relates to the inclusiveness for all population groups induced by the mobility hub, so this factor is relevant from the end user perspective as well.

For the end user, the usage of the mobility hub at a specified location leads to a certain increase or decrease in travel time/cost, compared to their current trip. Both the costs and time are incorporated in one indicator in the literature: The generalized travel costs (Koopmans et al., 2013). In this formula, the out-of-pocket costs are added to the travel time multiplied by a scaling factor, that takes the value-of-time, value-of-unreliability and inconvenience costs into account. The out-of-pocket costs and travel time of the end users can vary according to the hub location, whereas the scaling factor will remain the same, because this factor is fixed for each traveler. In this thesis, all changes in generalized travel time are aggregated to be able to include this factor in the methodology.

To attract users for the mobility hub, the facility should be an improvement to the existing (unattractive) situation. A low reliability of travel time for the end user may indicate a high potential for a mobility hub. Causes of a low travel time reliability might be congestion on the route from the potential mobility hub location to a nearby city, or parking problems in that city. The presence of these problems near the location can indicate a higher hub potential from the user perspective.

The previously named problems relate to the issue that lead to the introduction of mobility hubs: increasing greenhouse gas emissions and a deterioration of the quality of life in city centers. As the cause of these societal issues is found in congestion and parking problems, the capability of the mobility hub to solve these issues is an influential factor from the government perspective.

Table 2.3: The selection of influential factors to be used in the regional mobility hub location potential determination methodology, along with the involved perspective and explanation of the influence.

Factor	Perspective	Explanation of the influence
Demand	Operator	A higher number of users leads to higher earnings for the operator, causing a higher mobility hub potential from that perspective.
Costs	Operator & Government	Costs are a leading factor in deciding on the approval of a project. A convincing business case is needed to execute a transportation project, for both the operator and government. Therefore, lower costs increase the feasibility of the project.
Economic function	Government & End user	An integration with surrounding facilities limits the additional space usage, important for the government. For the end user, the attractiveness of the hub increases due to the economic function.
Added connectivity	Government & End user	The government aims to offer mobility for all inhabitants, the mobility hub can improve on this connectivity. A higher additional connectivity contributes to the inclusiveness induced by the mobility hub, and is therefore desired from the end user perspective as well.
Generalized travel costs of using the hub	End user	A decrease of the generalized costs of the trip due to the usage of a mobility hub increases the attractiveness for the end user.
Increase in travel time reliability	End user	A low travel time reliability means that the current situation is unattractive, due to congestion or parking problems. An increase in reliability of the travel time offered by the mobility hub makes the hub more attractive from the end user perspective.
Impact on quality of life & emissions	Government	A higher reduction of parking problems and congestion induced by the hub will lead to a higher impact on quality of life issues & greenhouse gas emissions.

2.5.9 Excluded influential factors

As this thesis adopts an aggregated approach on the topic of finding a mobility hub location, described in subsection 2.5.4, disaggregated data on individuals and their trips can only be incorporated in an aggregated way, by means of the (aggregated) generalized travel costs and increase in travel time reliability. Therefore, individual characteristics are not included in the methodology. This means that the psychological variables, individual/household characteristics and the travel patterns are left out. The characteristics of the population might influence the mobility patterns and habits of the population in a researched area, as certain characteristics like the age of the inhabitants can cause an increase or decrease in the potential shared mobility usage. The reason for not including this factor is the fact that it is hard to exactly determine the regional mobility hub usage with the available statistics on the population. This is partly due to the novelty of the mobility hub and the lack of information on the current users of similar facilities.

Furthermore, the locations at which bike/car sharing is currently offered will not be incorporated as a factor to determine the mobility hub potential of an area. It is assumed that the placement of a mobility hub will be accompanied by the development of a new shared mobility system, focused on the mobility hub. A shared mobility service is adjusted to the location of the mobility hub instead of the other way around. Looking at shared mobility services that emerged in The Netherlands over the past years, this assumption seems valid, for example in shared bike systems being placed at public transport nodes or existing bicycle parking facilities (Talen et al., 2018).

As factors influencing the potential of an area for a mobility hub are investigated in this thesis, factors related to the design and operations of the hub are left out. In the literature, some of these factors are marked as important, like the multimodal design of the hub, the quality of the transit service and site visibility. These hub characteristics should be considered in the hub design process, but not in the location potential determination methodology.

Some factors are taken into account implicitly in other factors. The urbanization level and daily transit ridership are integrated in the demand for a mobility hub. The demand, based on the population, workplaces, presence of activity nodes and current traffic volume, is a more comprehensive factor than the urbanization level and transit ridership, but since those factors are related, the choice was made incorporate the factors in the demand. The location with respect to congestion is integrated in both the increase in travel time reliability and impact on quality of life & emissions provided by the mobility hub. In the costs criterion, the physical integration is included, in which the environmental constraints are implicitly integrated. The expansion potential is also incorporated in the physical integration, thus in the costs criterion.

The remaining factors from the literature are not taken into account for varying reasons, shortly addressed in this paragraph. The proposed locations are left out because the methodology aims to provide the potential of an area without requiring pre-selected input locations. The last remaining factor is the distance to a city, not taken into account because of the ambiguous influence of this factor. For reducing greenhouse gas emissions in the transfer mobility function of the mobility hub, a higher distance is desired, as a larger part of the trips is traveled by public transport instead of the private vehicle. For the activity trip end function, the distance should be kept as low as possible, to enable users to cycle to the city center.

2.6 Conclusion

In the first sections of this chapter, the concept of the mobility hub is explored. An overview of the relevant information available on the definition, typology and features of the mobility hub is presented, leading to an adopted definition, typology and list of features. In this thesis, the adopted definition of the mobility hub is: "The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, possibly including other amenities, ranging from retail, workplaces to parcel pick-up points." A classification of mobility hubs into three types is made based on the literature, leading to the residential, city and regional mobility hub, their distinctive properties are given in Table 2.1. The possible features of the hub types are then investigated, but it became clear that the selection of features that should be included in a hub strongly depends on the local situation and needs. A general overview of the features that are necessary, optional and not required is given per hub type in Table 2.2.

Subsequently, the choice is made to focus on the regional mobility hub, as a location potential determination methodology is of the greatest added value for this hub type. The factors influencing the potential of a location for a regional mobility hub are determined in section 2.5, by means of an extensive literature review. The economic and mobility function of the hub are investigated in separate subsections, in which the literature on the mobility function is split up according to the three mobility functions of the hub: a mobility hub positioned at the activity side of the trip, the home side of the trip, and in between as transfer point. Important detail is that for all three functions, multimodal trips are considered. In combination with the interests of the three used perspectives, this leads to a selection of influential factors for the regional mobility hub location, elaborated in Table 2.3, which are input for the methodology developed in the next chapter.

Chapter 3

Methodology: Spatial Multi-Actor MCA

3.1 Introduction

In the previous chapter, a literature review is carried out to answer the first three sub questions. The chapter focused on what is present in the current literature on the topic of mobility hubs and the location choice of the hubs. In this chapter, the literature will be put into practice, by developing the methodology (Spatial MCA) as suggested in the introduction. A complete answer to the sub question "Which elements should be included in this methodology?" will be given in this chapter. The goal of this methodology is to determine the potential of areas for a regional mobility hub. Firstly, the conventional MCA will be explained, followed by the two adaptations of the MCA as proposed in the introduction. This leads to the methodology proposed in this thesis, and for this method, the required procedures and elements are discussed, after which the application of the methodology is introduced.

3.2 Multi-Criteria Decision Analysis

In chapter 1, it is found that the Multi-Criteria Analysis is undoubtedly the most widely used methodology to spatially evaluate multiple alternatives, taking the stakes of multiple stakeholders into account. This methodology, the Multiple-criteria decision analysis (MCDA) or Multi-criteria analysis (MCA), was introduced in decision making projects in the 1970s, and is currently one of the best-known evaluation methodologies.

The MCA is composed of three basic elements (Malczewski and Rinner, 2015, p.23): the decision maker, alternatives and criteria. Three types of interest groups form the decision maker: the proponents, the ones affected and the ones having the responsibility to influence the actions of the other groups. The set of criteria is composed of attributes and objectives. The criteria can be either qualitative or quantitative. Important in this element is that the number of evaluation criteria should be minimized for a successful execution of the method. An attribute is assigned to measure the objective, for example the trip production/attraction could be an attribute to measure the demand objective. The alternatives represent the actions the decision maker must choose from. In the next subsections, the multi-actor and GIS incorporation in the MCA are discussed, along with the implications of the MCA adaptations for the elements of the methodology.

3.2.1 Multi-Actor incorporation

One of the key characteristics of this research is the engagement of multiple stakeholder groups with conflicting interests. The stakeholders' opinions should be incorporated explicitly in the evaluation process in order to provide a transparent methodology. Performing a search on this "Stakeholders approach" in combination with MCA resulted in three highly-cited (cited in more than 100 other scientific articles) articles, all of which describe the Multi-Actor Multi-Criteria Analysis. This methodology was introduced by Macharis et al. (2009).

The MAMCA is unique due to the incorporation of the stakeholders in a very early stage, in order to derive the criteria from the stakeholders point of view. This methodology consists of six steps, adopted in this thesis:

1. Define alternatives: The alternatives are defined which will be used in the analysis.

2. Stakeholder analysis: All stakeholders are defined, and an understanding of the objectives of the stakeholders is obtained, to determine the relative importance of the criteria.
3. Define criteria and weights: The determination of the criteria and weights is done based on the stakeholder objectives. Multiple methods are possible for quantifying the weights.
4. Criteria, indicators and measurement methods: Indicators are constructed to operationalize the criteria. These indicators should be measurable, and are often quantitative. Multiple indicators per criterion can be needed, but using one indicator for multiple criteria is possible too.
5. Overall analysis and ranking: All alternatives are evaluated according to the determined weights and criteria.
6. Results: The scores of the various alternatives are given. A sensitivity analysis can be performed, to see the results of changes in the weights. The scoring for every stakeholder can be found in this stage, so the critical stakeholder group with the critical criteria can be identified.

The result of the MAMCA from the original paper (Macharis et al., 2009) is a graph, showing the preference of every alternative as a horizontal line, an example can be found in Figure 3.1. The vertical bars represent the actors, where the weights allocated to the stakeholders are shown by the height of the bar, and can be read from the left axis. The intersection of the horizontal alternative line graphs with the vertical objective lines shows the priority of the strategies (hub types) for the given objective, this value can be read from the right axis. The bottom (horizontal) axis shows the involved stakeholders and an 'OVERALL' axis element combines the stakeholders' opinions into a general score of the strategies among all stakeholders and for all included criteria.

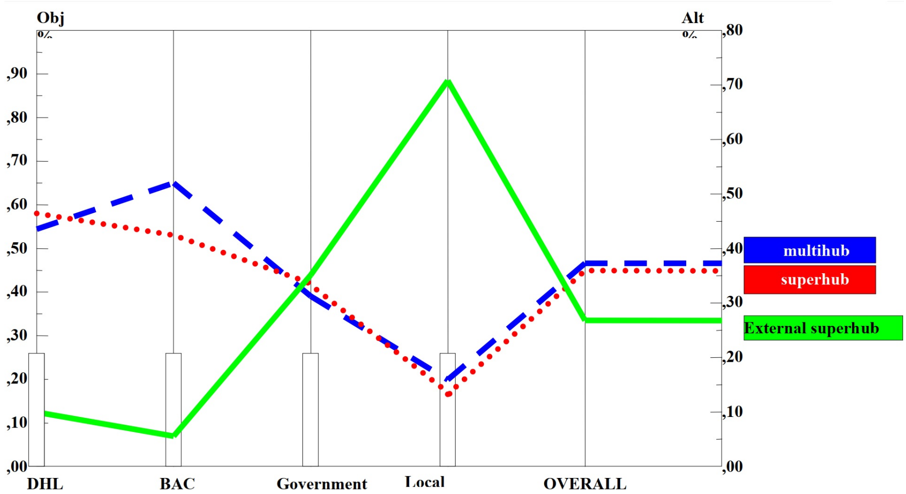

Figure 3.1: Example of a result of the MAMCA methodology (Macharis et al., 2009)

3.2.2 Combining GIS and MCA

The conventional MCA is aspatial, not taking spatial heterogeneity and dependency into account (Malczewski and Rinner, 2015, p.12). To do so, the Multi-Criteria Analysis can be combined with Geographic Information Systems (GIS). This combines the spatial analysis and decision support from GIS with the decision making process of MCA. GIS has the capability to identify a suitable area for a new facility, by performing overlay operations to find a location that satisfies all criteria. In order to include the preferences of the decision makers, Multi-Criteria Decision Analysis can be added into GIS.

The exact procedure for the GIS-MCA is presented in Figure 3.2. The problem, constraints and alternatives are spatially defined, whereas the regular MCA defines the decision maker's preferences and evaluation criteria. In the GIS-MCA methodology, the result of the evaluation of the alternatives is analyzed in a sensitivity analysis, leading to a recommended alternative (location).

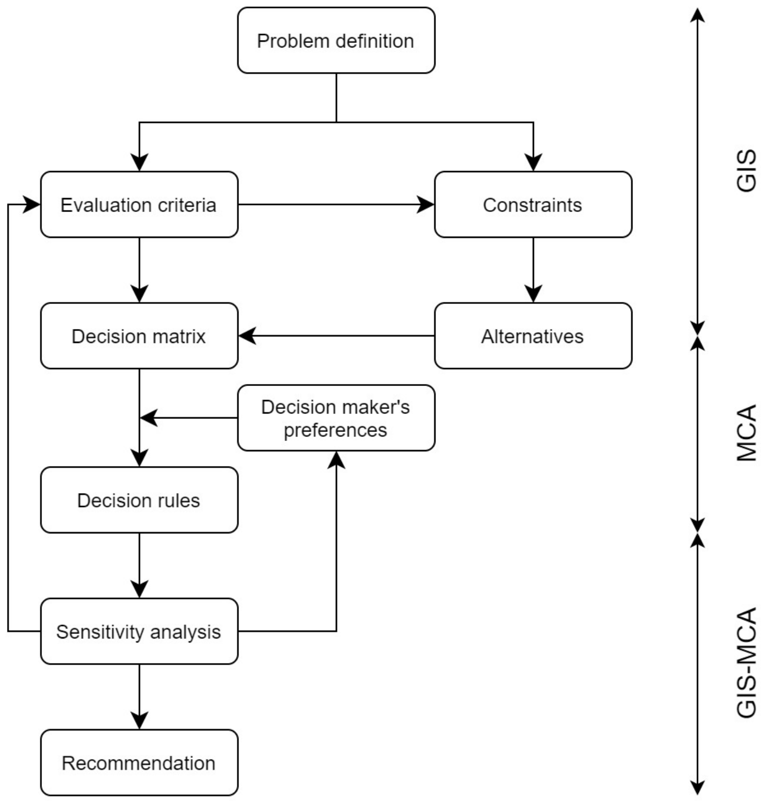

Figure 3.2: Flowchart for using the GIS-MCA method, adapted from (Malczewski, 1999)

3.2.3 Developed methodology

The steps of the Multi-Actor Multi-Criteria Analysis are adopted in this thesis, but with some changes in accordance with the GIS-MCA. In the following list, the six steps of the MAMCA are adjusted in order to incorporate the spatial component.

1. Define alternatives: All areas in the selected region that satisfy the posed constraints are identified as alternatives. The number of areas depends on the selected area size (accuracy) chosen in the method application.
2. Stakeholder analysis: All stakeholders are defined, and an understanding of the objectives of the stakeholders is obtained, to determine the relative importance of the criteria. This step has been executed in chapter 2.
3. Define criteria and weights: The determination of the influential factors is done in chapter 2. These factors are converted to criteria in the MCA. Multiple methods are possible for quantifying the weights, as elaborated in subsection 3.3.2.
4. Criteria, indicators and measurement methods: Indicators are constructed to operationalize the criteria. These indicators, referred to as attributes in this thesis, should be measurable for every area in the region. Multiple attributes per criterion can be needed, but using one attribute for multiple criteria is possible too.
5. Overall analysis and ranking: All areas are evaluated according to the determined weights, criteria and attributes.
6. Results: The regional mobility hub potential for every area in the region is given in a heat map. A sensitivity analysis will be performed, to check the result of changes in the weights. The scoring for every stakeholder group can be found in this stage.

With regard to the result, a combination of the MAMCA and GIS-MCA results will be used. Because of the spatial nature of the methodology in this thesis, and the high number of evaluated alternatives, a representation in a graph similar to Figure 3.1 would not lead to a comprehensible result. Therefore, a spatial representation of the result is chosen on the basis of five realistic scenarios, in which every scenario has a different stakeholder configuration. On the basis of the Multi-Actor Multi-Criteria Analysis methodology, three scenarios showing the regional mobility hub potential for only one of the perspectives is expected. However, weighted combinations of the three stakeholder groups better match the reality, in which decisions on projects are rarely made by one stakeholder group.

Within the developed methodology, the computations and procedures required for the correct implementation of the method are firstly explained. Two basic concepts are required to obtain the correct score out of the input data (Malczewski and Rinner, 2015) for the GIS-MAMCA. These concepts are value scaling and criterion weighing, described in the next section. Then, the elements on which the methodology is founded are discussed. As the alternatives are already known, namely the areas in the region, this element is not elaborated on. The determination of the criteria and attributes is explained in section 3.4. A visual representation of the elements of the methodology is shown in the overview in Figure 1.2.

3.3 Computations & Procedures

3.3.1 Value scaling

In order to make sure that the influence of an attribute is not dependent on the actual values of the input data, but on the relative value, the data is scaled. The least preferred attribute value is given the value 0, whereas the most preferred value is given the value 1. This procedure is called normalization, i.e. scaling all data into the range of 0 to 1. The scaling factors are completely dependent on the provided input data, a change in input data will lead to a change in scaling factor.

3.3.2 Criterion weighing

Weights are assigned to the criteria, measured by the normalized attributes, to indicate that not all criteria are of equal importance. To determine the importance of one criterion compared to another, ranking, rating, entropy-based and pairwise comparison methods are available. The ranking method ranks the criteria, according to the stakeholders' opinion from highest to lowest importance, thus this method is not suitable when it is necessary to have more specific weights than just a ranking. The rating method requires the stakeholder groups to rate every criterion on a predetermined scale. For this method, very precise input is needed from the stakeholders. The entropy-based method does not require input from the stakeholders, but is based on the amount of information available on the criteria. This method is rarely used in a GIS-MCA (Malczewski and Rinner, 2015), so there is less knowledge on the implementation of this method compared to the other methods. The final method is the pairwise comparison method, in which all criteria are compared to each other, and weights are assigned according to the importance of a criterion compared to another criterion.

For this thesis, the pairwise comparison method seems the most feasible method, as the stakeholders' opinions should be incorporated, more precise than only a ranking, but less specific than exact weights allocated to each criterion by each stakeholder. In the pairwise comparison method, multiple procedures are available, but the most common procedure is adopted in this thesis. This is the Analytic Hierarchy Process (AHP), the most frequently used procedure in GIS-MCA (Al-Shalabi et al., 2006), especially in transportation projects (Macharis and Ampe, 2007). AHP is a logical, well-structured framework which makes complex problems more manageable.

To identify the steps that have to be taken to run this process, an example is taken from the literature. An article on the application of the MAMCA procedure by using AHP is given by Macharis et al. (2010) and this is adjusted by the GIS-MCA AHP application (Malczewski and Rinner, 2015). The resulting GIS-MAMCA AHP works as follows: firstly, the values for every criterion are established per alternative. Then, the weights of the criteria were determined by the decision makers by comparing the criteria in pairs, in which the importance of a criterion relative to each other criterion is determined. Finally, the stakeholders could be given a weight as well, but this is usually not preferred to make sure that all stakeholders have the same importance in the project. This last remark will be addressed by the scenarios created in this thesis, in which the importance of the various stakeholder groups will be varied.

3.4 Criteria & Attributes

Based on the factors influencing the location potential in subsection 2.5.8, the criteria should be determined, with the corresponding (measurable) attributes to quantify the criteria. The main requirement for the attributes is that they should be quantifiable. The criteria should encompass all factors formulated in subsection 2.5.8.

That leads to five criteria which will be used in the determination of the regional mobility hub potential: potential demand, costs, link to surroundings, generalized travel costs and impact. The connection between the interests of the perspectives, the influential factors from chapter 2 and the criteria and attributes in this chapter, is visualized in Figure 3.3. Every subsection in this section separately describes a criterion with its attributes. To determine the attributes for every criterion, the literature in chapter 2 is consulted.

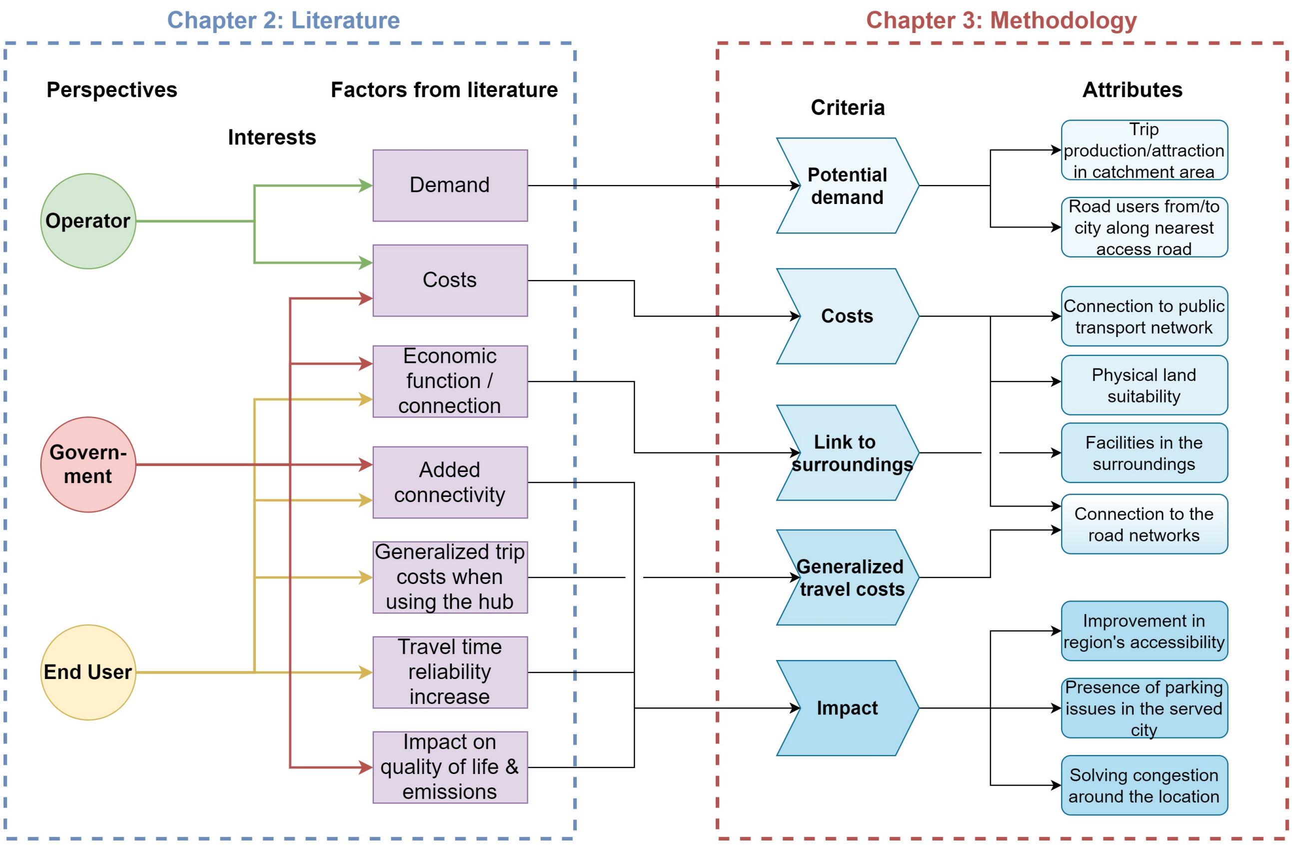

Figure 3.3: Connection between the stakeholders, literature and methodology

3.4.1 Potential demand

This criterion is of a high importance from the operator perspective, as it determines the passenger numbers of the offered mobility service. From a profit-making point of view, the demand should be as high as possible. In subsection 2.5.3, the target groups of the mobility hub are described, which is necessary to determine which user groups might actually use the mobility hub. A division between the mobility hub as access/egress point for the catchment area, both on the home and activity trip end, and the mobility hub as transfer point in a trip can be seen.

In a research on the optimal locations for Park&Ride locations (Faghri et al., 2002), it is found that 50% of the demand for such a facility originates from the surroundings, in a radius of 8 km of the location. For the regional mobility hub serving mainly transfer traffic, this underlines the importance to include the demand from the surrounding area, in addition to the potential demand for usage as Park&Ride facility. Therefore, the two attributes measuring the potential demand criterion are the trip production/attraction in the catchment area and the road users from/to the city along the nearest city access road.

Attribute: Trip production/attraction in catchment area

The trip production/attraction is a proxy of the social-economic data (population, workplaces and facilities) of the locations in the region. The trip production/attraction in the catchment area of the mobility hub is used to measure the potential demand from/to this catchment area. The word potential is used here, as not all travelers will make the switch from their currently used modality to a modality that uses the mobility hub.

Attribute: Road users from/to city along nearest access road

Next to the local demand, the demand for the facility as transfer location should be included. This is operationalized as the vehicle intensity at the nearest access road, usually being a road/highway, from/to the city center. This way, traffic with an origin outside of the studied region, headed for the city center is also included in the demand. This attribute relates to the transfer mobility function of the mobility hub.

3.4.2 Costs

From the operator and government perspective, the introduction of a mobility hub brings along costs. Two types of costs are important to take into account: the one-time investment costs and the operating costs of the mobility hub. The investment costs will be mostly relevant for the government, as these costs are mostly covered by a local/regional/national government, whereas the operating costs are more relevant for the operator. As a proxy for both costs, the connection to the current road and public transport networks and the physical land suitability are the measured attributes.

Attribute: Connection to the road & public transport networks

For the government, the connectivity to the road network relates to the costs. A road should be constructed to connect the mobility hub with the main road network, as road traffic flows may become too high for the local road network to process. As an indication of the length of the road and therefore the construction costs, the distance to this main road network is used as attribute. The same holds for the connection to the regional cycle route network, as bikesharing will generate traffic that will use this cycle route network.

For the operator, the connectivity to the public transport network is relevant, as costs are involved when adding or rerouting bus lines. This factor is composed of the distance to the public transport (bus/tram) network, a measure of the rerouting distance of transit lines, and the presence of a train stop. This distinction is necessary, due to the inflexibility of the rail (train/metro) network compared to the bus/tram network.

The bus/tram rerouting distance is a measure for the additional costs involved for the public transport operator due to the rerouting their lines via the proposed location. Ideally, the exact cost of rerouting and upgrading an existing public transport line (towards the city center) is used as attribute, but simplifications should be made as those costs can not be calculated directly, being based on many case-specific characteristics. The best possible approximation is the distance to a high-quality bus/tram line, to give an indication of the additional infrastructure and vehicle hours needed to redirect the service via the mobility hub.

Concerning railway lines, there is a fundamental problem which arises when adding a new stop, for example to place a regional mobility hub. An extra stop causes a change in the stop density of a railway line (Egeter et al., 1990), which is disadvantageous for the overall speed of the railway system. There are two solutions to this problem: combining the mobility hub with current stops, or expanding the public transport offer. Expansion is not always a possibility, for example in The Netherlands. The Dutch railway system is reaching its limits concerning the infrastructure, according to the railway infrastructure manager ProRail (Jacobs, 2017b). Therefore, the presence of a railway station, which might combine with a regional mobility hub, is taken as attribute to measure the connectivity, instead of the presence of a railway line. This train station should be well-integrated with the mobility hub, because short walking times are key to the success of a mobility hub.

Attribute: Physical land suitability

With respect to the costs of integrating the mobility hub, the physical integration in the available space is most relevant. For the construction of a regional mobility hub, space is needed to accommodate a public transportation stop, bike/car parking and sharing and additional facilities. Comparing the land usage of these facilities, car parking will require the largest area of land. Therefore, the presence of a car parking facility would ease the integration of the mobility hub significantly. Furthermore, the integration with respect to existing structures should be noted, as relocation of these structures would bring along high costs. The zoning plan should allow for the integration of a mobility hub, so the presence of, for example, an environmental protection area makes it more difficult, and with that more costly to implement the hub.

The land should be acquired from a land owner. Land could possibly be in possession of the municipality, leading to a lower integration cost, as the acquisition of land is against a cost. Publicly owned land is generally less expensive than privately owned land (Faghri et al., 2002), therefore this will be taken into consideration in the evaluation of regional mobility hub locations.

3.4.3 Link to surroundings

The economic importance of the mobility hub, as described in the previous chapter, leads to the link to surroundings criterion. The inclusion of other facilities in the mobility hub, like retail, catering and parcel pick-up points, improves the potential of a mobility hub. To incorporate this factor in the location potential, the presence of one of these relevant facilities in an area can be used, as this provides an opportunity to integrate mobility at that location. For example, the presence of a supermarket would lead to a higher potential for a regional mobility hub, as the mobility function can be integrated with the existing economic function in the area.

Attribute: Facilities in the surroundings

A selection of facilities should be made in order to include this criterion in the analysis. Based on the features that can offer an added value for the mobility hub, established in the previous chapter, the following facilities are relevant: a library, healthcare facility, sports center, grocery store, parcel pick-up point and retail facilities. The presence of these facilities at a location leads to a higher mobility hub potential due to the potential collaboration/integration of the mobility function with the economic function.

3.4.4 Generalized travel costs

Incorporating the costs for the end user is more difficult due to the disaggregated nature of the data. The saved costs/time when using the mobility hub at a specified location is important for the end user, but for the mobility hub location, an aggregation of all these costs/time savings would be relevant. To give an indication of these savings in an aggregated attribute, the connection to the current main road and cycle network is used, which is related to the additional travel time and costs imposed when driving/cycling to the mobility hub.

Attribute: Connection to the road networks

The road network connectivity is the leading factor in determining the additional costs/travel time for users, and this factor is split up in two parts: The distance to a main road/highway and the distance to a regional cycle route. More information on the distance to a main road is found in a paper on the usage of GIS to determine the best locations for a Park&Ride facility in the United States (Farhan and Murray, 2005). In this paper, the street network and locations of users and major activity centers are input for a model. The model determines whether the location of the Park&Ride facility is in the travel direction of the user. If not, it should be within an acceptable deviation and additional travel time of the direction, to be of any use to the user. As the determination and aggregation of every individual additional travel time for every single area in the region would require too much calculation time, a simplification is done in this thesis. The absolute distance to the main road/highway is used to measure this condition. There is no general value for the maximum distance a user is willing to deviate in order to use a use a mobility hub, so an arbitrary maximum value should be adopted.

As the (electric) bike is an upcoming alternative to public transport and the car as commuter mode (van Esch et al., 2013), the distance to a regional cycle route is taken into account from the end user perspective. The most preferred situation is the location of a mobility hub along the route, this would give the highest value for this criterion. In case the mobility hub is not located along a regional cycle route, an additional cycle path from the hub to the regional cycle route should be constructed, leading to additional travel time (so generalized travel costs) for the end user.

3.4.5 Impact

For the traveler, current traffic problems lead to additional travel time and a lower travel time reliability for their trip. Furthermore, for the government, these traffic problems have consequences. The quality of life in the city and around the main roads, along with the accessibility of a city, decreases due to congestion, whereas pollution and nuisance cause problems for the inhabitants of a municipality. These problems can exist in the city which is served by the regional mobility hub, or on the route to/from the city.

Additionally, the regional mobility hub can have a positive impact on the accessibility of an area. Both the connection between the region and the city center can be improved by placing a regional mobility hub, and the accessibility of a region itself can be improved by providing shared mobility and a connection to the public transport and road network. To be sure of the impact of the researched mobility hub location on the traffic problems, the occurring congestion and the region's accessibility should be redetermined upon introduction of a regional mobility hub in every area of the region.

Attribute: Improvement in region's accessibility

The improvement in a region's accessibility can be measured in terms of the increase in facilities and workplaces that can be reached from the selected location within an arbitrary travel time, due to the introduction of a regional mobility hub. This change in accessibility should be determined for every area in the region of choice.

Attribute: Presence of parking issues in the served city

The presence of parking issues in the served city might indicate a need for a regional mobility hub, as the provision of a replacement for the car, or transfer of the car to a different modality tackles the limited space problem in the city. Car parking is therefore provided at the regional mobility hub. Shared modalities and public transport require less space in a city, so these parking issues are mitigated for both the end user and the government when the regional mobility hub is used.

Attribute: Solving congestion around the location

The aim of this attribute is to give a higher score to locations from which the car route to the city center is congested. In this way, it is attempted to improve the score of locations upstream of where the congestion occurs, as a location in the middle of or downstream of the congestion is a less favorable location for a mobility hub, since users will encounter congestion before reaching the hub in that case.

This aspect is crucial for determining the sustainability impact of the mobility hub. When the facility will decrease traffic problems in and from/to the city, pollution will be decreased, leading to a sustainable transportation solution offered by the regional mobility hub. This marks the importance of this aspect from both the government and end user perspective.

3.5 Method application

As the attributes of the criteria are known, the methodology can be validated by means of an application to a case. This method application also aims to give an idea of how the results of the methodology will look like, and serves as a guideline for potential users of the methodology. In chapter 1, the steps are clearly explained, which are as follows:

1. **Region selection**: In the application, the first step is to select a region for which the regional mobility hub potential will be evaluated.
2. **Expert interviews**: Experts are interviewed to gather information on the weights for the trade-offs between the criteria, in order to be able to execute the AHP for criterion weighing, and to provide additional insights in the facilities included in a mobility hub.
3. **Scenario formulation**: Multiple scenarios with varying stakeholder configurations are developed, in order to gain more insight in the differences in the result when changing a stakeholder group influence.
4. **GIS tool selection**: A GIS tool is selected that is able to execute the developed methodology in an application.
5. **Data gathering**: The needed data to operationalize the attributes is gathered from various sources. The data sources should be found by an internet research and additional information from experts.
6. **Data preparation**: The data is prepared for usage in the GIS tool, by means of the value scaling procedure described in subsection 3.3.1. Additional preparation might be needed in case the data is not in the right format.
7. **Method execution**: The method application is executed, leading to the results.

The result of the methodology is the potential of a regional mobility hub for every area in the region, in other words: the score of the locations from the end user, operator and government perspective. From the end user perspective, this score is high when more travelers are intended to use the mobility hub. From the operator perspective, the location of the mobility hub with regard to the existing public transport infrastructure is important. From the government perspective, the mobility hub as a solution to quality of life issues and greenhouse gas emissions is relevant. The result is visualized in a heat map covering the selected region, consisting of a separate map for every scenario.

Chapter 4

Method application: Rotterdam region

This chapter provides an application of the developed methodology, in which the steps defined in section 3.5 are followed. Firstly, a region is selected, where after expert interviews are performed and the findings from these interviews listed, leading to a determination of criteria weights for the analysis. Subsequently, scenarios with varying stakeholder configurations are presented, and a GIS tool is selected to execute the calculations. This is followed by a selection of used data sources, and from this input data, several limitations and assumptions follow. These limitations and assumptions are shortly described in a separate section. Then, the data is prepared, after which the final step is executing the method application.

4.1 Region selection

In order to apply the methodology on a region, the region should be determined in the first place. From the introduction, it become clear that this choice should be made by considering existing congestion and quality of life issues in the region. In addition, it must be determined whether the needed data for the operationalization of the attributes can be gathered for the specified region, by exploring the available data sources for the region. Due to a higher data availability and the familiarity with data from the Netherlands, the region selected for the application will be situated in this country.

Concerning congestion, traffic problems in The Netherlands mainly concentrate around Rotterdam. Six locations out of the top 10 traffic jams in The Netherlands in the first months of 2020 are located close to Rotterdam, on highways leading to/from or along the city (Rijkswaterstaat, 2020). Combined with high parking fares and a low parking capacity in the city center (ANWB, nd), there is a demand for alternatives to reach the city center of Rotterdam.

A traffic model is expected to be an important data source for the method application. Therefore, a region should be selected for which a detailed traffic model is developed. Traffic models for every region are developed by the government, in a model called the Dutch Regional Model (NRM), but the level of detail should be noted for the reliability of the method application results. For example, the NRM West contains 735 zones for the province of Zuid-Holland (Provincie Zuid-Holland, 2019). This is approximately detailed up to the level of the four postal code digits, which is neighborhood level. For the potential determination methodology developed in this thesis, this is not detailed enough, as information on zone productions and attractions has to be accurate enough to produce distinctive results for different parts of a neighborhood.

To be sure of the availability of a traffic model for the investigated region, the expertise of Sweco is consulted. For the region of Rotterdam, the traffic model is easily accessible. On the basis of this certainty of data and the potential added value of a mobility hub in that region, the region of Rotterdam is selected.

The region of Rotterdam is located within the metropolitan region of Rotterdam-The Hague (MRDH). The MRDH is a collaboration of 23 municipalities, established to improve the accessibility and the economy of the region (Metropoolregio Rotterdam Den Haag, 2020). This region is one of the most important areas in The Netherlands, with 2.4 million inhabitants and 1.2 million jobs. The MRDH also fulfills the role of public transport authority, being responsible for the public transport in the region. The position of the Rotterdam region in The Netherlands is shown in Figure 4.1.

Figure 4.1: The Rotterdam region with respect to The Netherlands, adapted from Rijkswaterstaat (2020). Orange and red stretches on the left map represent congested roads.

The MRDH itself created a report on the future of mobility in the region (de Kleuver et al., 2020). The mobility transition already started, but measures are needed to ensure a high safety and quality of life in the city. The combination of multiple measures can help in keeping the city livable, whereas individual measures would not lead to the desired effect. A combination of mobility hubs (both regional hubs at the city borders and inner-city hubs) and measures to reduce car traffic in the city would be effective. The mobility hub network has the function of a place where car users can transfer to either high-quality public transport or bike to reach the city center. This mobility hub network is further investigated in chapter 5, in which the proposed hub locations are compared to the output of the method application. Other suggested measures to reduce car traffic are congestion charging, reducing the speed limit and increasing the parking fares.

For the 'Road users from/to city along nearest access road' attribute in the GIS-MAMCA, a definition of the city center of Rotterdam is required. This is defined by the zone in which the highest parking fares can be found, which is the area within the S100 city ring road, extended by the area between the S100 and the Nieuwe Maas river on the south side, and the area between the S100 and the railway tracks on the northern side. This area is in line with the definition of the city center established by the municipality of Rotterdam (Gemeente Rotterdam, 2019). The exact location of the city center of Rotterdam with respect to the region is visualized in Figure 4.2.

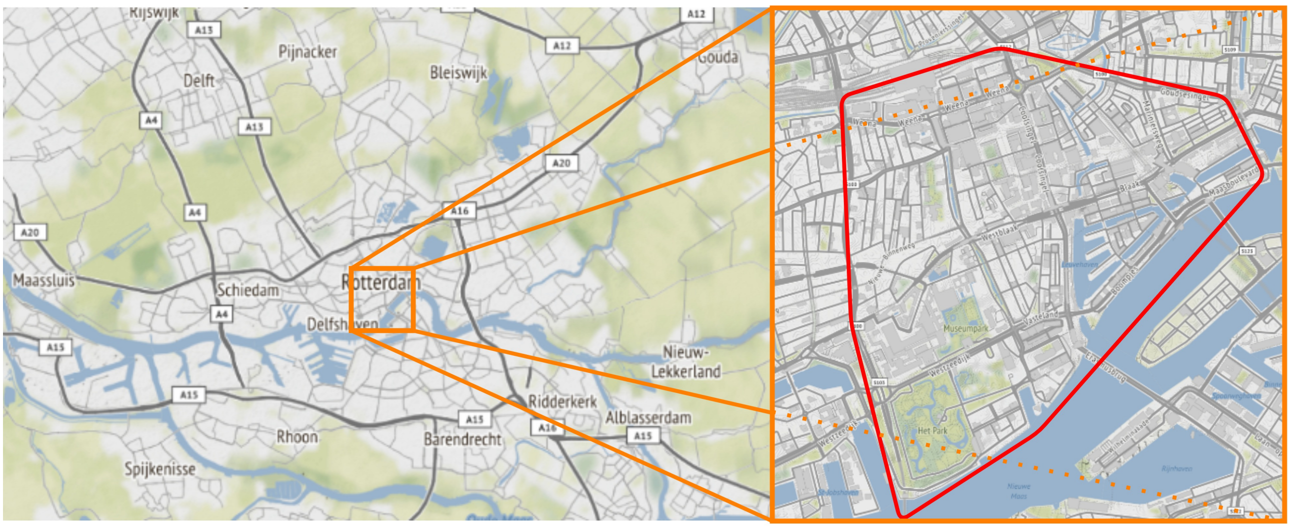

Figure 4.2: The city center of Rotterdam with respect to the region. The red line is the city center border.

4.2 Expert interviews

One of the procedures required in the application of the GIS-MAMCA is a criteria weighing procedure. To carry out the procedure in this thesis, the AHP is adopted. In the AHP method, criteria are compared in pairs by the stakeholders, after which the final criteria weights can be calculated. To be able to obtain information on the comparisons, expert interviews are conducted. The experts can be independent, or part of one of the three perspectives: the end users, operators and governments. In order to have all perspectives represented in the methodology, experts from all stakeholder groups are interviewed. This section provides an introduction to the interviewed organizations, the motivation for choosing these specific organizations, their relationship with either the (regional) mobility hub or mobility in the Rotterdam region, and the relevant information gathered from the interviews. Due to the availability of close contacts, and the fact that the selected region is situated in The Netherlands, the scope of the expert interviews is limited to Dutch organizations. Next to the gathering of information on the trade-offs, the expert interviews provide additional insights in the facilities included in a mobility hub, and a vision on the future of hubs in The Netherlands.

Independent experts are consulted throughout this research, to obtain a second opinion on the elements of the methodology, in order to create a widely supported overview of criteria. The short calls with employees of Sweco are not mentioned in this section, but these calls provided input for chapter 3 as well as this chapter. Next to Sweco, a research group linked to the Technical University of Delft, SmartPT Lab, is relevant to consult, due to their current projects on Mobility as a Service.

From the government perspective, experts from the municipal and provincial government, or regional collaborations are relevant. For example, the provinces of Noord-Brabant and Gelderland did research on the topic of mobility hubs. The municipality of Amsterdam is currently studying the mobility hub (both regional and city hubs), while in Groningen+Drenthe, the 'Kerngroep' mobility hubs is established by a collaboration of the provinces of Groningen and Drenthe, and the municipality of Groningen. This group and the named municipality and provinces are relevant to consult, as the regional mobility hub has been under investigation by these organizations. For the region of Rotterdam, the municipality of Rotterdam is the most relevant organization, as this municipality is engaged in the development of hubs. Surrounding municipalities (Schiedam, Lansingerland, Capelle aan den IJssel, Ridderkerk, Barendrecht and Albrandswaard) can be e-mailed to find out whether any knowledge on the topic of mobility hubs is present.

From the operator perspective, experts can be found at organizations serving the hub, like the public transport company, or bike/carsharing operator. These companies can also be the operator of the mobility hub. NS, Arriva and Keolis are of further interest, as these companies are big players in the field of public transportation in The Netherlands, currently dealing with shared mobility and mobility hubs as well. Keolis stated in an interview with a Dutch public transport magazine (Jacobs, 2017a) that Keolis is occupied with a change from public transport provider to mobility provider. NS plans on integrating shared cars into the application (Rottier, 2020b), whereas the company already provides a shared bike system, the OV-fiets. Arriva has won a tender for a MaaS-pilot in the Dutch province of Limburg, integrating shared bikes, shared cars, taxi and public transport (Jacobs, 2019). In the region of Rotterdam, two organizations are relevant. The mobility hub operator Hely has three mobility hubs in service in the Rotterdam region (Hely.com, 2020), although two of the hubs are situated in an extremely urbanized area. The organization RET is the current public transport operator in the city of Rotterdam, their public transport lines also serve less urbanized areas in the region. Furthermore, RET is part of the Dutch mobility alliance, a collaboration of 25 Dutch companies which is established to improve on the future of Dutch mobility (Mobiliteitsalliantie, 2019). This alliance is occupied with innovations in the mobility sector, including Mobility as a Service and mobility hubs. On these grounds, RET is an essential organization to interview for this thesis.

From the end user perspective, experts can be possibly contacted at local or national traveler associations like Rover. This association acts on behalf of the interests of all public transportation travelers in The Netherlands, and might have information on the users needs with regard to a (regional) mobility hub. The association for people driving for business purposes (VZR) will be contacted as well, to find out which criteria are important for this group of end users. In addition, the ANWB is found to be relevant for this thesis. This organization provides services to car users, such as insurances, a route planner and an overview of parking/Park&Ride facilities around cities. Their involvement in the regional mobility hub is therefore expected. The three aforementioned associations are identified due to their involvement in the Dutch mobility alliance. The organizations described in this paragraph are not tied to a specific area in The Netherlands, so an additional search for organizations in the Rotterdam region is not necessary.

The content of the interviews is very straightforward: a few questions are posed, starting with an introductory question, in which the role and background of the interviewee is asked for. This is followed by questions on the content, in which the view of the company (stakeholder perspective) on mobility hubs in general, and specifically on the location choice and criteria is sought. The interview is concluded by asking for general advice on the investigation. All interviews are conducted in Dutch, translated to English and verified with the interviewee for possible mistakes or misinterpretations. The full expert interviews can be consulted in Appendix C.

4.2.1 SmartPT Lab

One of the interviewed experts is from the SmartPT Lab @TU Delft. His research is on the (shared) modalities that should be integrated in the public transport network, how these different modalities interact and the adoption of these services.

It is important for a mobility hub to be situated at a current high-quality public transport link, and the location should be easily accessible by bike. For shared mobility, it is important that the quality of the vehicles is at a certain level, the vehicles are close to the public transportation node, the availability is high and the information is provided via an application. The adoption of this new, digital technology is hindered by digital inequality, resulting in some people not using the new shared mobility system at all. Concerning the offered modalities, the shared bike and car are the most interesting options. The e-moped is in service in several cities in The Netherlands and gains popularity, but is still less used than other shared modalities, and offers limited added value.

4.2.2 Gemeente Rotterdam

The municipality of Rotterdam, 'Gemeente Rotterdam', is the second largest municipality in The Netherlands by population, having just over 650,000 inhabitants (CBS, 2020). Regarding mobility, the population and number of workplaces make Rotterdam an interesting city to study. The city houses an extensive metro and tram network, stretching into adjacent municipalities. The ring road of Rotterdam appears multiple times in the list of the most congested road sections in the Netherlands (Rijkswaterstaat, 2020). Parking fares in the city center can be as high as €35 per day (Interparking Group, nd), a consequence of the shortage of parking places in the city.

The municipality is interviewed to add input from the government perspective. The criteria are the main focus of the interview. To prioritize the criteria from the government perspective, the interviewee is asked to prioritize the criteria adopted in the methodology. Additional input on the criteria is asked for as well in the interview.

The Gemeente Rotterdam has a few employees working on the topic of mobility hubs. Both small, residential hubs and higher level, strategic hubs functioning as Park&Ride or Park&Bike facility are supported by the municipality. The impact and the existing traffic problems should come first when establishing a mobility hub location. Furthermore, the physical suitability of the location should be considered in terms of land usage, whereas the other criteria in the methodology are less important for the mobility hub.

4.2.3 Arriva

Arriva is one of the market leaders in the public transport sector in Europe, with operations in 14 countries (BizClik Media Limited, 2020). The total number of buses operated by Arriva counts up to 20,000, plus about 1,000 train sets. A subsidiary of Arriva is 'Arriva Nederland', being one of the largest regional public transport companies in the Netherlands, with approximately 6,000 employees in different regions spread across the country. Currently, Arriva operates several bus lines just east of the region studied in this thesis, with a total of 8 bus lines extending into the region of Rotterdam. Furthermore, Arriva is also working on MaaS projects in the Netherlands, making it a highly relevant company to consult for the expert interviews.

This company is interviewed for the input from the operator perspective, therefore these criteria are discussed. For the operator, the demand and connectivity to the current public transport network are found to be influential criteria. These will be discussed, including the attributes leading to these criteria, whereas the criteria from the other perspectives are shortly mentioned to be able to gather additional input. The interviewed employee is manager transport engineering at Arriva Nederland, being responsible for the mobility strategy and development of timetables at Arriva.

According to the interviewee at Arriva, new mobility hubs are always placed on the basis of the current public transport network. Adding shared mobility is particularly interesting for an operator like Arriva to boost passenger numbers on their public transport network. That said, the potential demand is the most important factor for determining a mobility hub location. As Arriva will not operate a hub by itself, the suitability of the land is not of importance to Arriva. The occuring congestion on the road might indicate a higher need for a mobility hub, but in case of a bus connection to the city, this bus should use separate infrastructure to prevent the bus from encountering the same congestion as the vehicles on the road face. A final remark is the importance of incorporating the end user perspective in determining a hub location. The hub should provide an added value to the end user in order to become successful.

4.2.4 RET

RET is the public transportation provider in the city and region of Rotterdam, operating the bus, tram and metro system in the second largest Dutch city. RET provided for over 800,000 traveler kilometers in 2016, giving the company a market share of 12.4% in the regional transportation market, making it the fourth largest local/regional transportation company in The Netherlands (CROW, 2017).

The existing traffic problems in Rotterdam, together with the size of the company make RET a very interesting company to interview from the operator perspective. In Rotterdam, shared mobility is taking over the city center, with multiple shared e-moped systems in operation. RET should take this development into account, as it may be relevant for the future of their transportation system. That makes their opinion on shared mobility significant for this research.

For RET, shared mobility is only seen as a solution for the first/last mile of a public transportation trip. Shared mobility might be implemented at metro stops, and some bus/tram stops with a high passenger number. The potential demand is the most important factor determining the potential of a mobility hub, but as this is highly correlated with the presence of a public transport line, these criteria can not be prioritized. Availability of space is essential for the placement of a mobility hub, and areas in which the bus/tram network is less developed can also be interesting locations to introduce shared mobility. An additional remark from the interview is the difficulty of involving all necessary organizations at a certain location. Some of these organizations might not be positive on the proposed location, and refuse to cooperate.

4.2.5 NS

An organization that could not be left out of the list is NS, the Dutch national railway company. The company has been the operator of the main train services in The Netherlands since the merger of several companies in the middle of the 20th century. The company is a semi-public company, as the state owns all shares of the company. NS provides not only train services, but owns the bike sharing company OV-fiets since 2008 and exploits all train stations in The Netherlands. The combination of public transport operator and potential hub operator makes NS a relevant organization to interview. Two interviewees working at NS Stations, the train station department of NS, are interviewed.

The quality of the mobility service is of high importance when designing a mobility hub. In the design of new locations for the OV-Fiets bike sharing system, the demand is the most important factor. Sometimes, a mobility hub can be placed at a location without a public transport connection, like the Park&Bike concept explored in Amsterdam. The definition used by the interviewee is a bit different from the definition in this thesis, as a mobility hub is considered a location where at least two traffic flows (in which walking is not regarded as a traffic flow) come together, but shared mobility is not necessarily included. The presence of facilities can improve the potential of a location for a mobility hub.

In the vision of NS, the accessibility of the Netherlands using public transport is one of the top priorities. A further goal is to let people walk/cycle to the station, instead of using vehicles with an engine. The choice for using public transport should be made before starting the trip, not halfway at a Park&Ride facility. Factors taken into consideration when locating a vehicle sharing system are the demand and the presence of a staffed bicycle parking. The latter causes lower operating costs for the system.

4.2.6 OV-Consumentenplatform Drenthe

The mobility hub network in the Dutch provinces of Groningen and Drenthe is named several times in this report, because this serves as an example for the investigated regional mobility hub. This network of over fifty mobility hubs, ranging from small-scale regional hubs in a regional urban context to a main train station (city hub), is established in the two sparsely populated provinces in the northern part of The Netherlands. All hubs are connected to the public transport network and include bike parking facilities. As not all hubs offer shared mobility, the Groningen/Drenthe definition of the hub differs from the definition in this thesis.

The OV-Consumentenplatform Drenthe represents the end users of public transportation in the province of Drenthe, and has been closely involved in the establishment of the hub network. The interviewee has been involved in the developments for regional mobility hub Gieten, a frequently used public transport node in Drenthe.

The success of current hubs is attributable to the presence of high-quality bus lines which offer seamless connections. All hubs in this region have been placed at pre-existing public transport stops. Integration of facilities at the hub make the trip more attractive for the end user. Important to note in the Groningen/Drenthe hub project is that the goal was to create a network, in which the maximum distance to reach a hub by bike/car is 15 kilometer. Hubs are required to connect to the existing public transport network. The presence of facilities might also be advantageous for the introduction of a hub, just as the connection to the car/cycle network. Traffic problems in the city have given a large boost to the popularity of hubs around the region's big cities. An essential consideration concerning the hub design is to create a sense of safety around the hub. A low sense of safety can, especially in a rural setting, lead to people avoiding public transportation.

4.2.7 VZR

As a member of the Dutch mobility alliance, VZR represents the interests of all business drivers in The Netherlands. This means that VZR is involved in the future of mobility from the traveler perspective, so the experts in this organization might provide relevant insights for this thesis. As commuters are an important target group for the regional mobility hub, this organization is specifically relevant.

The preferences of the end user are important to take into account when designing a mobility hub. The end user is only interested in case the mobility hub comes with an advantage to the user. This advantage can be found in either a gain in (reliability of) travel costs or time, or in additional facilities offered at the hub. The connection to the road network also proved to be important, looking at a case in Utrecht. Even more important than the travel time is the reliability of the travel time. This also relates to the psychological aspect of being caught in traffic, which proves to have a high influence on choices the end user will make.

4.2.8 ANWB

This organization, part of the mobility alliance, is mostly known for offering roadside assistance and insurance. ANWB is also engaged in the mobility transition and the future accessibility of cities. As ANWB is a lobbyist for road users in The Netherlands, this organization provides a highly interesting different perspective on the topic of mobility hubs.

It is often difficult to locate a mobility hub due to space issues. In a regional setting, this is less of a problem, but in cities it can lead to the hub being placed at an unattractive location. The hub should be of added value to the end user, whereas a transfer is rarely a welcome addition. This added value can be achieved by integrating facilities in the hub, and making the hub a socially safe place. Furthermore, the reliability of the travel time is of high importance to users. This also means that a shared vehicle should be available to users at all times in order to be reliable. The main target group that can be attracted to a mobility hub are the city visitors, as a change in behavior is the easiest to achieve for this group. The mobility hub is much needed since an alternative for private vehicles, especially in highly urbanized regions, is required.

4.2.9 Weight determination

A problem encountered in several expert interviews, is the shift of focus from the regional mobility hub to the city mobility hub. As most organizations are only familiar with the mobility hub in a city, it proved to be hard to gather information useful for a regional mobility hub. Besides, the interviews have not lead to an exact weight determination, as not all experts have the knowledge available to quantify the relative importance of criteria. Nevertheless, an effort is made to determine the trade-offs as accurately as possible. The outcomes of the expert interviews related to the criteria weight determination are listed below.

- From multiple interviews, it becomes clear that the mobility hub should be connected to the current public transport network. New mobility hubs are rarely placed at locations which are not connected to the public transport network, only locations with a current bus/tram stop are being considered as mobility hub location. However, the mobility hub can also serve as an expansion to the public transport system in poorly connected areas.
- The potential demand can be seen as the most important factor in finding a mobility hub location. The success of a hub hinges on the potential passenger numbers, in order to minimize the losses arising from the mobility hub construction.
- The mobility hub requires a convincing business case, before the project will get approval from the paying authority (usually the government). Therefore, costs are of high, if not the highest importance in the project.
- It becomes clear from the VZR interview that the reliability of the travel time is very important to the end user, even more important than the generalized travel costs. An unreliable trip has a high impact on the user appreciation of the trip.
- A mobility hub location should have an easy access to the cycle network, as shared bikes will be the most important shared modality offered at a mobility hub. The access to the road network is of importance too, mostly for travelers using the hub as a transfer point from/to the private vehicle.
- In finding a mobility hub location, the physical space available at that location should not be the first priority. Space should be allocated to a mobility hub because of its societal importance. However, the space availability can complicate the construction of a mobility hub, so the physical suitability of a location should be taken into account in some way.
- The presence of facilities, like a library, can increase the potential of a location for a regional mobility hub. Furthermore, the presence of staffed bicycle parking facilities can lead to an easier and less costly integration of shared bikes.

For the operator, the two involved criteria are the potential demand and the costs. Both are of high importance to the operator, as a connection to the current public transport system is required by the operator, just as a certain demand. When asking the experts for a comparison in importance between these two criteria, the potential demand is mentioned as the most important criterion. This is partly due to the expected government contribution to the costs.

The government is interested in the costs, the link to the surroundings and the impact of the mobility hub. The suitability of the location is important, which is incorporated in the costs criterion. The societal problem leading to this research can be found in congestion and space issues in cities, therefore the impact criterion should have the highest importance from the government perspective. The link to surrounding facilities is mentioned in the interviews, but not particularly important for the government, so this criterion is given the lowest value in the trade-offs.

The criteria of interest for the end user are the generalized travel costs, the link to the surroundings and the impact. For the end user, it is very important that the hub provides added value, and this added value can be achieved by the integration of facilities at the mobility hub. Pre-existent facilities at a location result in a higher potential for a mobility hub. Furthermore, the generalized travel costs have an influence, which is smaller than the influence of the link to surroundings criterion, on the location potential, but much more important is the impact. For the end user, a high impact of a hub can lead to an increase in travel time reliability, because of a reduction in traffic problems. Additionally, the improvement in a region's accessibility is important for the users in the region, further increasing the importance of the impact criterion.

The trade-offs between the criteria as determined from the expert interviews are given per perspective in Table 4.1, Table 4.3 and Table 4.2. If the criterion in the row is more important than the criterion in the column, the value is higher than 1. The opposite is true for the more important criterion in the column. All trade-offs per criterion are consistent, as all trade-offs match each other, so determining a trade-off based on two other trade-offs leads to the same value for the trade-off.

Table 4.1: Trade-offs for the method application from the government perspective.

Government perspective	Costs	Link to surroundings	Impact
Costs		2	0.5
Link to surroundings	0.5		0.25
Impact	2	4	

Table 4.2: Trade-offs for the method application from the end user perspective.

End user perspective	Generalized travel costs	Link to surroundings	Impact
Generalized travel costs		0.5	0.25
Link to surroundings	2		0.5
Impact	4	2	

Table 4.3: Trade-offs for the method application from the operator perspective.

Operator perspective	Potential demand	Costs
Potential demand		2
Costs	0.5	

The steps taken to convert the trade-offs to actual weights are according to the AHP, a widely used weighing methodology for a Multi-criteria analysis which is also frequently used in the GIS-MCA and MAMCA (Macharis and Ampe, 2007). The exact steps are elaborated in Appendix B.

4.2.10 Other lessons from the expert interviews

The expert interviews did not only provide insight in the weighing of the criteria in this methodology, but also lead to a better understanding of other aspects of the mobility hub, like the features which should be included in the facility. This list will not influence the results of the methodology and its application, but the lessons can be incorporated in the design process of the regional mobility hub. Therefore, some of the findings are reflected in the recommendations for policy makers.

- The mobility hub should provide an added value to users, in order to prevent the hub from being unused. This added value can be offered in terms of additional facilities, or a gain in travel time/costs/time reliability. The facilities relate to the design and the economic function of the hub, the gain in travel time/costs/time reliability relates to the mobility function and the location of the hub.
- Next to the added value, basic user needs should be satisfied by the mobility hub: walking distances between modalities must be kept small, the certainty of availability of a shared vehicle must be very high and the shared mobility must satisfy quality standards imposed by the end user. Additionally, an integrated tariff for all mobility services is desired by the end user.
- For the public transport operator, the mobility hub is considered as an extension of their public transport network. From their point of view, the hub should increase passenger numbers on their network, it should not replace existing public transport services.
- A mobility hub is highly relevant and needed in this era, as inner cities become increasingly congested, and local and national governments aim to reduce both parking issues and emissions in their city centers. The fact that the private vehicle is inefficient, as it remains unused for 96% of the time, has a positive influence on the future potential of shared mobility and (regional) mobility hubs.
- Space within city centers is scarce, and strategic locations will probably not be assigned to mobility hubs in the first place, as other functions (housing, office space) can be of higher importance for policy makers. For regional mobility hubs, this issue is less relevant.
- One very important aspect of the mobility hub is the sense of safety in and around the hub. The hub will become a place to stay and safety is one of the leading factors in achieving this. Furthermore, an unsafe facility will deter people from using the hub.
- A change in behavior among travelers is not easy to achieve. This makes the mobility transition (to shared mobility and mobility hubs) difficult, as people will not automatically shift to a different modality when it becomes a more attractive alternative. A major impulse is needed to achieve this change, and the current COVID-19 pandemic can be a good opportunity for this modal shift.

4.3 Scenario formulation

The result of the regional mobility hub potential determination methodology will be a visualization of the potential for placing a mobility hub, but there will not be one result. Five scenarios are established, in which the influences of the different stakeholders vary. These scenarios are created with the assistance of Sweco, in order to incorporate important practical experience in the methodology. The criteria will be evaluated according to the following scenarios:

1. Scenario 1: All stakeholder groups are equally important: 33.3% operator, 33.3% government, 33.3% end user.
2. Scenario 2: The government is more important than the other stakeholders. This is a realistic scenario, as the government has the largest financial contribution to the project. In most cases, the government makes the final decision whether the hub development can proceed or should be stopped. The stakeholder influence in this scenario: 16.7% operator, 66.7% government, 16.7% end user.
3. Scenario 3: The stakes of the end user are the most important in this scenario. This scenario is realistic when focusing on the interests of the end user, which is an important approach, as the number of end users determines the success of a hub. The stakeholder influence in this scenario: 16.7% operator, 16.7% government, 66.7% end user.
4. Scenario 4: The operator is allocated the highest influence weight in this scenario. This scenario is useful, as the operators are the providers of the services at the mobility hub. A low potential of a location from the operator perspective will lead to a lower willingness of the operator to offer their services at the regional mobility hub. The stakeholder influence in this scenario: 66.7% operator, 16.7% government, 16.7% end user.
5. Scenario 5: In this scenario, the weights are equally distributed over the three stakeholder perspectives. What changes in this scenario is that the costs criterion is given a three times higher weight in scenario 5 compared to the original weight in the trade-offs, from both the operator and government perspective. This scenario is realistic in present times, as governments are currently very hesitant when it comes to funding new projects. Furthermore, the costs criterion has a high level of uncertainty, as no literature on the costs of a mobility hub is consulted, so the costs might be a lot higher than expected.

Using the defined scenarios, the final weights resulting from the trade-offs in subsection 4.2.9 are established. The criteria weights in Table B.2 are multiplied by the stakeholder weights for the corresponding scenario. The resulting weights for every criterion in the scenarios are found in Table 4.4.

Table 4.4: Weights allocated to the criteria in the scenarios used in the method application.

Criterion	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Potential demand	0.2222	0.1111	0.1111	0.4444	0.1333
Costs	0.2063	0.2460	0.1032	0.2698	0.3818
Generalized travel costs	0.0476	0.0238	0.0952	0.0238	0.0476
Link to surroundings	0.1429	0.1429	0.2143	0.0714	0.1255
Impact	0.3810	0.4762	0.4762	0.1905	0.3117

4.4 GIS tool selection

In order to execute the GIS-MAMCA, a GIS tool is needed that is able to do the necessary calculations. The tool must handle the imported files containing the data on the attributes, and combine this data into a resulting score for every area in a selected region. The input format of the data is not yet determined, but Shapefiles for usage in a GIS tool are expected in any case. Support for a large range of file formats makes a GIS tool more suitable for this application.

To find out which tools are capable of performing the necessary calculations, an internet research for a Multi-Criteria Analysis using GIS is executed, and experts at Sweco are consulted for the GIS tools used within the company. Three GIS tools resulted as being suitable for usage in this thesis, which are QGIS, ArcGIS and FME. All three tools have been used in previous researches for performing a Multi-Criteria Analysis (Gandhi, 2019; Majury, 2013; Environmental Systems Research Institute, Inc., nd)

In ArcGIS, multiple data sets can be combined into one result, using weighted overlay. In weighted overlay, multiple rasters containing integer values are used as input, such that the GIS tool can calculate the resulting value in every grid, given the weights. Each input criteria layer should be reclassified into a common preference scale, to be able to combine the layers (Environmental Systems Research Institute, Inc., nd). Next to the weighted overlay, a weighted sum method exists in the application. Since the weighted overlay method can only handle integer values, the weighted sum method is better suitable for this thesis, since this method can handle both floating point and integer raster layers. Proximity tools are used in ArcGIS to measure distances, for example the distance to the highway. This is calculated as the shortest distance from a point (or grid) to a point on the line.

The application QGIS has also been used for performing a multi-criteria overlay analysis (Gandhi, 2019). This methodology is described to be used in site-suitability analyzes. Firstly, all source vector data should be converted to raster data, then the criteria values for each area can be calculated. What follows is an overlay operation to calculate the suitability of every site, based on the used criteria. The suitability of every site can then be displayed on a map.

In FME, each area can be evaluated to a set of criteria and corresponding weights (Majury, 2013). This has been used to design a tree planting plan for a UNESCO World Heritage site in Sweden. After the data preparation and evaluation of non-feasible sites (dependent on certain criteria), the multi-criteria analysis is applied, meaning that each area is evaluated by multiplying criteria values to their weights to calculate the potential of a site for planting a new tree.

Taking into account that all three tools meet the specified requirements, the final decision for a GIS tool was made based on expert judgement of employees at Sweco. Based on their ideas on the user-friendliness with regard to importing files, doing calculations and exporting data, FME is recommended. This recommendation is accepted in this thesis.

4.5 Data sources

The next step in the method application is the gathering of the actual data, needed to measure the criteria in the analysis. Mentioned in chapter 1 is that the data should be available, complete and reliable, in order to be useful for the method application. The overview of criteria and corresponding attributes is shown in Figure 1.

4.5.1 Attributes in the method application

The collection of input files is a time consuming process, as a lot of different data sources are consulted in the search for useful data. For every attribute, the possible input data is looked into by means of an internet research, supported by the insights of experts at Sweco. After finding the needed datasets, every discovered file should be analyzed on included information, format and usability. Furthermore, some time passes between requesting the needed files and receiving the files from the responsible authority. The data sources resulting from the search are specified per criterion in the following paragraphs. An overview of all attributes used in the method application and the corresponding data sources can be found in Table 4.5.

The potential demand attributes could possibly be extracted from a traffic model. A traffic model contains an estimation of all trips that are made within a region, and the assignment of the trips to the roads in the region.

For the (generalized travel) costs, multiple data sources are needed. Information on the public transport and road network can be gathered from various sources. Topographic data includes information on the main road and cycle route network, and possibly information on the public transport network. All information can also be extracted from the traffic model. For the cycle route network, a database containing all routes is also available in The Netherlands. Multiple possible measurements of the land suitability come forward from chapter 2 and chapter 2: The presence of a parking area, the physical suitability concerning land usage and the land owner. The presence of a parking area and land usage might be available in a topographic dataset, but information on the land owner should be requested from the municipalities in the region.

The facilities in the surroundings can be operationalized in multiple ways, as a topographic dataset might include information on the usage of buildings in the region. However, when incorporating the function of a building into the analysis, the importance of the building is not captured. From the features of a mobility hub described in chapter 2, it resulted that the retail function is the most important economic function of the mobility hub. This data might be captured, at a slightly less detailed level than the topographic data, by the information on the number of retail workplaces from the traffic model.

The most difficult attributes to find data for, are the impact attributes. The 'Presence of parking issues in the served city' attribute does not change across the region, as the served city (Rotterdam) is the same for all areas in the Rotterdam region. Therefore, the choice is made to not include this attribute in the model application. However, in this case, the city of Rotterdam is a city which has parking issues in the city center, and therefore the city center (the zones with the highest parking fares) is the zone for which the traffic from/to is measured for the demand. This simplification is, among the other assumptions and limitations of the methodology and its application, addressed in section 4.6.

The improvement in a region's accessibility can be measured by finding the accessibility of the region before and after the implementation of the mobility hub. This could be measured using a traffic model. However, the choice is made in this thesis to not insert locations into a traffic model, as this would a high number of traffic model variants, as explained in section 4.6. Therefore, the number of users within the catchment area of the regional mobility hub is taken as a proxy for this attribute, as data on this proxy is available in the traffic model. This is not exactly the same as the accessibility, as the accessibility relates to the travel time of the users, but no aggregation of all travel times in the catchment area of a hub is available for this research. The same issue arises in finding the degree to which the mobility hub solves the congestion around the location: this should be recalculated in a traffic model. What can be easily measured is the current congestion around the hub, by taking the maximum value of the road congestion in the vicinity, measured by dividing the intensity of a road by the maximum capacity (the I/C-ratio). Generally, an I/C-ratio of more than 0.7 on a multi-lane highway with a speed limit of 80 km/h, which is common on highways near a city and on main roads in general, means that the Level of Service is in the category D (City/County Association of Governments of San Mateo County, 2005). This letter is used for roads approaching unstable operations, as a small increase in volume can produce high increases in delay. To be able to capture roads which might become congested in case of increasing mobility in the near future, roads with an I/C-ratio of more than 0.6 are taken into account in the application.

Table 4.5: The criteria and attributes from the methodology, with the corresponding attribute and the data source for the method application.

Criterion	**Attribute (methodology)**	**Attribute (method application)**	**Data source**
Potential demand	Trip production/attraction in catchment area	Production/Attraction	Traffic model (V-MRDH 2.6)
	Road users from/to city along nearest access road	Traffic along road from/to city center	Traffic model (V-MRDH 2.6)
Costs	Physical land suitability	Presence of parking area	Topographic file (TOP10NL)
	Physical land suitability	Physical land suitability	Topographic file (TOP10NL)
	Physical land suitability	Land owner	BRK Rotterdam
	Connection to public transport network	Presence of high-quality bus/tram link	Traffic model (V-MRDH 2.6)
	Connection to public transport network	Presence of light rail/metro/train station	Topographic file (TOP10NL)
	Connection to the road networks	Presence of regional cycle route	National cycle route database
	Connection to the road networks	Presence of main road	Topographic file (TOP10NL)
Generalized travel costs	Connection to the road networks	Presence of regional cycle route	National cycle route database
	Connection to the road networks	Presence of main road	Topographic file (TOP10NL)
Link to surroundings	Facilities in the surroundings	Number of retail workplaces	Traffic model (V-MRDH 2.6)
Impact	Solving congestion around the location	Maximum I/C-ratio in vicinity	Traffic model (V-MRDH 2.6)
	Improvement in region's accessibility	Reached users (SEGs)	Traffic model (V-MRDH 2.6)
	Presence of parking issues in the served city	-	-

Full explanations of the attributes in the method application are found in the upcoming subsections on the individual data sources. It appears from the table that two attributes are both used to measure two criteria. This results in a correlation between the generalized travel costs and the costs, which can be logically explained by the methodology: an increase in generalized travel costs for the end user due to an additional distance leads to an equal increase in costs for the operator/government. This is due to an increase in distance that has to be covered by public transport to reach the hub, and additional construction costs for the road/cycle path to the hub.

4.5.2 Area size specification

One important choice is still to be made in this application: the size of the areas should be specified. This is necessary, because all attributes have to be calculated for every area, as the areas represent the evaluated alternatives in the GIS-MAMCA. The input data accuracy is leading in the choice for an area size, as choosing an area size which is smaller than the accuracy of the input data will lead to higher calculation times, without actually delivering more accurate results. Choosing an area size larger than the accuracy of the input data, will lead to a loss of detail in the result.

The two most important data sources used in this application are the traffic model and the topographic file, as the weights of the attributes which are measured by these data sources are the highest. Taking a quick look in the topographic file reveals that this dataset is very detailed, up to the level of an individual building. The traffic model is less accurate, as the distances between the zones (the smallest unit for which social-economic data is specified) in the traffic model are approximately 100-200 meter in urban areas. To make sure that the full potential of the input data is used while the calculation time is kept to a minimum, an area size of 100x100 meter is adopted in this method application.

The boundaries of the investigated region follow from the topographic data. The Netherlands is divided in 112 sections of 20x25 km in size in the topographic data, of which only one section is used in the method application in order to reduce the calculation time. The center of the used section is located very close to the city center of Rotterdam. The exact boundaries of the section are x coordinates 80,000 to 100,000 and y coordinates 425,000 to 450,000 in the Rijksdriehoekstelsel EPSG:28992 coordinate system.

4.5.3 Attribute weights within criterion

For all criteria except for the 'Link to surroundings' criterion, multiple attributes are used to measure the criteria. Therefore, trade-offs between the attributes are made to determine which attribute should be assigned a higher weight within the criterion. The justification of the weights are shortly described per criterion in the following paragraphs. The remark is made that this justification is based on information from the previous chapters, supplemented by own reasoning and insights from discussions with Sweco employees. Additional literature research is needed to make well-substantiated trade-offs, but for the application of the methodology in this thesis, this is left outside of the scope.

The two attributes in the 'Potential demand' criterion relate to the position of the mobility hub in the passenger's multimodal trip. The 'Production/Attraction' attribute relates to the users in the catchment area, whereas the 'Traffic along road from/to city center' relates to users that can potentially use the mobility hub as transfer facility to switch from the car to a sustainable and space-efficient modality. As both attributes are important and the information for an exact weighing is not available, the weights are set to equal importance.

The 'Costs' criterion is composed of many attributes, for which trade-offs should be made that concern the costs of a regional mobility hub in the selected area. The physical land suitability is the most important attribute from this criterion, as this can pose a constraint for the mobility hub location. The position relative to a regional cycle route is the least important attribute, since the costs of the construction of a cycle route are relatively low, compared to the other attributes. Looking at the other attributes, the presence of a parking area and land owner are considered as more important than the presence of a main road, station and high-quality bus/tram link, as a change in these attribute values might lead to a relatively higher increase/decrease in costs. All trade-offs are given the value 2 within the costs criterion, leading to a more important factor to be considered twice as important in the application. One exception is made for the presence of a regional cycle route, which is 3 times less important than the presence of a main road, station and high-quality bus/tram link attributes due to the large expected difference in costs.

For the 'Generalized travel costs' criterion, the importance of the presence of/distance to a main road and regional cycle route should be determined. In essence, this relates to the additional travel time users will face when using a hub in the evaluated area. As the regional cycle route (usually for longer distances) is assumed to be used by a smaller number of hub users than the closest main road, the distance to the main road is more important. However, the cyclist will need more time to cover the same distance compared to a car user. Therefore, the weight for the presence of a main road is limited to two, relative to the weight for the presence of a regional cycle route.

Within the 'Impact' criterion, two attributes are present: 'Maximum I/C-ratio in vicinity' and 'Reached users (SEGs)'. Not all mobility hub users will encounter the congestion, which is usually only present during peak hours. Furthermore, this attribute relates to the transfer position of the mobility hub, while the number of reached users relates to both the home trip end and activity trip end position. Taking these factors into account, the 'Reached users (SEGs)' is deemed as more important, and the factor 2 is used to give a value to the trade-off.

Based on the attribute trade-off values in this subsection, the weights of the individual attributes are determined. All weights assigned to the attributes in the five scenarios are shown in Table 4.6. The next step is to specify the data sources and the used measurement methods. In the following subsections, this will be described per data source. Firstly, the constraint following from Table 2.1 is introduced, as constraints should be addressed upfront according to the GIS-MAMCA methodology Figure 3.2. The relevant data for this constraint is given in the address density file.

Table 4.6: Weights allocated to the attributes in the scenarios used in the method application.

Criterion	Attribute	Importance in criterion	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Potential demand	Production/Attraction	1	0.1111	0.0556	0.0556	0.2222	0.0667
	Traffic along road from/to city center	1	0.1111	0.0556	0.0556	0.2222	0.0667
Costs	Presence of parking area	6	0.0364	0.0434	0.0182	0.0476	0.0674
	Presence of high-quality bus/tram link	3	0.0182	0.0217	0.0091	0.0238	0.0337
	Presence of light rail/ metro/train station	3	0.0182	0.0217	0.0091	0.0238	0.0337
	Physical land suitability	12	0.0728	0.0868	0.0364	0.0952	0.1348
	Land owner	6	0.0364	0.0434	0.0182	0.0476	0.0674
	Presence of regional cycle route	1	0.0061	0.0072	0.0030	0.0079	0.0112
	Presence of main road	3	0.0182	0.0217	0.0091	0.0238	0.0337
Generalized travel costs	Presence of regional cycle route	1	0.0159	0.0079	0.0317	0.0079	0.0159
	Presence of main road	2	0.0317	0.0159	0.0635	0.0159	0.0317
Link to surroundings	Number of retail workplaces	1	0.1429	0.1429	0.2143	0.0714	0.1255
Impact	Maximum I/C-ratio in vicinity	1	0.1270	0.1587	0.1587	0.0635	0.1039
	Reached users (SEGs)	2	0.2540	0.3175	0.3175	0.1270	0.2078

4.5.4 Address density file

To determine the potential of an area for placing a regional mobility hub, the set constraints for a regional mobility hub should be satisfied. The most distinguishing feature of the regional mobility hub with regard to the location is the urban context. A regional mobility hub is placed in a non-extremely urbanized area, i.e. an area with a address density of less than 2500 addresses/km², as explained in subsection 2.3.2. Insight into the address density is provided by a dataset containing demographic and economic statistics for all 500x500 meter squares in The Netherlands. The source of this data is Statistics Netherlands (CBS), an organization that publishes reliable statistical information of the Netherlands. The accuracy of the data is lower than the selected area size, which is 100x100 meter, possibly leading to some areas mistakenly not being evaluated in the method application, and some areas with an address density of more than 2500 addresses/km² being evaluated. The used data dates from 2019 and the dataset is available as open access Shapefile.

4.5.5 Topographic file (TOP10NL)

For the land usage, multiple datasets have been tested. In PDOK Viewer (PDOK, nd), it is possible to represent governmental open datasets in an online map viewer. The tested datasets are: CBS Bestand Bodemgebruik (BBG) 2015, BGT Standaard, TOP10NL and TOP25raster.

As an example to choose the right map, a parking area near Rotterdam is shown in the four investigated map types. The result can be seen in Figure 4.3. The BGT Standaard map indicates parking facilities (field 'bgt-functie': value 'parkeervlak'), but provides too much detail in the small area depicted in Figure 4.3. The BBG map only shows that the area is built-up, with no further detail. The TOP10NL and TOP25raster maps are suitable for the purpose. Since the TOP10NL dataset is available as gml file, which can be directly imported and read in FME, this dataset is more suitable than the TOP25raster dataset.

Figure 4.3: Comparison of the suitability of the four investigated maps from PDOK (nd).

The TOP10NL file is updated every year by Kadaster, and is part of the Key register Topography (BRT). The current file is dated from 2019. This is a reliable, governmental dataset, put together using aerial photography. In the documentation of this dataset (Kadaster, 2020), it is mentioned that the dataset is particularly suitable to use as basis for a GIS analysis. The scale of this file is 1:10.000.

Multiple object classes exist within the TOP10NL file, of which the terrain, building, functional area, design element and road section object class are relevant for the method application. The terrain element is the main element that determines the physical suitability of an area for placing a mobility hub, and the resulting value is corrected for unsuitable land usage by using the building and functional area object classes. The design element and road section object classes are used to determine the presence of a parking area/main road/station near the area.

Values in the range of 0 to 100 are given to the physical land suitability attribute of a 100x100m area, dependent on the type of land usage specified by the TOP10NL terrain dataset. A 0 value is given if the land usage is boat dock, basalt blocks, cemetery, railway track or sand. Placing a mobility hub at this type of land is not possible or very costly. The value is set to 25 if the land is used as cultivated land, orchard, tree cultivation, built-up area or woods. The value is set to 75 for areas with grassland or heath as land usage, whereas the maximum value of 100 is assigned to areas with other land usage. The value 'Other' in the topographic dataset is used for all non-categorized land, such as empty land, land in between buildings, parking areas and private industrial land. A building present in an area decreases the land suitability attribute value of an area by 75%, as relocation of buildings can be costly, whereas certain functional areas may further lower an area's physical land suitability value to 25 or 0.

The division of functional areas leading to a lower mobility hub potential is made on the basis of own judgement, with the information from the literature on the physical placement of a mobility hub in mind. The functional areas that lower the value of the attribute to 25 are:

- Botanical garden
- Campsite
- Trailer park
- Racetrack/motocross track
- Zoo
- Helicopter pad
- Ice rink
- Recycling center
- Open-air museum
- Production site
- Ski slope
- Power substation
- Garden center
- Holiday park
- Allotment
- Hospital
- Public swimming pool
- Barrack
- Sports field/tennis court
- Amusement park

The functional areas that make an area unsuitable for the placement of a mobility hub, leading to a physical land suitability attribute value of 0 for that area, are listed below. These areas are mostly areas that should be left untouched, like a nature reserve or cemetery, or areas that are very costly to relocate, like a wind farm or rail yard.

- Airport
- Cemetery
- Duck decoy
- Rail yard
- Oil & Gas installation
- Marina
- Nature reserve
- Recreation area
- Lock complex
- Watershed
- Wildlife crossing
- Wind farm
- Sewage plant

The design element object class of the dataset is used to extract the locations of all metro, train and light rail stations in the region. To exactly determine the value of the 'Presence of light rail/metro/train station' attribute of an area, a 5 minute walk, 400 meter distance, is used as standard to check whether there is a station available close to the evaluated area. The distance of 400 meter is based on the suggestion of keeping the walking distance low between the facility and transit service, a maximum of 0.25 mile (0.4 km) is recommended (Holguín-Veras et al., 2012). One of the unique characteristics of the mobility hub is the seamless transfer between modalities, so walking distances of more than 400 meter are not desirable. Therefore, the attribute value 0 is given to areas for which a station is not present within a 400 meter airline distance. The value 1 on this attribute is given to areas in which a station is located, and for all distances in between 0 and 400 meter, the value is calculated based on a linear gradient from 1 (0 meter) to 0 (400 meter).

The road section object class serves two purposes: it is used to find the locations of parking areas in the region, and it contains a complete overview of all main roads (A, N and S-road, being highway, primary road and a city access road respectively). These main road locations will be used to check whether an area is close to the main road network, as a shorter distance to the main road network implies that a shorter section of road has to be built to connect to the network. This reduces the costs for a mobility hub in that area. As literature on the (relative) costs of the construction of a road segment is not consulted in this thesis, an arbitrary maximum value for the distance to a road of 1000 meter is used in the method. The attribute value 0 is given to areas for which a main road is not present within a 1000 meter airline distance. The value 1 on this attribute is given to areas through which a main road crosses, and for all distances in between 0 and 1000 meter, the value is calculated based on a linear gradient from 1 (0 meter) to 0 (1000 meter).

The presence of a parking area is another measurement of the physical land suitability attribute within the cost criterion. This is due to a parking area being the perfect foundation for a mobility hub, as the surface is suitable for a mobility hub. Besides, the car parking facility of the hub consumes the largest part of the required hub space, so the pre-existence of such a facility reduces the costs for a regional mobility hub. For this attribute, either the value 0 or 1 is given, indicating the lack respectively the presence of a parking area in the evaluated area.

4.5.6 BRK Rotterdam

Related to the topography of the region is the land owner plan, from the Key register Kadaster (BRK). This file contains all lots within the municipality's borders and the corresponding land owner code. This land owner code refers to the owner of the land: the municipality or a third party. The other possible land owner codes are a partial ownership of the municipality, or the municipality has leasehold, right of superficies or easement on the property. In these special cases, the actual owner of the land will be used. The land owner dataset is available on request from the municipality of Rotterdam, in the Shapefile format.

To calculate the value for the attribute 'Land owner', only the sites for which the land owner code indicates a possession of the land by the municipality are incorporated. Then, in every area in the region, the percentage of land owned by the government is calculated. This results in a value of 1 for areas that are 100% in municipal possession, and 0 for areas that have a non-municipal owner and areas that are located outside of the municipality of Rotterdam. A value in between is given corresponding to the percentage of municipal ownership, if the land in the area is partially owned by the municipality.

4.5.7 Traffic model (V-MRDH 2.6)

The traffic model V-MRDH has been developed on behalf of the cooperation of the municipalities in the surroundings of (and including) The Hague and Rotterdam, the MRDH. The traffic model was developed as a tool for supporting policy decisions on traffic and mobility projects in the region. The current version (2.6) has been released in February 2020. Several variants are defined, corresponding to the year for which the variant is representative (base year 2016 and estimations for 2020, 2023, 2030 and 2040), in which a road network and public transport/cycle network are separately provided.

The information in this V-MRDH originates from official Dutch governmental sources (CBS, NRM, DUO and PAR), and is therefore deemed reliable. The region of The Hague and Rotterdam which is encompassed by the traffic model is divided into 7786 zones, of which 700 zones in the influence area and 386 external zones, not situated within the region, but included for modelling purposes. The zones contain relevant data for this thesis, this data is described first, where after the data from the traffic model links is elaborated.

Information on the facilities present in an area are found in the zones of the traffic model: the zones have a column describing the number of retail workplaces, which will be used to estimate the number and size of the relevant facilities in the evaluated areas. Some facilities are not included in this dataset, like important regional facilities such as a recreation area, library or sports facilities. This is a limitation of the available data which is added to the list in section 4.6. To exactly determine the attribute value, the retail workplace values of all zones within a 400 meter distance (the recommended maximum walking distance) of the area are included, and these values are multiplied by a factor to correct for the distance between the zone and the area. This factor is calculated based on a linear gradient from 1 (0 meter distance) to 0 (400 meter distance). All distance-corrected zone retail values are summed for every evaluated area in the region to arrive at the retail workplace attribute value.

Furthermore, the zones contain information on the ’Reached users’ attribute: the number of inhabitants, workplaces and number of educational (school/university) places in the zone. The exact same calculation procedure is used for this attribute compared to the previously named number of retail workplaces attribute, except for the value of the maximum distance. The catchment area of the regional mobility hub is larger than the maximum recommended walking distance (400 meter) within the hub. In this thesis, a widely accepted walking distance of 800 meter (see section 4.6) is used on the ’Reached users’ attribute, so all traffic model zones within a distance of 800 meter of the evaluated area are taken into account, leading to a distance correction factor of in between 1 (0 meter distance) and 0 (800 meter distance).

For the calculation of the production/attraction of every zone, the total car day loads on the access/egress links to the zones are extracted from the car traffic link Shapefile, where after this data is joined into the zone Shapefile. Then, the actual values of the areas with regard to the ’Production/Attraction’ attribute can be calculated. Then, the exact same calculation procedure as for the ’Reached users’ attribute is used, with the same maximum distance of 800 meter.

Next to the zones, both the public transport and road links are included in the traffic model, with the assigned traffic loads on every link. The attributes ’Maximum I/C-ratio in vicinity’, ’Traffic along road from/to city center’ and ’Presence of high-quality bus/tram link’ can be deducted from the road and public transport link data.

The ’Maximum I/C-ratio in vicinity’ attribute, acquired from the traffic model by applying the steps described in Appendix D, is an approximation of the ability of the hub to solve congestion around the evaluated area, as explained in section 4.6. The attribute value assigned to an area is the maximum I/C-ratio found within 1000 meter of the area, taking both the morning and afternoon rush into account. A correction for the distance to the road is not applied for this attribute.

To find the value on the traffic from/to the city center attribute, the value of the number of trips from/to the city center are considered. In order to obtain this value, only the 45 city center zones are selected, which are the zones with a high parking fare. These zones correspond with the borders of the city center in Figure 4.2.

After selecting these zones, the total day loads on all links are calculated in OmniTRANS, based on the trip production/attraction from the V-MRDH. Then, these links and corresponding loads are exported to a Shapefile. In the GIS tool, the traffic from and to the city is summed for every link. To calculate the actual value for the 'Traffic along road from/to city center' attribute for every area, all links within an airline distance of (an arbitrary value of) 1000 meter of an area are selected, and the distance to the link is corrected for in a factor, based on a linear gradient from 1 (0 meter) to 0 (1000 meter). The link with the highest distance-corrected load provides the value for the 'Traffic along road from/to city center' attribute.

In order to calculate the value for the 'Presence of high-quality bus/tram link' attribute, the high-quality bus/-tram links are extracted from the public transport links export of the traffic model. This selection is done by only selecting the links on which public transport has separate infrastructure (links without slow traffic), a speed in one of the directions of at least 25 km/h, a load in one of the directions of at least 500 passengers, and not being a metro or train link. A limitation to this procedure is that some parts, mostly of the Rotterdam tram system, will lack as the speed does not exceed 25 km/h in one of the directions. This can also be explained as a justified constraint, as the tram is not always high-quality public transport. The value of 25 km/h is established looking at the minimum speed of high-quality public transport in the Netherlands. As the 'Presence of high-quality bus/tram link' attribute is only used to approximate the costs for the high-quality public transport connection to the hub, the exact characteristics of the links are not relevant. The attribute value will therefore be 0 if a link is not within an arbitrary distance of 1000 meter, 1 if a link is present within the evaluated area, and in between if the distance from the area to a high-quality bus/tram link is in between 0 and 1000 meter, based on a linear gradient from 1 (0 meter) to 0 (1000 meter).

4.5.8 National cycle route database

For determining the presence of a regional cycle route near every area in the region, a dataset containing all regional cycle routes in The Netherlands is used. This dataset is available as open data by the Dutch organization Het Fietsplatform. This independent organization focuses on the realization of regional and national cycle routes in The Netherlands, and making the corresponding data accessible for everyone. The dataset is available as WMS (Web Map Service), meaning that a spatially referenced map is retrieved from the national geographic registry server.

The cycle route data is processed by measuring the distance for every area in the region to a regional cycle route. When this distance is larger than 1000 meter (an arbitrary value), the value 0 is allocated to the cycle route attribute. Upon finding a distance of 0 meter, indicating a cycle route inside of the evaluated area, the value 1 is given to the attribute for that area. For a distance in between 0 and 1000 meter, the value is calculated based on a linear gradient from 1 (0 meter) to 0 (1000 meter).

4.5.9 Numerical description of the input data

Before taking steps to process the data, it should be clear whether the input data is usable in this application. This is determined by looking at the relevant descriptive statistics for the input data, shown in Table 4.7. Noticeable in these statistics is the absence of both a rail station and parking area in 95% of the areas. This is explained by the fact that the value for the parking area attribute is 1 only if the parking area is present inside of the evaluated area. As the number of parking areas in urban context is limited, it can be imagined that only a low number of areas will score 1 on this attribute.

For the rail station attribute, the maximum distance to a station for which the attribute value is more than 0 is 400 meter (to ensure a quick transfer between modalities), and together with a low number of rail stations in the area (69 in total), this leads to the value 0 for most areas in the region. For the land owner, it appears that 75% of the areas have either no value, or are not owned by the municipality. This makes sense as the extents of the researched region are much broader than the municipality's borders, so many areas in the region have no value for the land owner. Furthermore, the attributes 'Number of retail workplaces' and 'Traffic along road from/to city center' have a relatively high standard deviation compared to the average and median values, meaning that the spread in these values is high. Due to the scaling of these factors, it also means that only for the areas in which the attribute value is among the highest 5% of the calculated values for this attribute in the region, this attribute has a significant contribution to the end result.

Table 4.7: Input data analysis. The red cells indicate remarkable results, described in the text in this subsection.

	Retail	Parking area	B/T Link	Station	Cycle route	Land owner	Road distance	Land suitability	Max I/C-ratio	Production/ Attraction	Traffic from/ to city	Reached users
Average	16.851	0.047	0.362	0.013	0.803	0.151	0.406	43.216	0.471	3043.440	310.287	1854.008
Std. Deviation	44.961	0.212	0.364	0.084	0.233	0.307	0.383	21.032	0.459	3166.753	591.671	2064.728
Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25th perc.	0.000	0.000	0.000	0.000	0.693	0.000	0.000	26.863	0.000	352.789	0.000	189.416
Median	0.877	0.000	0.278	0.000	0.886	0.000	0.365	47.540	0.629	1847.970	81.338	1067.611
75th perc.	10.872	0.000	0.699	0.000	1.000	0.000	0.779	57.530	0.872	5099.581	321.659	3067.869
95th perc.	216.404	0.000	0.993	0.000	1.000	0.945	1.000	73.836	1.162	9329.844	1488.484	5694.089
Maximum	747.485	1.000	1.000	1.000	1.000	1.000	1.000	100.000	1.349	15447.196	7259.032	21667.539

4.6 Assumptions and limitations

This methodology and its application do not lead to a perfect result, as simplifications in the developed methodology and data availability limit the performance of the method. All made assumptions and limitations of the method and its application are specified in this list.

- Costs are not explicitly taken into account, since the cost differences between locations are hard to estimate precisely. Estimating the costs for placing a regional mobility hub at a selected location is a difficult and time consuming process, as there are a lot of variables and uncertainties involved in such a cost estimation. Literature on the costs for placing a mobility hub is very limited for now due to the novelty of the topic. The inestimable nature of this very important criterion is a problem in this research. To deal with this problem, and to be able to incorporate the costs in a substantiated way, other factors that are a proxy for the cost differences between the locations are taken into consideration in the methodology.
- It is assumed that a direct public transport connection with a competitive travel time to the city will be established upon introduction of the mobility hub, or this connection is already present. This assumption is necessary, as behavioral choices are not included in this methodology. The costs for constructing the infrastructure will be lower at a location connected by a high-quality public transport service, so this is incorporated as an attribute in the costs criterion.
- As mentioned in the previous item, traveler behavior is not incorporated in the methodology. This thesis will assume present-day travel behavior and all travelers will be taken into account for the regional mobility hub. However, not every traveler will be equally inclined to use the mobility hub. There are methods to alter the travel preferences of people, leading to a possible modal shift. These methods are important to achieve a higher usage of public transportation and shared mobility in the modal split, but it is complex to model this. Concerning future travel behavior, developments tend to be positive for the mobility hub potential, as there is a growing demand for non-ownership services (Durand et al., 2018). This enables people to have more freedom of lifestyle, since they do not have to take the possession of a car into account in their (travel) decisions. The motivation for not including this factor is the complexity of modeling and the spatial unfamiliarity of this factor. It is not known whether these developments differ along areas in the region.
- An important simplification is made for the demand with regard to the transfer mobility function of the regional mobility hub: only traffic from/to the region's main city is taken into account. However, the mobility hub can serve as a transfer point for traffic from/to multiple cities in the region, as parking issues might exist in other cities in the region, for which the mobility hub can be a solution. Therefore, the demand for the transfer mobility function is probably underestimated. This monocentric approach is adopted in this thesis, as it is very complex to determine for every area in the region which relevant sub-centers might be served by the hub.
- In the elaborated method application, a recalculation of the traffic model after the placement of a regional mobility hub is not performed, due to time constraints. A recalculation would require hundreds or thousands of traffic model variants to be evaluated. To give an indication of the needed calculation time: a single recalculation of the traffic model requires several hours. For the impact criterion, this means that not the impacts of the placement of a hub are incorporated, but approximations of the impacts. The ability to solve congestion around the location attribute is converted to a potential reduction in experienced congestion by the end users. In order for the hub to have a high potential, the mobility hub should offer an alternative to the traffic problems that influence the travel time or travel time reliability. This comes down to an area being suitable for placement of a mobility hub because it can be an alternative to spending time in a traffic jam, or the inability to find a parking space in the city, so a lower travel time or higher reliability can be offered when traveling via the mobility hub. Therefore, the presence of a busy road within an arbitrary distance of 1000 meter of the area is used as attribute. This simplification can lead to errors, as the busy road does not necessarily serve traffic in a relevant direction with respect to the hub, or the busy road is situated before the regional hub on the route to the city, meaning that the access to the

hub is not free of congestion. In both cases, the hub does not provide an alternative to the current traffic problems.

- Due to the lack of a recalculation of the traffic model after the placement of a regional mobility hub, the impact in terms of increase in the region's accessibility caused by the introduction of the mobility hub can not be measured. Instead, the number of inhabitants, workplaces and education places in the catchment area of the hub is measured, to indicate the number of people that might benefit from the introduction of a mobility hub. The number of inhabitants, workplaces and school places are of equal importance in this calculation.
- Another data limitation is posed by the land owner data. This data is only supplied by the municipality of Rotterdam, automatically leading to a value of 0 on the land owner attribute for all areas outside of the municipality of Rotterdam. Therefore, the final scores of these areas might be underestimated. Furthermore, land owned by the regional/national government results in a value of 0 on the attribute, due to the view from a municipal perspective. In reality, land owned by the regional/national government might be easily obtainable for a regional mobility hub.
- Not all relevant facilities for the link to surroundings criterion are included in this application. Important regional facilities such as a recreation area, library or sports facilities are not included, as data on the exact locations, size and importance of these facilities is not available. As a simplification, the number of retail workplaces is incorporated as an attribute, due to the availability of this attribute in the traffic model and the relevance of retail facilities for the integration of a regional mobility hub.
- The methodology relies on existing geographic data and information, and will not be corrected for future developments. New housing developments will change social-economic data of areas in the region, possibly leading to a change in the potential of areas for a regional mobility hub.
- The catchment area around an area is set to 800 meter, which is the distance that can be covered by foot in 10 minutes. This value is globally used for the catchment area of public transport nodes, but probably underestimates the actual catchment area (Ahmed et al., 2009). The regional mobility hub will eventually have a larger catchment area, as shared mobility will increase the distance that can be covered in a certain amount of time, compared to walking. However, as it becomes increasingly likely for users on a distance of more than 800 meter of the hub to use another public transport node, the users living at a larger distance are not taken into account in the calculation. Within this catchment area, zones at a higher distance of the area will provide less demand than zones close to the potential location. To correct for this distance, a linear gradient is applied for the distance from the area, starting at 1 for a distance of 0 meter to the value 0 for a distance of 800 meter. This principle is based on the distance decay function, indicating the willingness to walk to a public transport node plotted against the distance to the node, shown in Figure 4.4 (CROW, nd). A problem arising from this simplification is the fact that some users might be willing to walk more than 800 meter to a hub, especially in less urbanized areas. These users are mistakenly not taken into account in this application.

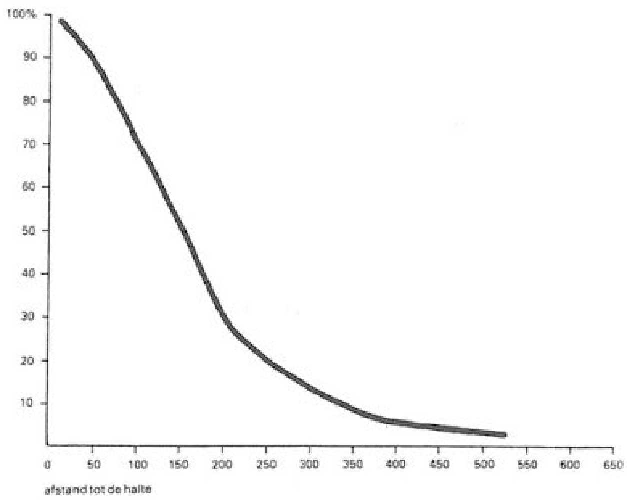

Figure 4.4: Distance decay function, in which the distance to a bus stop is plotted against willingness to walk to a bus stop (CROW, nd).

4.7 Data normalization

After preparing the data, all data should be normalized to be able to execute the MCA, a procedure explained in subsection 3.3.1. This means that all attribute values should be scaled from 0 to 1, to make sure that every attribute is on the same scale, so that the weights can be multiplied by the attribute values. This normalization process is redundant for the attributes indicating the presence of a link/road/station/parking area and the land owner, as these attributes already have a value in between 0 and 1. For the other attributes, a value of 0 is given on that attribute to the area with the least matching attribute value, and a value of 1 to the area with the best matching attribute value, thus the highest regional mobility hub potential concerning that attribute. The applied scaling factors can be found in Table 4.8.

Table 4.8: The scaling factors used to normalize all attributes in the method application.

Attribute	Maximum value	Scaling factor
Production/Attraction	15447.196	0.00006474
Traffic along road from/to city center	7259.032	0.0001378
Presence of parking area	1	1
Physical land suitability	100	0.01
Land owner	1	1
Presence of high-quality bus/tram link	1	1
Presence of light rail/metro/train station	1	1
Presence of regional cycle route	1	1
Presence of main road	1	1
Number of retail workplaces	747.485	0.001338
Maximum I/C-ratio in vicinity	1.349	0.7413
Reached users (SEGs)	21667.539	0.00004615

4.8 Method execution

The methodology is executed in FME Desktop. This is a GIS tool which is very easy to understand, does not require any coding to build workflows, and features a handy preview option. FME Workbench 2020.2 is used to assemble the workflow, and the visual inspection of the results is done in FME Data Inspector 2020.2. The elaboration of the method application, including the workflow and all used transformers, can be found in Appendix D. On execution of the model, no errors pop up, although 721 warnings are given. The following warnings appear, with a short explanation of the warning:

- "Failed to evaluate <null>, the result is set to <null>." A field value lacks, meaning that either one of the I/C-ratios is <null> as the value is lower than 0.6. The result is that this value is not taken into account.
- "Polygon feature must have at least 4 coordinates to be valid for the shape file. The feature will be skipped." This happens in the MapnikRasterizer (an explanation on this transformer is provided in Appendix D) in the process of determining the percentage of building in a cell, when a feature is not a polygon but a point. In this case, this feature is not relevant, as only areas should be taken into account.

The output from FME is processed to create visualizations of the results. FME is less suitable for visualizing output than other GIS tools, so the switch to another tool is made at this point. The output of every scenario is separately exported to a Shapefile, which is read in QGIS. In QGIS, a new column is created that translates the text string of the 'MCA score' column into a value, in order to make a classification possible. The values in this column are visualized on a gradual scale, in which the color red is assigned to the lowest scoring areas, and the color green to the highest scoring areas. The intervals of the classes in the scale are equal, meaning that all color intervals have the same length, and not necessary the same number of areas in it. As a consequence, more red areas than green areas appear in the result. The output and the analyzes which are carried out using that output are described in chapter 5.

Chapter 5

Results: Mobility hub potential

In this chapter, an answer is given to the sub question "How can the results from the methodology and its application be interpreted?" In order to find the answer, the output of the methodology is presented in the following section, where after multiple analyzes are carried out to substantiate the performance of the method and its application. The goal of these analyzes is to test whether the methodology can successfully be applied to a case. In this context, successfully means that the response of the method application to the input and changes in the input is plausible.

5.1 Results

In a separate subsection per scenario, the maps show the mobility hub potential for each area in the region. The MCA scores are calculated for every area by multiplying the attribute values by the corresponding attribute weights for the selected scenario as found in Table 4.6. In total, 41550 areas in the Rotterdam region are evaluated, out of the 50000 areas created in the method application. The omitted areas are situated in an extremely urbanized part of the region and with that, these areas do not satisfy the posed constraint for regional mobility hubs. The evaluated areas are colored based on their MCA score, revealing their regional mobility hub potential: a red color indicates a low potential, a yellow color a medium potential and a green color a high potential. The thresholds for the colors are determined based on a classification into seven classes/intervals, of which the upper three classes are green, the middle class yellow and the lower three classes red. This way, all areas with a MCA score of more than 0.363 are classified as high-potential areas. As the highest MCA score in the region is 0.642 across all scenarios, a threshold of 0.363 for a high scoring area is plausible.

5.1.1 Scenario 1: Equal stakeholder importance

In this scenario, the weights are equally distributed over the three perspectives: the government, operator and end user influence the regional mobility hub potential score in an equal way. The output of the method application for scenario 1 is visualized in Figure 5.1.

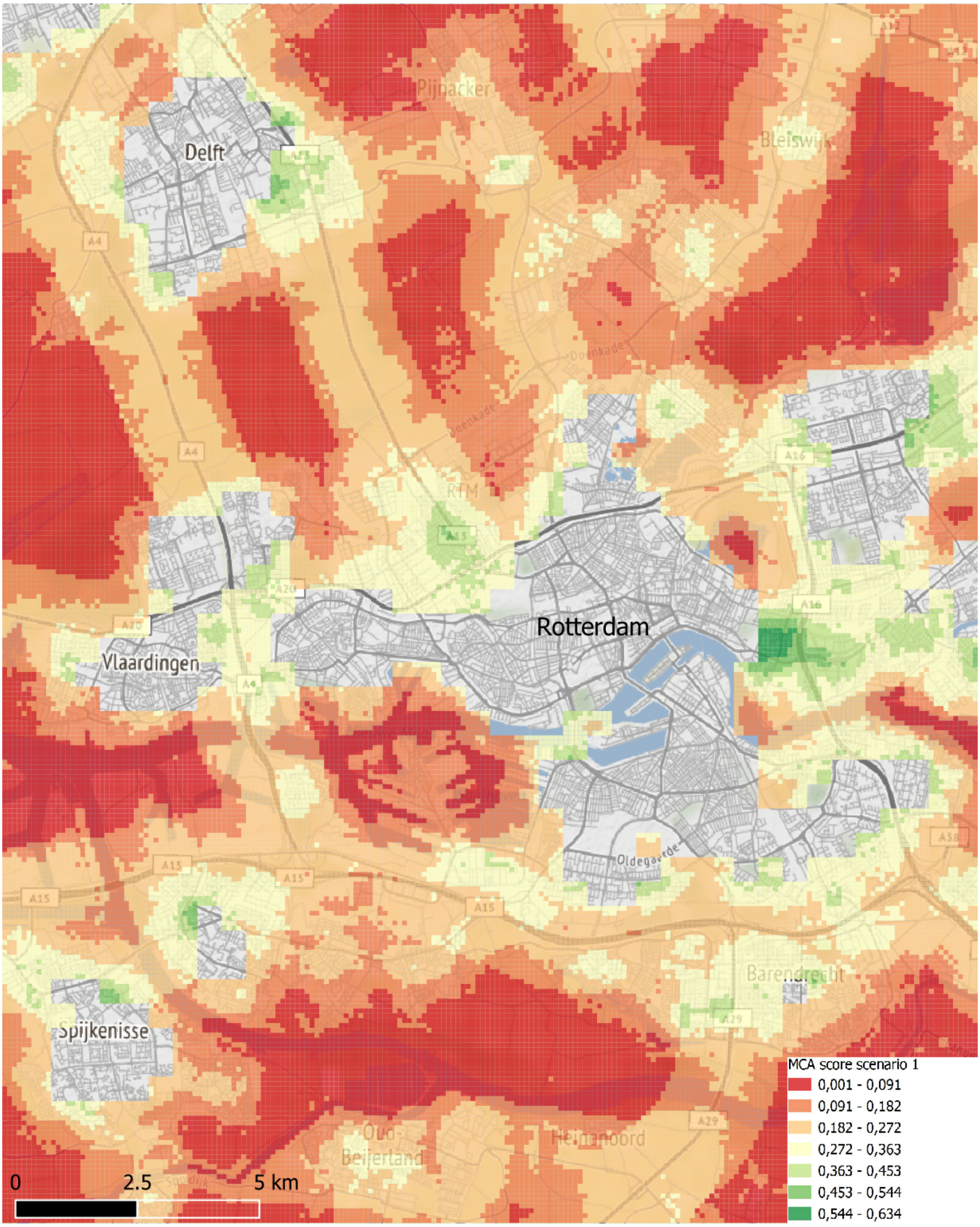

Figure 5.1: MCA score of the areas in the Rotterdam region in scenario 1.

5.1.2 Scenario 2: High governmental influence

In this scenario, the government has a much higher influence, so the weight of the government perspective is increased to 67% of the total perspective weight. The output of the method application for this scenario is found in Figure 5.2.

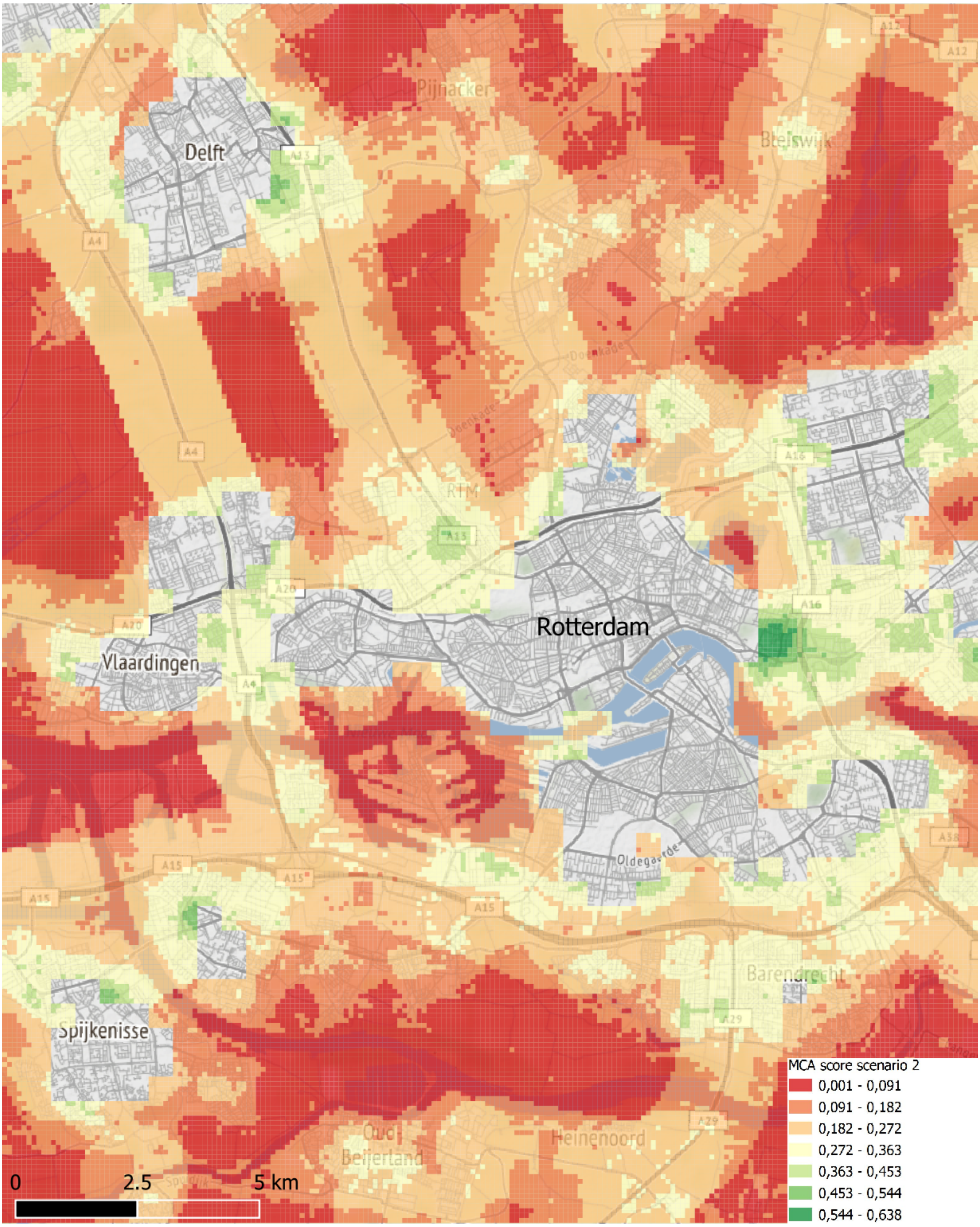

Figure 5.2: MCA score of the areas in the Rotterdam region in scenario 2.

5.1.3 Scenario 3: Focus on the end user needs

The third scenario focuses on the end user needs: the end user perspective is allocated 67% of the total weights of the perspectives. For this scenario, applying the method to the Rotterdam region leads to the area scores in Figure 5.3.

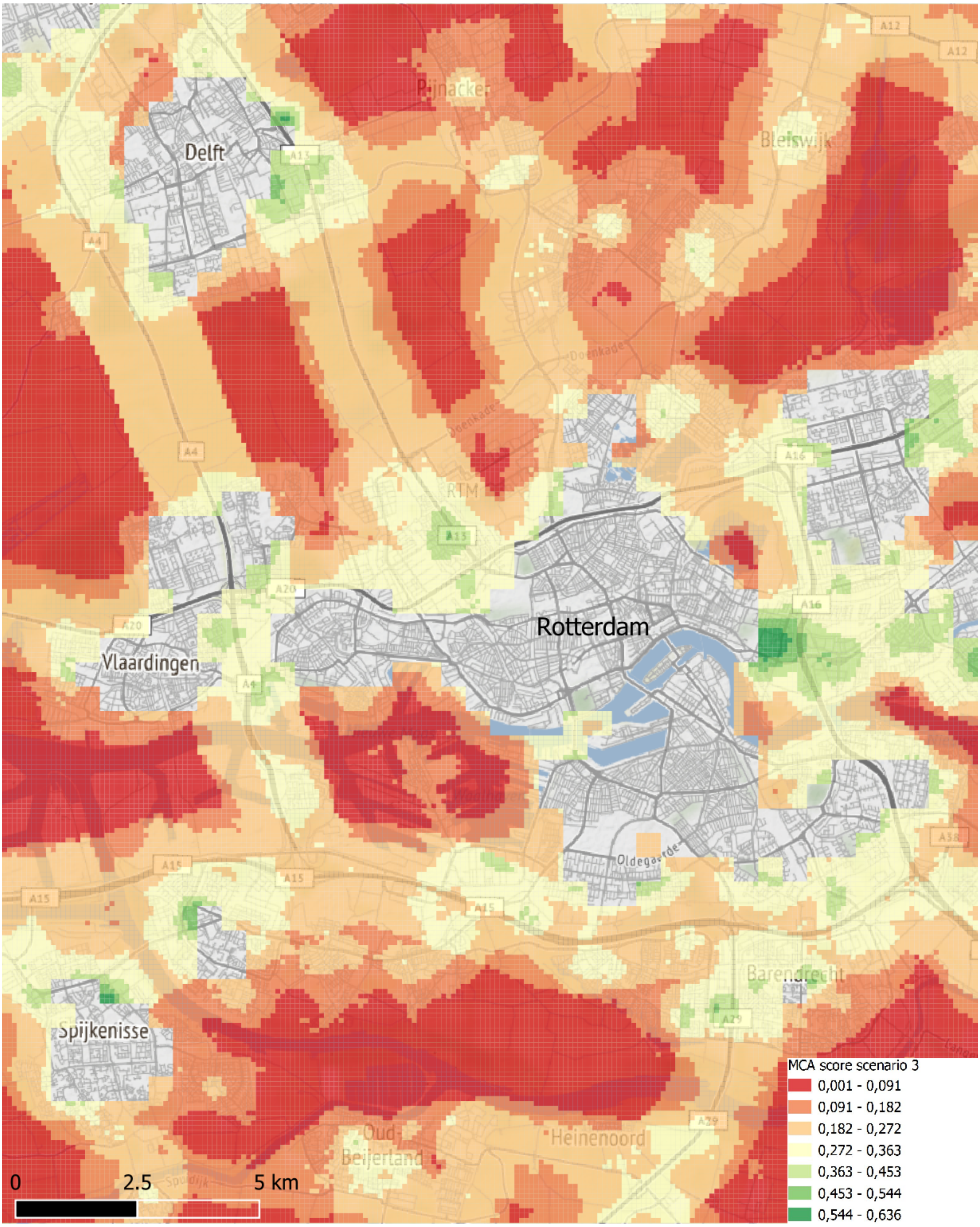

Figure 5.3: MCA score of the areas in the Rotterdam region in scenario 3.

5.1.4 Scenario 4: Focus on the operator needs

In the fourth scenario, the operator perspective is the most important perspective for determining the regional mobility hub potential. Therefore, this perspective is assigned 67% of the total perspective weights. This results in the scores visible in Figure 5.4.

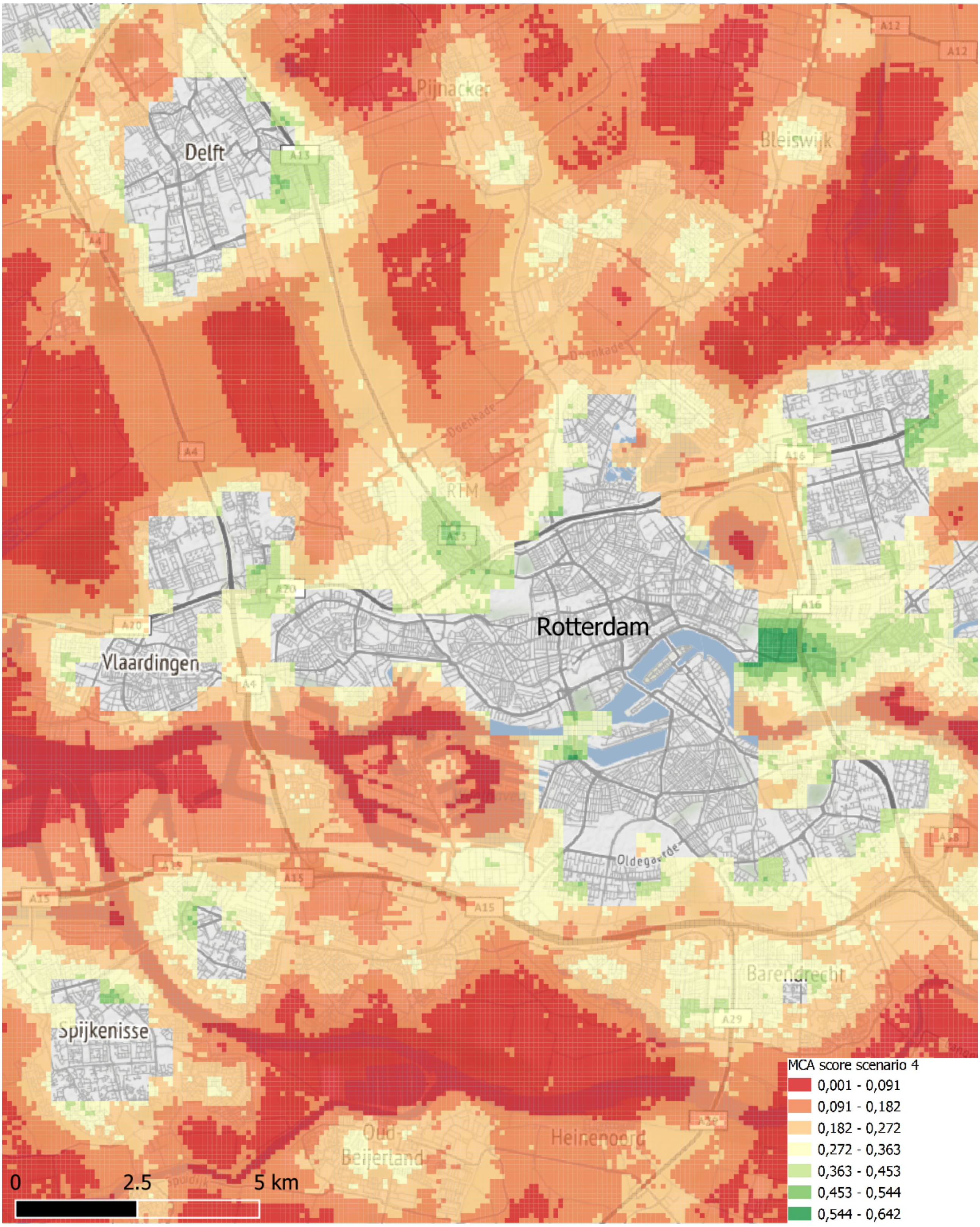

Figure 5.4: MCA score of the areas in the Rotterdam region in scenario 4.

5.1.5 Scenario 5: High focus on investment/operating costs

In this scenario, all perspectives are equally important, so the perspective weights are identical to the weights in scenario 1. The adjustment in scenario 5 is a three times higher weight given to the cost criterion in the trade-offs. The effect of this change is visualized in Figure 5.5.

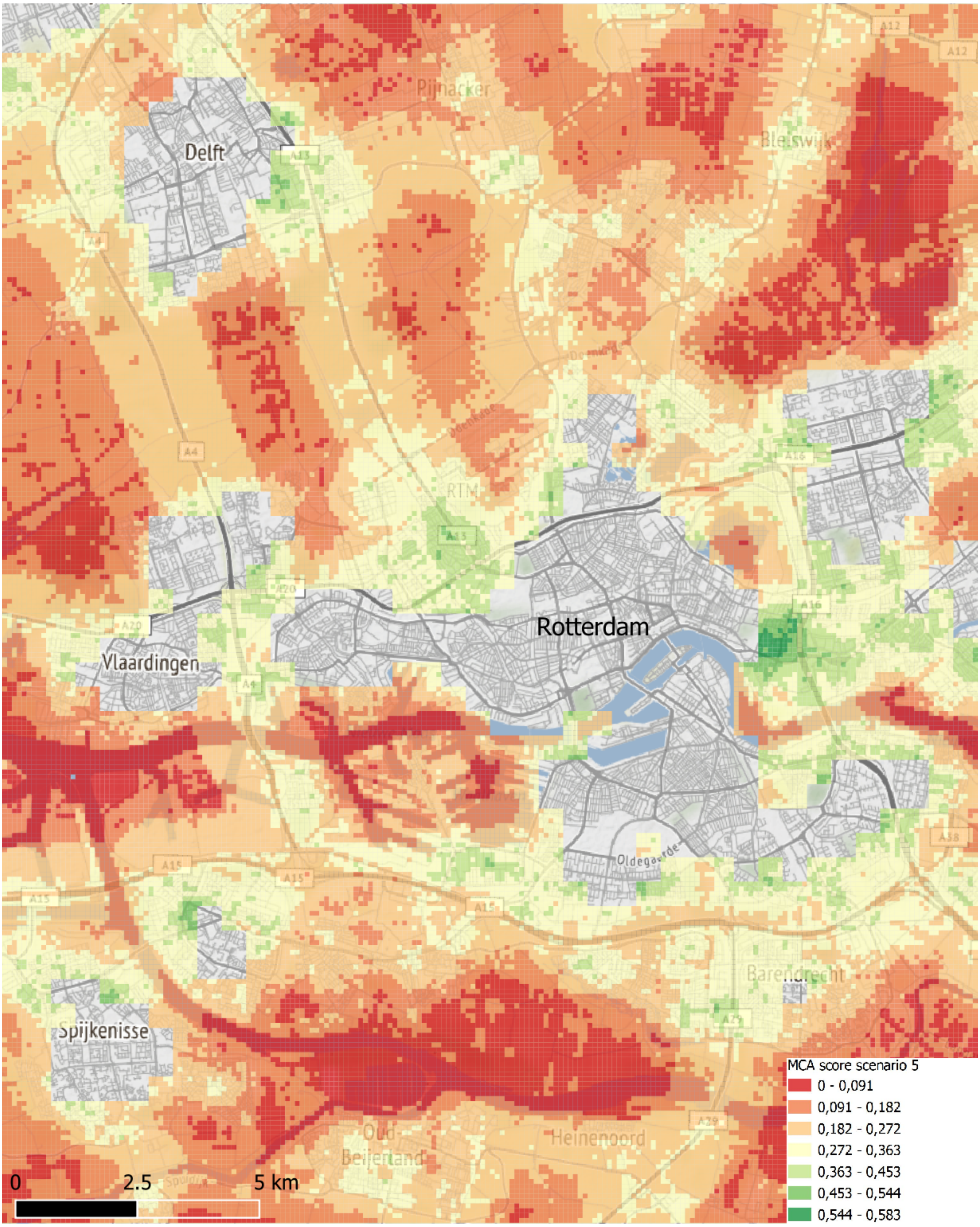

Figure 5.5: MCA score of the areas in the Rotterdam region in scenario 5.

5.2 Analysis of the output

To analyze the suitability of the methodology for determining the potential of areas for a regional mobility hub, multiple tests are carried out. It is expected that the methodology can easily identify obvious low-potential areas like water, rural areas without roads and agricultural or industrial areas. This is tested in the first output analysis. Additionally, some discovered particularities of the output are described.

Looking at the visualization of the scenario results and the corresponding attribute tables, a few observations stand out. Firstly, the differences between the scenarios are not found to be very large, and the same high-potential (green colored) areas come forward from the five scenarios. Low potential areas are rural areas with no main roads in the close proximity. The methodology should evaluate all land areas for the regional mobility hub potential, the evaluation of water areas is not necessary. In the evaluation, it becomes clear that water areas are given a low MCA score, so the methodology correctly identifies water areas as lower potential areas. In addition, large industrial and agricultural areas have a very low MCA score, which is consistent with the expectation. The areas close to the highway have a higher potential for a regional mobility hub, which corresponds with the reality, as hubs need to be well-connected to the road network.

The attribute 'Maximum I/C-ratio in vicinity' does not significantly vary among the highest scoring areas. This can be an indication of an excessively high weight allocated to this attribute. The second possible explanation is that every high-potential area is situated near a congested road. From the application, it appears that the second explanation is correct. Table 4.7 shows that 50% of all areas in the region are within 1000 meter of a road having an I/C-ratio of more than 0.629, which leads to a scaled value on this attribute of 0.466 for more than half of the areas in the region, resulting in the fact that every high-potential area is situated near a congested road.

5.2.1 Scenario comparison

Scenario 1 is the base scenario, the other four scenarios are compared to this scenario. A comparison reveals particularities of the scenarios, which gives information on the usefulness and truthfulness of the scenarios.

Scenario 2 does not differ much from scenario 1, but remarkable is the higher score given to the areas around the highways from Delft to Rotterdam. This is caused by the higher weight of the impact criterion in scenario 2 combined with the higher impact of a mobility hub at that location, due to the location close to the congested highways. In reality, this is only partially true, as a regional mobility hub located close to the highway does not necessarily lead to a solution to traffic problems. This limitation has been uncovered in section 4.6, a consequent recommendation for usage of this methodology is given in section 7.3.

Comparing scenario 3 with scenario 1, it is noticeable that the borders separating the MCA score categories are smoother, meaning that characteristics of the specific square area are less important than characteristics based on a distance to a certain element (station, road, traffic model zone). This observation logically results from the weights given to the attributes, as the physical land suitability and presence of a parking area have a lower weight in scenario 3. These attributes do not correlate among the areas, as the value depends on the land usage/parking area presence in the evaluated area only. The other attribute values are correlated with surrounding areas, as all features within the specified distance (400/800/1000 meter) are incorporated in the attribute value calculation. Furthermore, it appears that in scenario 3, the areas around the southernmost exit of the A29 (at the bottom of Figure 5.3) have a relatively high potential compared to scenario 1. This is due to a combination of a higher weight allocated to the I/C-ratio in scenario 3 and serious congestion occurring at this location. The same applies to the A15/A16 intersection in the bottom right of the map, in which the score in multiple areas is higher in scenario 3 compared to scenario 1.

In scenario 4, the wishes of the operator are clearly reflected in the result, as areas in the vicinity of a highway have a relatively low score compared to scenario 1. Areas close to a high-quality public transport line or rail station score significantly higher in this scenario, which is very logical, as the placement of a mobility hub close to existing public transport infrastructure will lead to lower costs for the operator. This is related to the adjustments that need to be made to their public transport routes upon introduction of a regional mobility hub. The placement of a hub along an existing high-quality public transport line will lead to no rerouting costs. The higher score of the areas which are favorable from the operator perspective can be seen most clearly in the area just northwest of the city center of Rotterdam, as a high-quality bus line passes through this area, the area just north of the city center in which metro stations are present, and the area around the Kralingse Zoom metro station, which is the large cluster of green areas east of the city center.

In scenario 5, a significantly higher number of areas are given a high score (MCA score of more than 0.363) compared to scenario 1 to 4. More clusters with high scoring areas exist in this scenario, some at a larger distance to the city center. The fact that an increase in the importance of the costs leads to more high scoring areas indicates a better match of this scenario to the non-urbanized context of the regional mobility hub. The attributes which are not related to costs mainly have high values in and around city centers, due to more inhabitants, workplaces and student places, leading to the generation of large traffic volumes. The other substantiation of the larger number of high-scoring areas is the relatively high value, compared to other attributes, of the costs attributes in the data after normalization, leading to an overall higher score. Looking at Table 5.1, it becomes clear that the costs attributes have a contribution to the final score which is relatively higher than the weights allocated to these attributes.

5.2.2 Contribution of attributes to score

To ensure a logical result from the method application, the contribution of the attributes in the calculated final score is checked for all scenarios. An excessively high contribution of a single attribute can indicate inconsistent behavior of the method or its application. The contribution of the individual attributes to the final score should not deviate substantially from the weight of these attributes in this analysis. In order to find out which criterion is actually dominant in the top scoring areas in all scenarios, the relative contribution of every attribute to the final MCA score is calculated for scenario 1 to 5. The average contribution divided by the final MCA score in the 5% top scoring areas is calculated, these insights are provided in Table 5.1. In the adjacent column, the weights of the attributes in the different scenarios are shown. What stands out is that the contribution of the 'Station' and 'Retail' attribute are far lower than expected. This means that in the 5% top scoring areas, a station is generally not present, and the number of retail workplaces is particularly low. This corresponds with the findings from the input data described in subsection 4.5.9.

The 5% top scoring areas are usually close to a regional cycle route, main road, high-quality bus/tram link and road with a high I/C-ratio. A surprising result from the table is the relatively high contribution of the 'Production/Attraction' attribute, whereas the contribution of the 'Reached users' attribute is lower than the allocated weight. These two attributes are closely related to each other, as an area with a high number of reached users is typically an area with a high trip production/attraction. The trip production/attraction is calculated per zone in the traffic model based on the social-economic data (inhabitants, workplaces and education places) of that zone. This irregularity is therefore caused by an inconsistent scaling factor among these two attributes.

Table 5.1: The contribution of the individual attributes in the final MCA score in the different scenarios. A green color indicates a relatively high contribution of the attribute to the final score, a red color a relatively low contribution, compared to the weights allocated to the attributes.

Attribute	Weight normalized	Scenario 1 weight	Scenario 1 contribution	Scenario 2 weight	Scenario 2 contribution	Scenario 3 weight	Scenario 3 contribution	Scenario 4 weight	Scenario 4 contribution	Scenario 5 weight	Scenario 5 contribution
Production/Attraction	0.5	11.1111	17.6175	5.555556	8.820387	5.555556	8.769409	22.22222	34.18216	6.666667	9.330181
Traffic along road from/to city center	0.5	11.1111	4.897541	5.555556	2.127543	5.555556	2.172749	22.22222	11.05206	6.666667	2.771544
Presence of parking area	0.176471	3.6415	2.249624	4.341737	2.86658	1.820728	0.940271	4.761905	3.001564	6.737968	5.366697
Presence of high-quality bus/tram link	0.088235	1.8207	3.497333	2.170868	4.137419	0.910364	1.735979	2.380952	4.42237	3.368984	6.195073
Presence of light rail/ metro/train station	0.088235	1.8207	0.270654	2.170868	0.334644	0.910364	0.117976	2.380952	0.379537	3.368984	0.48743
Physical land suitability	0.352941	7.2829	9.590112	8.683473	11.87717	3.641457	4.746417	9.52381	11.76887	13.47594	17.8355
Land owner	0.176471	3.6415	2.62555	4.341737	3.144257	1.820728	1.046151	4.761905	3.797023	6.737968	6.086416
Presence of regional cycle route	0.029412	2.1942	4.497876	1.517274	3.111865	3.478058	7.18389	1.587302	3.15616	2.710296	5.426297
Presence of main road	0.088235	4.9953	9.90239	3.75817	7.317238	7.25957	14.6839	3.968254	7.611832	6.543587	12.91219
Number of retail workplaces	1	14.2857	4.031793	14.28571	4.051506	21.42857	6.638445	7.142857	1.807731	12.55411	3.169673
Maximum I/C-ratio in vicinity	0.333333	12.6984	22.26864	15.87302	28.87379	15.87302	28.73507	6.349206	9.891089	10.38961	16.92984
Reached users	0.666667	25.3968	18.55163	31.74603	23.33759	31.74603	23.22974	12.69841	8.929613	20.77922	13.48915

5.3 Verification

A more in-depth analysis of the attributes is necessary to make sure that all attributes are correctly measured in the method application. This so-called verification process is done by analyzing the response of the method application to a high attribute weight. In this verification, the weight of every attribute is set to a high value (1.0), after which the high scoring areas are identified and compared to (preferably) another data source. This process is further elaborated in Appendix E. In general, the method and its application work as expected, but some irregularities emerged from the verification.

Some imperfections came up from the input data, in particular from the 'Presence of high-quality bus/tram link' attribute. Bus-only lanes which are bundled with cycle paths are labeled as mixed traffic link in the source data, the traffic model, leading to the exclusion of these links in the method application. Furthermore, the 'Number of retail workplaces' attribute includes all retail workplaces, but not every retail workplace will increase the potential for a regional mobility hub by the same value. For example, a large furniture store and a supermarket lead to the same type of retail workplaces in the data, but the contribution of these different types of retail to the potential for a regional mobility hub is expected to be unequal. In reality, a supermarket better suits the economic function of a mobility hub than a large furniture store, as this retail facility might be integrated in the hub. The division in type of retail facility lacks in the data. A further method application issue is uncovered with regard to the used GIS tool (FME). As explained in Appendix D, transformers are used in FME to process the data, but the transformer used to determine the percentage of land in an area owned by the municipality is not capable of taking multiple land parcels into account for one area. This means that only one land parcel can determine the percentage of municipality-owned land in an area, so if the area contains two or more land parcels, only one of the land parcels is taken into account for the calculation. The result is that the value of this attribute is sometimes lower than it is supposed to be.

One discovered malfunction is caused by the value scaling method in the developed methodology. The normalization of all input data leads to a very small number of areas that score high on the 'Number of retail workplaces', 'Traffic along road from/to city center' and 'Reached users' attributes. The actual significance of the values in the input data is discarded by normalizing all attributes. In chapter 6, this methodological malfunction is addressed.

5.4 Sensitivity analysis

As part of the results, the developed methodology requires the execution of a sensitivity analysis, to examine the results of changes in the weights on the final score. From the assumptions and expert interviews, it became clear that the weights used in the method application show some uncertainty. The question arises how a small change in the weight allocated to either an attribute or stakeholder group affects the final score. Will this change lead to a relatively smaller or larger change in the total score?

The sensitivity to a change in weight is calculated for the attributes and stakeholder perspective weights. Sensitivity to a change in input or a change in criteria weight is not calculated. Input uncertainty occurs to a lesser extent in this thesis, due to reliable data, and is partially addressed in the sensitivity to a change in attribute weight. Trade-offs for the criteria weights are made on the basis of experts interviews, so these weights have been established with a higher certainty. Besides, varying criteria weights are implicitly incorporated in a change in perspective weight, which is studied in this analysis.

The weights allocated to the perspectives and attributes in the first scenario are used in the sensitivity analysis. An increase and decrease of 5% is given to one stakeholder group or attribute weight, leading to a slight increase or decrease in the weights of the other stakeholder groups or attributes. The sum of all weights for both the perspectives and attributes should still count up to 1 after this change. After changing the weights, the score is calculated for every area. The difference in score between scenario 1 and scenario 1 with the adjusted weight is calculated for every area, divided by the score in scenario 1 to obtain a percentage increase/decrease, where after the average is taken of the absolute values of all individual area score differences. The absolute value is used, to prevent a negative difference in one area cancelling out a positive difference in another area. As a result, it can not be determined whether the change in score is negative or positive. In Appendix F, all weights used in the sensitivity analysis are listed. The results of the sensitivity analyzes on the perspectives and attributes are tabulated in the following subsections.

5.4.1 Sensitivity for change in perspective weight

In Table 5.2, the sensitivity of the method application to a change in weight of one of the perspectives influences, compared to the weights in scenario 1, can be found. It is noticeable that a change in weight of the government perspective leads to a relatively smaller average and maximum change in final score than a change in weight of the operator or end user perspective. For all examined weight changes, the change in the final score for every area in the region is smaller than the change in weight. This means that the methodology is not highly sensitive to changes in the perspective weights, especially not for a change in weight of the government perspective.

Table 5.2: Method sensitivity for a change in weight of one of the perspectives. The red cells indicate the lowest sensitivity to a change in perspective weight.

Perspective weight change	Average change in score	Maximum change in score
-5% Government	±0.2999%	±1.8469%
+5% Government	±0.2879%	±1.4186%
-5% End user	±0.5607%	±2.7397%
+5% End user	±0.5538%	±3.1963%
-5% Operator	±0.6264%	±2.2551%
+5% Operator	±0.6401%	±2.2578%

5.4.2 Sensitivity for change in attribute weight

There is uncertainty in the exact allocation of weights to the attributes in the criterion. From the literature and expert interviews, clear trade-offs between the attributes in a criterion are not available, therefore a check on the sensitivity of the final score to a change in attribute weight is of high importance.

Not every individual attribute has to be changed, as the Link to surroundings criterion only consists of one attribute, and the Potential demand, Generalized travel costs and Impact consist of two attributes, so a change in one of them induces an opposite change in the other attribute. Because of this, only 10 attribute weights will be changed. The weight of one attribute, existing in two different criteria, will be changed for both criteria separately. The results of the sensitivity analysis can be found in Table 5.3, the used weights in Appendix F.

Table 5.3: Method sensitivity for a change in weight of one of the attributes. Red cells indicate a low sensitivity, green cells a high sensitivity.

Attribute weight change	Average change in score	Maximum change in score
+5% Production/Attraction	±0.2388%	±1.4124%
-5% Production/Attraction	±0.2473%	±1.4647%
+5% Presence of parking area	±0.3106%	±2.7220%
-5% Presence of parking area	±0.3919%	±2.5817%
+5% Presence of high-quality bus/tram link	±0.1559%	±1.6440%
-5% Presence of high-quality bus/tram link	±0.2023%	±1.5190%
+5% Presence of light rail/metro/train station	±0.1441%	±0.4346%
-5% Presence of light rail/metro/train station	±0.2396%	±0.5495%
+5% Physical land suitability	±0.5710%	±3.0499%
-5% Physical land suitability	±0.5733%	±3.1825%
+5% Land owner	±0.3328%	±4.1209%
-5% Land owner	±0.4056%	±4.1209%
+5% Presence of regional cycle route (Costs crit.)	±0.1668%	±1.3699%
-5% Presence of regional cycle route (Costs crit.)	±0.1774%	±1.3699%
+5% Presence of main road (Costs crit.)	±0.1639%	±1.1173%
-5% Presence of main road (Costs crit.)	±0.2253%	±1.2368%
+5% Presence of regional cycle route (Gen. costs crit.)	±0.3389%	±2.7397%
-5% Presence of regional cycle route (Gen. costs crit.)	±0.2824%	±2.2831%
+5% Maximum I/C-ratio in vicinity	±0.6449%	±2.6737%
-5% Maximum I/C-ratio in vicinity	±0.6759%	±2.8043%

The small change in the final score due to a change in weight of one of the costs attributes with a low weight (presence of regional cycle route/main road/station/bus/tram link is rational. Remarkable is the high sensitivity of some areas in the Rotterdam region to a change in land owner weight, this means that for some areas, the land owner is the only attribute contributing to the final score. Overall, the methodology is not highly sensitive to changes in the attribute importance, but big adjustments to the 'Physical land suitability' attribute weight, or one of the attributes in the 'Impact' criterion, can induce a significant change in the final score.

5.5 Robustness of the locations

Among the scenarios, small differences are visible concerning the potential of areas for a regional mobility hub. To find out which areas are suitable for a regional hub in every scenario, so independent of the chosen perspective, the locations with approximately the same result in every scenario are analyzed. To do so, the relative difference in score between the scenarios is calculated for every area, and visualized in a map. In Figure 5.7, it is visible that for most high scoring areas, the relative differences between the scores of the scenarios are low. Additionally, the minimum value of the four individual stakeholder scenario scores, so excluding the high costs scenario (scenario 5), is taken to find out which area scores best over all scenarios. The results are not very remarkable, as most high-potential areas score high in all scenarios. The result can be seen in Figure 5.6. For the 2702 areas that score 'green' on the map, so having a score of 0.363 or higher, it is found that 501 areas have a score difference higher than 0.2 (18.5%) and 117 areas a score difference of more than 0.3 (4.3%). This means that for the largest part of the areas that score high in one of the scenarios, the score difference is relatively small. In most low scoring areas though, it appears from Figure 5.7 that differences are relatively large, meaning that the result is not robust. This can be attributed to the fact that the absolute differences are not specifically large for low-scoring areas, but divided by the score, this leads to a large relative difference. Concluding, the high scoring areas from the method application are robust, as the variation between the scenarios is relatively low.

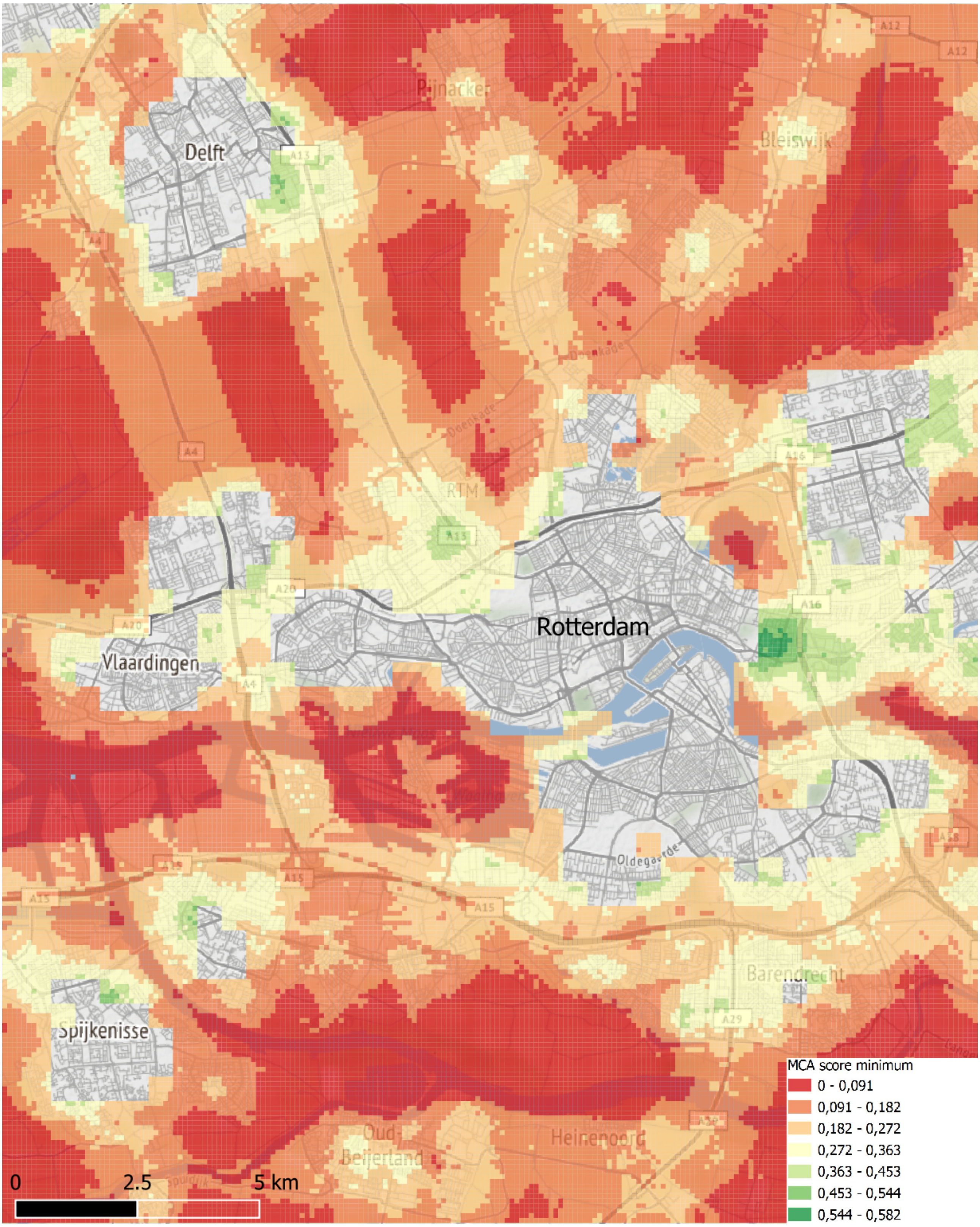

Figure 5.6: The minimum score from the method application among all scenarios.

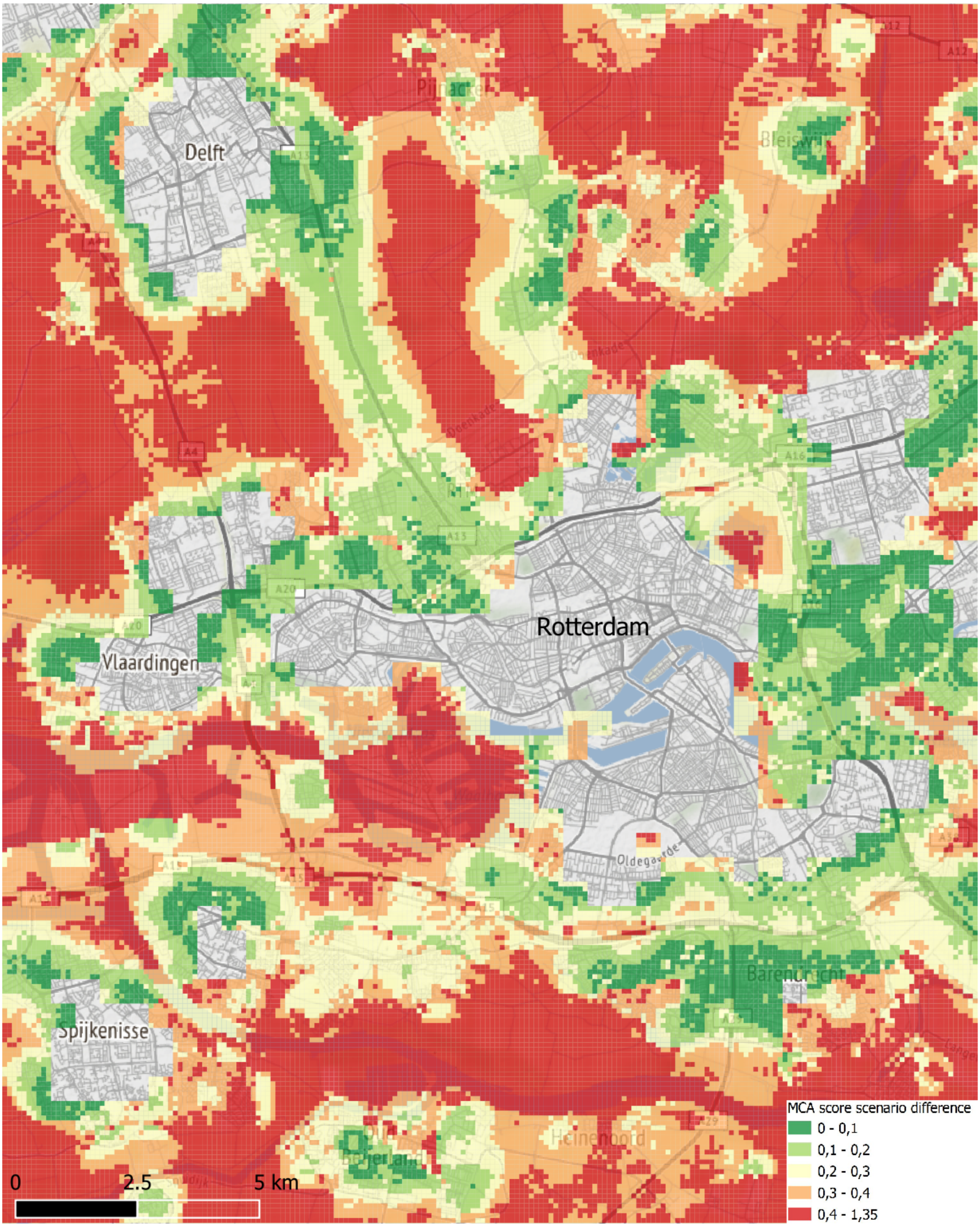

Figure 5.7: Relative differences in scenario 1-5 output. For every area, the largest score difference between the scenarios is used to determine the MCA score scenario difference.

5.6 Omitting the urbanization constraint

The aforementioned urbanization constraint raises the question of what the result will be when omitting this constraint. By leaving out the urbanization constraint, highly urbanized areas will also be taken into account for the mobility hub location potential determination. The expectation is that centrally located areas score high, however the regional mobility hub location potential methodology does not take into account that space in city centers is more expensive than space outside of the city center. Therefore, the criteria and weights have to be adjusted for usage in extremely urbanized areas. Still, the result shows that the Rotterdam city center, the adjacent neighborhoods and the area around the big shopping malls in Rotterdam have a very high potential for a mobility hub, due to a high number of trips generated/attracted by the zones in these areas. Other extremely urbanized city centers in the region also score high concerning the mobility hub potential, as these areas also have a high trip production/attraction and high number of people living/working/going to school around these areas, although the scores are lower than the scores of the areas in the city center of Rotterdam.

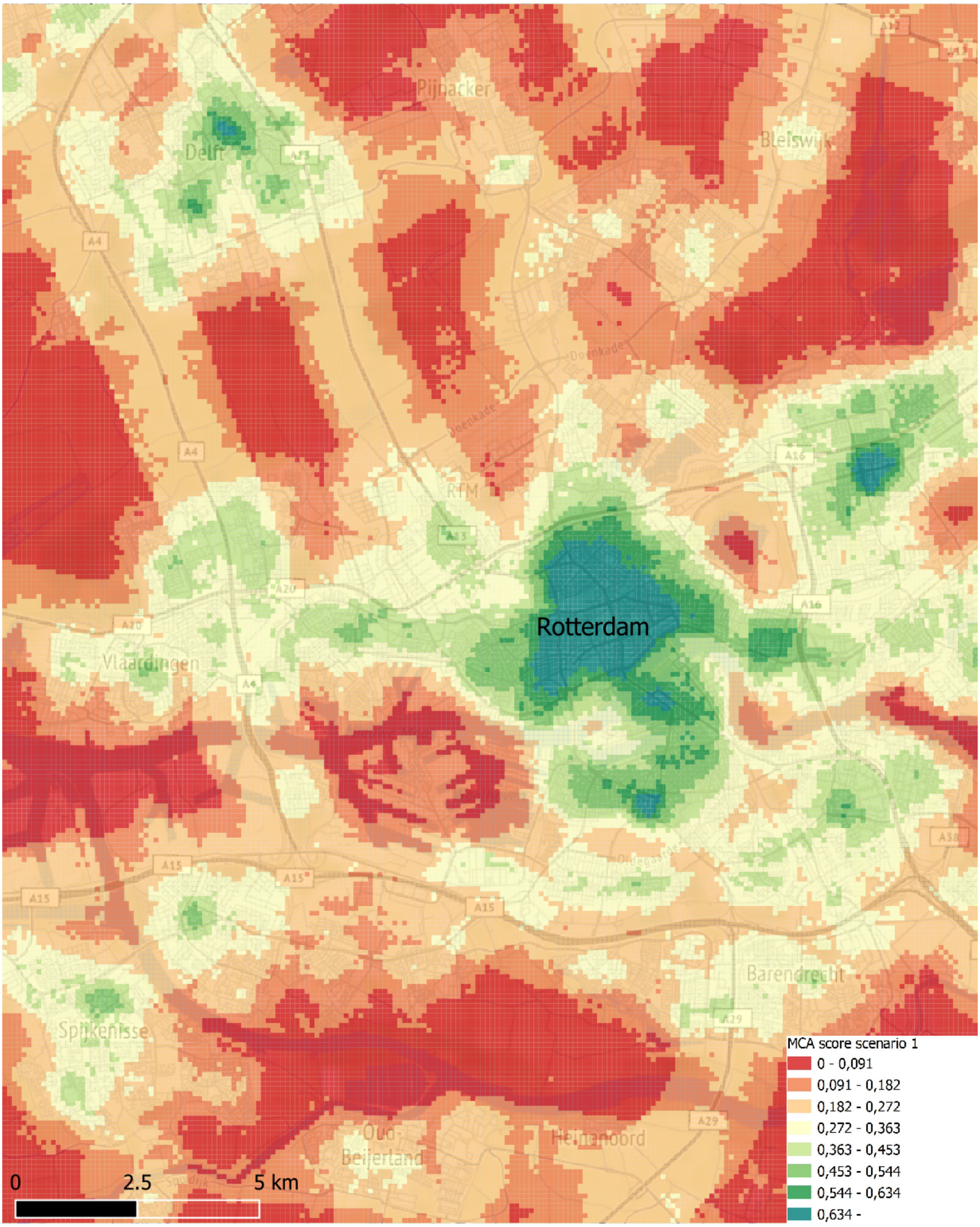

Figure 5.8: Output of the method application in scenario 1 without the urbanization constraint.

From Figure 5.8, it becomes clear that the methodology leads to MCA scores higher than 1 for several areas inside of the city center of Rotterdam. This is due to the scaling of the 'Production/attraction' and 'Reached users' attributes, which should be adjusted such that the maximum value of the attribute is 1 in the researched region. A different scaling factor should therefore be applied when changing the researched region, or when including the city center in the analysis.

5.7 Analysis of high-potential areas

After the previous, somewhat technical analyzes of the output of the method application, the high-potential locations from the output are analyzed for both their methodological correctness and their actual usefulness in the future mobility system. By doing so, a possible application of the results is introduced. In all scenarios, one cluster of areas results in the best scores in the MCA (see Figure 5.9): Around number 1 on the map, which is the Kralingse Zoom/Rivium business park/Erasmus University area. This area has a very high number of workplaces and school/student places, and therefore produces a very high potential demand. High-quality public transport links are close, namely a tram line to the city and multiple bus lines using the highway in southern direction. The congested A16 highway is very close, giving the cluster of areas a high score on the potential impact criterion. Furthermore, high traffic numbers from/to the city center of Rotterdam exist close to this region, as the s107, the main access road from/to the city for the southern and south-eastern direction, is situated right next to this high scoring cluster. As most factors influencing the regional mobility hub potential are positive, the score should logically be high. In other words, this means that the location of the highest scoring area in the method application is logically explainable. This area also seems to be very useful in the transportation networks. Users from the catchment area, being mostly commuters and students of the Erasmus university, can use a regional mobility hub to switch from public transport to a shared bike, in order to accelerate their last mile from the hub to their company/university. With that, public transport is made more attractive due to a decreased total travel time. Besides, car users from both southern and south-eastern direction can make the shift at the regional hub from their car to a more space-efficient modality like the metro or a shared bike, to bypass any congestion or parking problems in the city center. As this area is situated along the route to the city center, additional travel time/costs for the end user can be limited to just the transfer time. When making this transfer more attractive by the offering of facilities at the hub, it is very likely that travelers will actually use the hub.

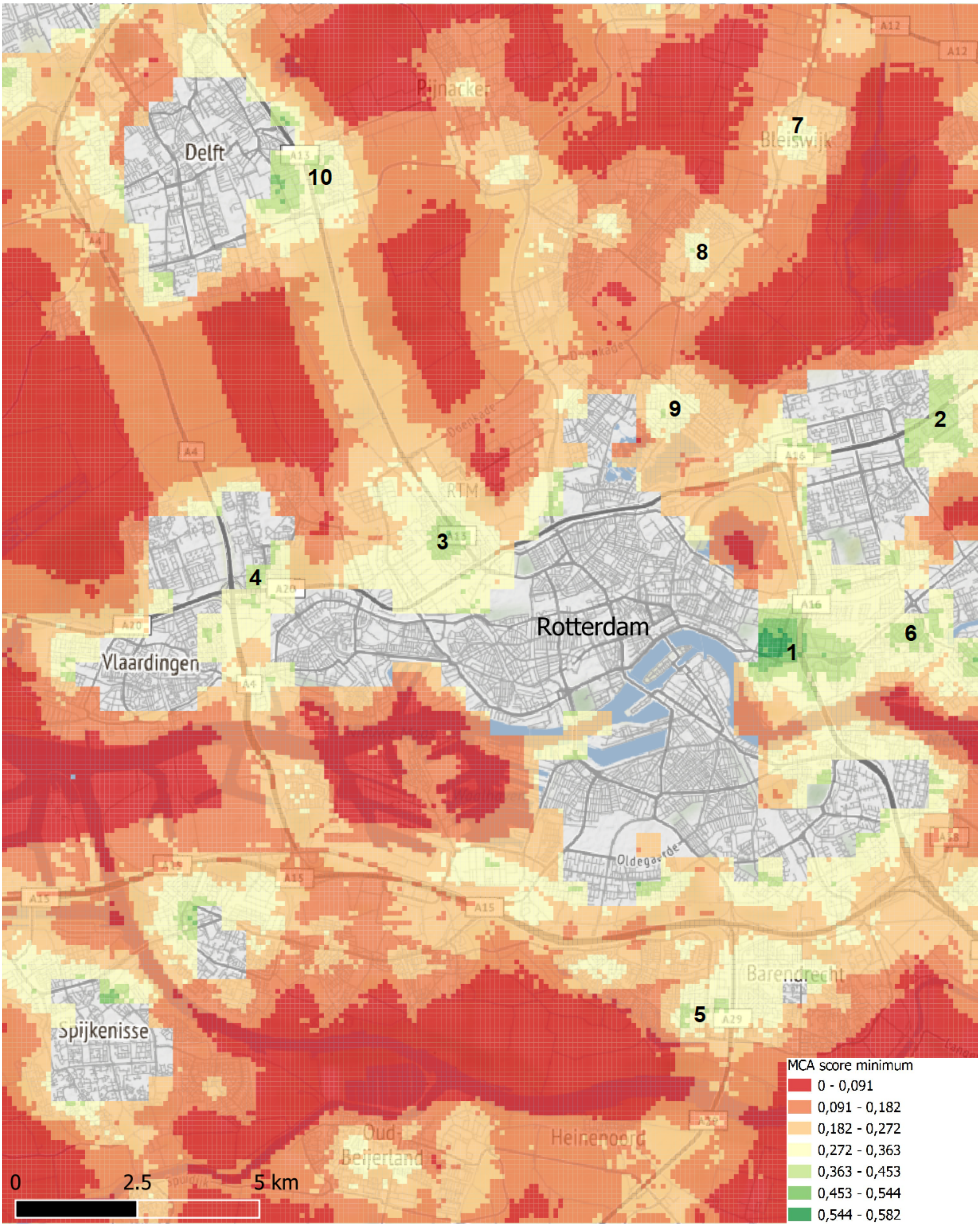

Figure 5.9: The minimum score from the method application among all scenarios, the numbers 1 to 10 indicate high-potential areas which are explained in the text.

The other numbered points on the map are shortly elaborated in this section. The reason for not describing all high-potential (green colored) areas is the location of these areas close to the city center. It can be seen in Figure 5.8 that the high MCA score of several high-potential areas is caused by the closeness to a city center with a very high number of inhabitants and workplaces, due to a high address density. The objective of the developed methodology is to determine the potential of a regional mobility hub, so high-potential areas neighboring the city center should not be taken into account.

Number 2 on the map is a cluster of high scoring areas in between two light rail stations (De Tochten and Ambachtsland), and a train station (Capelle Schollevaar). Other factors leading to the high MCA score in these areas are high trip production/attraction values, a high number of reached users due to a high number of inhabitants north of the A20 highway, and a high number of workplaces south of the highway. As the A20 highway has a high I/C-ratio in both the morning and afternoon rush, the potential of all areas within 1000 meter of this highway is higher. This hub can very well serve both transfer passengers and users from/to the catchment area. Added value to the trips of inhabitants might be offered by facilities at the hub, which can be used by these users as they transfer from their private bike to public transport for their trip to another part of the city/region of Rotterdam. For commuters to the companies in the catchment area arriving by public transport, quick last mile transportation is offered by shared vehicles. Visitors of the city center originating in the central or eastern part of The Netherlands can use this hub to switch to a metro or train serving all parts of the city center without encountering congestion.

The numbers 3, 4, 5, 6 and 9 on the map represent areas which are located around an urban center of a suburb of Rotterdam. Number 3 and 9 are the urban centers of Overschie and Hillegersberg, two neighborhoods in the municipality of Rotterdam. Both areas are connected by a frequent, high-quality public transport link to the city center of Rotterdam and have relatively high trip production/attraction and retail workplace values. Both areas are mostly owned by the government and have compatible land usage. Furthermore, number 3 (Overschie) scores higher than number 9 due to the location close to the A13 highway, which is congested in both rush hours and processes high traffic volumes from/to the city center. As the potential location of the regional mobility hub in Overschie would be in the middle of the congestion on the A13, city visitors/commuters to the city might take less advantage of this hub. Still, they can avoid high parking fares in the city center by parking at the hub and continuing by either a shared bike/moped or using the high-quality bus connection to the city center. For the inhabitants in the catchment area, the hub provides big advantages for their trip to other parts of the city, as shared mobility increases their transport options, and facilities add value to their trip. The same improvement for the inhabitants holds for a regional mobility hub situated at number 9 (Hillegersberg), although it is not likely for this hub to serve city visitors from other parts of The Netherlands.

Number 4, 5 and 6 indicate areas at an urban center outside of the Rotterdam municipality. Number 4 is around the urban center of Groenoord (Schiedam), number 5 at Carnisselande (Barendrecht) and number 6 in Capelle West. High MCA scores in these neighborhoods are caused by the presence of high-quality public transport links and high trip production/attraction values. Number 4 and 5 are close to a congested highway, whereas number 6 is close to a congested main road (non-highway). Furthermore, the land usage is suitable for a mobility hub in these areas. All three high-potential regional hub locations can serve city visitors/commuters to the city: Location number 4 can serve traffic from western/north-western direction, number 5 from southern direction and number 6 from eastern direction. As the hubs are situated before the congestion occurs in the trip to the city, these locations provide the opportunity for car users to avoid the congestion, and continue their trip from the hub by public transport or shared e-bike/moped to the city center. The inhabitants in the catchment area might also take advantage from the offering of shared mobility, as a way to decrease their travel times to the city. As these three urban centers are situated at a slightly larger distance from the city center compared to the previously mentioned areas, the offering of shared e-bikes and mopeds should be considered in addition to the shared bikes. By the offering of shared cars, inhabitants in the catchment area can consider the replacement of their private vehicle by a shared vehicle at the hub.

Number 7 (Bleiswijk) and 8 (Bergschenhoek) on the map represent areas which are not located in a suburb of the big city, as these areas are located in urban centers in smaller towns. The location close to a shopping area and high-quality public transport lead to the high MCA score, which is even higher in scenario 5. Furthermore, relatively large traffic volumes have their origin/destination in the urban center. Some car users originating in Zoetermeer, heading for the city of Rotterdam might make the switch to public transport or a shared e-bike/moped at the regional hub located in one of these areas. More important is the function of the hub for the inhabitants of the served regional centers: the hub can greatly accelerate their trips throughout the region and to the city center by the high-quality bus connection and the offered shared cars/mopeds/bikes. Due to the integration of the hub with retail facilities, the possible transfer time can be well-spent. Visitors of the catchment area can reduce the time spent in the last mile of their multimodal trip by using one of the shared bikes at the hub.

The final cluster of high scoring areas is around number 10 on the map, in the urban center of Delfgauw, just outside of the municipality of Delft, the second largest city in the Rotterdam region. Similar to the other urban centers, the high MCA score is mainly due to a high trip production/attraction, presence of a high-quality public transport link and a main (congested) road in the vicinity. Car traffic from southern, eastern as well as northern direction can use this hub to switch to public transport or a shared bike to reach the city center of Delft, in order to avoid high parking fares existent in the city of Delft. From the northern direction, traffic to Rotterdam might use a high-quality public transport service to quickly reach the big city. Inhabitants of the catchment area may accelerate their trip to other areas in the region, by using the high-quality bus service or one of the offered shared modalities.

5.8 Comparison with proposed hub locations

As part of the validation of the results, a comparison with existing information on future mobility hubs around Rotterdam is made. This information is from a report on the mobility transition in the MRDH (The Hague-Rotterdam metropolitan region) (de Kleuver et al., 2020). In this report, the mobility concept designed by the MRDH is elaborated. One of the three main elements of this concept is a hub network around The Hague and Rotterdam, to let users switch from car to public transport, bike or shared mobility. A mobility hub is primarily considered as a node in the network to facilitate the transfer between modalities, and for this purpose, two types of hubs are described in the report: the Park&Bike and the Park&Ride hub. The name implies that the potential users of the hub are city visitors that park their car and continue by public transport or bike, so the potential demand from the direct surroundings is of less importance in this concept.

Included in the mobility concept is an improvement of the public transport network that serves the projected hub network. Compared to the hub definition adopted in this thesis, the MRDH report does not state anything on the economic function, the integration with other facilities, at the mobility hub. With regard to locating the mobility hubs in the region, this might have led to a reasoning that differs from the one used in this thesis, leading to other results. The hubs are in place to capture traffic from the highway, in order to shift these users to public transport or bikes to reach the city center. As a consequence, the key factor to determine the locations is the connection to the current networks, whereas other factors are not explicitly named in the report.

This proposed hub concept, with the corresponding hub locations, is further elaborated in the appendix of that document, and the proposed locations are projected on the minimum MCA score output map in Figure 5.10. The minimum MCA score output is used, as the expectation is that the projected hub locations correspond to areas that score high in every scenario. According to the mentioned report, hubs can be easily accessed from outside of the city by car from the main road network, and for the access to the city, the focus is on either bike or public transport. It is unknown which other factors influenced the choice of locations for this hub network. Important to mention is that the MRDH research projects a hub network, while this thesis focuses on determining the potential of one regional hub in the network, without investigating interaction effects between hubs. Despite the relatively short distances between the proposed hubs in some cases, it is assumed that interaction effects will not play a large role in the designed hub network.

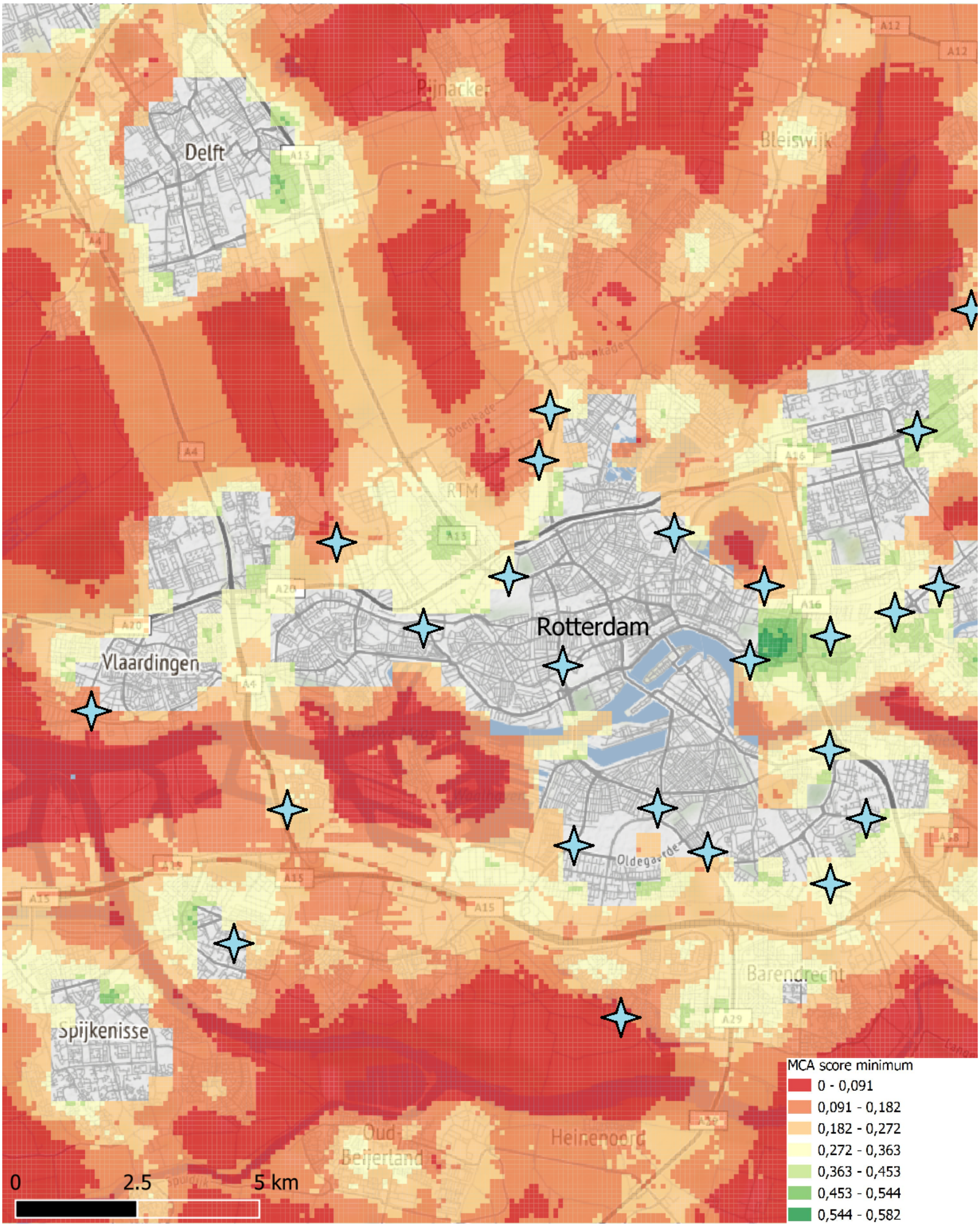

Figure 5.10: Proposed hub locations in the Rotterdam region represented by blue stars, with the minimum output of the scenarios as background map.

What stands out, is the low calculated potential for a regional mobility hub for some proposed hub locations from the MRDH research. Multiple factors could have led to this mismatch:

- The MRDH research takes future (housing) developments into account, leading to higher scores for areas in which projects are planned. This issue is studied in the upcoming paragraphs.
- The methodology and influential factors used to locate the proposed hub are different from the ones adopted in this thesis. It appears from the report that the proposed hub locations are based on the position relative to the road, bike and public transport network, other factors are not explicitly mentioned.
- The minimum scenario is used as background map, in which the minimum regional hub potential score is taken for every area from all scenarios. Not every scenario from the method application might be suitable in the comparison with this proposed hub network. The following text goes into detail with regard to this issue.

Some developed scenarios might be a better fit to the proposed hub locations than the other scenarios. To check this, all proposed locations are inserted in the various scenarios, after which a check is performed whether a proposed location is close (<500 meter in absolute distance) to a high-potential area, i.e. an area with a score in a green category (>0.363). In the MRDH research, 25 hubs are placed on the map, three of them are not placed in an evaluated area, meaning that those hubs are placed in either an extremely urbanized area, or outside of the map extents. This leads to the result in Table 5.4.

Table 5.4: The number of regional hubs from the MRDH mobility concept hub network report (de Kleuver et al., 2020) that match a high-scoring area in the various scenarios.

Total	**22 hubs**
Scenario 1	12 out of 22
Scenario 2	12 out of 22
Scenario 3	10 out of 22
Scenario 4	17 out of 22
Scenario 5	18 out of 22

Comparing the proposed hub locations in the MRDH research with the output of the scenarios in the Rotterdam region method application, scenario 5, which is the high costs weight scenario, appears to be the best match, as 18 out of the 22 proposed locations score relatively high in this scenario, resulting in an 82% match. The map with the proposed hub locations projected on the scenario 5 output is shown in Figure 5.11. Scenario 4 is the second best matching scenario. A higher number of high-scoring proposed hub locations in scenario 4, compared to scenario 1 to 3, means that the operator needs are highly represented in the MRDH methodology. These needs are a high potential demand and low costs, measured in, amongst other factors, the connection to the current public transport network.

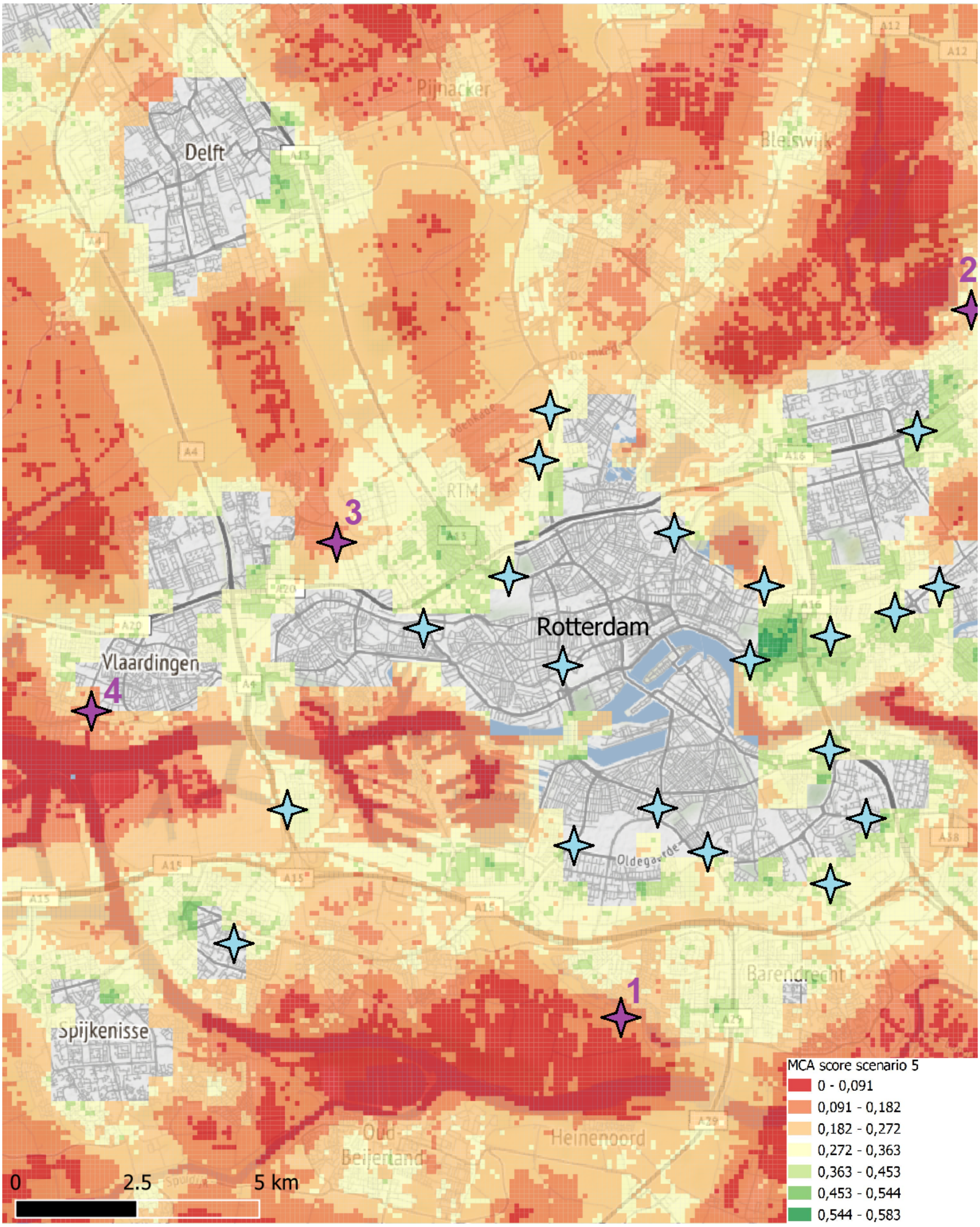

Figure 5.11: Proposed hub locations in the Rotterdam region represented by blue stars for high-potential locations in the method application and purple stars for lower potential locations, with the output of scenario 5 as background map.

The 4 locations with a low hub potential in the fifth scenario, marked by a purple star, should be examined. By looking into detail at these locations, the reason for the low potential can be determined, in order to make statements on the validity of the method application or imperfections in the planned MRDH hub network.

From the MRDH report, it becomes clear that two of the four low-potential locations are situated in areas at which future developments are planned, the numbers 1 and 3 in Figure 5.11. A stop along the railway line is planned at Schiedam Kethel, between Rotterdam and Delft, indicated by number 3. A metro extension to Portland is studied, with a station located at number 1. As future developments are not taken into account in the method application, it can not be determined what the potential of these proposed locations will be in the future according to the methodology. The gathering of detailed information on future projects is not within the scope of this application. However, it can be imagined that due to the establishment of a regional mobility hub at a station offering a quick train/metro connection to the city center, the traveler will be more inclined to use the hub. Therefore, the hub potential is substantially increased for these locations in the future.

The two remaining hub locations proposed in low potential areas are situated at a metro station. Number 2 on the map is placed at the Nesselande metro terminus, in a suburb at a distance of 10 km of the city center of Rotterdam. Number 4 is placed at the Vlaardingen-West metro station, at a slightly larger distance from the city center. No future real estate development projects leading to a higher demand are known within the catchment area of these two proposed locations. The contributions of the attributes to the final MCA score in scenario 5 are compared to the average contribution in high scoring areas in Table 5.5, to reveal the causes of a low/medium potential from the method application. For both locations, a metro station, parking area and regional cycle route are present, positively influencing the score. This means that the hub is theoretically suitable for usage as a Park&Ride location, which is proposed by the MRDH report. The number of users in the catchment area, trip production/attraction and land suitability attributes are approximately equal to the expected value for high-scoring areas. Due to the trip production/attraction, the hub might provide attractive last mile transportation for visitors of the catchment area. These areas score much lower than expected because of the absence of a main road and facilities close to the location, the absence of a congested road around the location and a very low traffic volume from/to the city. This is remarkable, as the mobility hubs in the MRDH report are proposed with the focus on the transfer function of the mobility hub, so a location near the main roads from/to the city would be expected. A low score of these locations in the method application is justified, as a relatively low potential for a regional mobility hub of the locations is expected in reality.

Table 5.5: Percentage contribution of the individual attributes to the MCA score in scenario 5, compared to the average contribution of the attributes to the scenario 5 MCA score in the top scoring areas in the region. A green cell color indicates a relatively high contribution of the attribute, a red cell color a relatively low contribution.

Attribute	**Average % score contribution**	**Hub 4: Actual contribution**	**Hub 2: Actual contribution**
Production/Attraction	9.33%	12.38%	8.34%
Traffic along road from/to city center	2.77%	0%	0%
Presence of parking area	5.37%	25.06%	21.28%
Presence of high-quality bus/tram link	6.2%	0%	10.30%
Presence of light rail/metro/train station	0.49%	11.96%	10.64%
Physical land suitability	17.84%	20.35%	14.57%
Land owner	6.09%	0%	15.08%
Presence of regional cycle route	5.43%	10.08%	8.56%
Presence of main road	12.91%	0%	0%
Number of retail workplaces	3.17%	2.59%	0%
Maximum I/C-ratio in vicinity	16.93%	0%	0%
Reached users	13.49%	17.54%	11.20%
MCA score	**100%**	**100% / 0.268772476**	**100% / 0.316615053**

5.9 Overview

Multiple steps have been executed in this chapter to obtain information on the performance of the methodology and its application. An overview of these steps is given in Table 5.6, along with the implications for the suitability of the method (application) to determine the potential of areas for a regional mobility hub.

Table 5.6: Result of the steps taken to analyze the performance of the methodology and its application.

Analysis step	**Result**	**Description**
First output analysis	Logical	Rural areas with no roads nearby and water areas have low potential, areas close to the highway have high potential.
Scenario comparison	Insensitive method	The method is relatively insensitive to a change in stakeholder group influence. The various scenarios are only slightly different.
Attribute contribution	Some irregularities	The used scaling factors in the normalization cause unwanted deviations from expected attribute contributions to the final score.
Verification	Some irregularities	Irregularities related to the input data and used GIS tool. Normalization leads to a very small number of areas that score high on certain attributes.
Sensitivity analysis	Insensitive method	This analysis results in a relatively low sensitivity of the method for both a change in perspective weight and attribute weight.
Robustness analysis	Robust method	The outcome is robust for a large part of the high scoring areas in the region, meaning that the spread in MCA scores is low for most areas that score high in one of the scenarios.
Omitting urbanization constraint	Logical	The highest scoring areas can be found in city centers. The lack of space in the centers causes this methodology to be less suitable for application to extremely dense city centers.
Analysis of high-potential locations	Logical	Regional urban centers and suburban centers are identified as high potential areas, along with areas around rail stations and congested roads.
Comparison with MRDH hub network	Logical	The proposed hub locations are an 82% match to the high-cost scenario (scenario 5), the mismatch can be substantiated by future developments and the other criteria used in that report.

Chapter 6

Discussion: Reflection on results

In this chapter, an answer is given to the sub question "What can be learned from the application of the methodology to a case?" This is done by discussing the results and identifying and examining the existing strengths and weaknesses of the developed methodology. In the first place, this is done by discussing this thesis in general, and the applicability of the methodology to other cases outside of the chosen region. Next to that, overall and chapter-specific shortcomings and comments on the used method are identified. Each part of the research is separately examined in a section.

The mobility hub is a topical issue in the mobility sector, as new literature, reports, researches, thesis and innovations follow up very quickly. New researches have been added during the writing of this thesis, some of those have already been consulted in the previous chapters. In doing so, this thesis provides a very recent view on the topic of mobility hubs. Nevertheless, insights from future or current researches might alter the assumptions and with that, the results of this thesis. An effort is made to incorporate all past and current literature into this thesis, but some information might be overlooked, due to time constraints which are in place for the execution of this thesis.

In the introduction, it is stated that a Park&Ride facility and a regional mobility hub can be difficult to distinguish. In chapter 5, the differences become clear, as not all existing Park&Ride facilities are located in high-potential regional mobility hub areas, and not all high-potential regional mobility hub areas are close to an existing Park&Ride location. The incorporation of the economic function of the hub and the demand from the direct vicinity lead to a unique methodology applicable to the regional mobility hub.

An intentional exclusion is made in selecting the stakeholders for this thesis. The three most important stakeholder groups (end user, operator, government) are selected, and in the expert interviews, the point of view of these stakeholders is uncovered with regard to mobility hubs. By selecting the three most important perspectives, satisfactory results are produced. However, other stakeholders, like land owners, local hotel managers and environmental protection groups, might also be included to obtain an even better method. As an example of the possible influence of the other perspectives, environmental protection groups might prevent the placement of a mobility hub at certain protected areas, a scenario which is not taken into account by the methodology. Next to that, inhabitants might want to block the development of a regional mobility hub close to their house, because the hub will generate additional traffic as it also facilitates transfer traffic.

As mentioned in the scope, the determination of the regional mobility hub location potential, resulting from the method, should be elaborately tested on suitability for placing a mobility hub. The proposed methodology provides a rough estimation of the suitability concerning land usage, but the location should be studied in detail to be able to say something about the suitability. Subsequent steps with the focus on the effects of the mobility hub on both the mobility and socio-economics in the region are needed to provide a more accurate determination of the suitability of a selected location. The developed methodology provides very suitable input for such a research.

Another limitation of this research follows from the objective. The objective is to present a methodology to determine the potential of an area for a regional mobility hub. The objective of this research is not to understand exactly what type of hubs exist, or to evaluate all present hubs on their functionalities and features. For some mobility hubs, it may not even be possible to place it into a specific class. In the literature research part, enough information is gathered to have a clear understanding of the mobility hub, the typology, facilities and function, in order to find out which factors may influence the potential of an area for placing a mobility hub, but the literature research on the definition, typology and facilities is not comprehensive. A more elaborate research subdividing the mobility hubs into a larger range of hub classes can be feasible, as a better understanding of the target groups might be obtained. This might lead to an even better performing methodology.

6.1 Applicability of the methodology

Within the objective of this thesis, it is described that the methodology should be designed in a way such that it can be applied to any region throughout the world. This is relevant in order to maximize the usefulness of this thesis, as the methodology contributes to solving a societal problem. In this section, this applicability is evaluated.

Determinants with regard to the applicability of the methodology are found in the literature research. A literature research narrowed down to only one country will reduce the applicability, in order to prevent this, literature from various countries is used. An important note in the literature is that the only researched regions are North-America and Europe, as mobility hubs in other continents are not yet developed. In Australia, shared mobility and mobility as a service have been under investigation (Vij et al., 2020), but information on mobility hubs is not yet available for that country.

In the definition literature review, literature from both North-America and multiple European countries is used. Literature from The Netherlands is over-represented, but this will not complicate the applicability, as the definition is very broad. For the mobility hub classification, an important note is appropriate. The current classification of the hubs on the basis of the urban context is inspired by the levels of urbanization defined by Statistics Netherlands, different standards may be used for the urban context in other countries. The list of mobility hub features is highly applicable to other situations, as the list is composed on the basis of literature from both North-America and European countries, and many elements are marked as optional, to make sure that the list can be applied to a mobility hub anywhere in the world.

The literature used to determine the criteria and attributes originates from various countries throughout Europe and North-America, but the Netherlands is over-represented in this literature review. However, in determining the influential factors, only relevant factors are taken into account, with a substantiation that holds up in every country. Therefore, the methodology is highly applicable in other countries, it is not limited to the application elaborated in this thesis. Nevertheless, the smallest number of adjustments to the application have to be made when applying the methodology to a region in The Netherlands. The data sources in the elaborated method application can be used for every region in The Netherlands, as the application relies mainly on open data sources. The availability of a traffic model is the most important additional requirement when applying the methodology to a Dutch region through the application provided in this thesis. Land owner data is a second data requirement, but this should be a lower priority, as the land owner attribute has a lower impact on the final score than the traffic model attributes.

6.2 Reflection on the developed methodology

Methodological limitations are identified and explained in this section. Described are the exclusion of traveler behavior from the methodology, not treating the network function of the hub and a flaw in the methodology due to normalization. Finally, two factors not taken into account are presented, the transportation deprivation and demand generated by the hub itself.

In chapter 2, the choice is made for an aggregated approach on the hub potential determination, meaning that disaggregated data, in which individuals and their trips are considered, is excluded from the factors. These individual trips are aggregated and taken into account in the generalized travel costs criterion. By making this simplification, however, the human behavior aspect in mobility is ignored. Population characteristics and their current mobility patterns might influence the adoption of shared mobility and a regional mobility hub. Certain population groups might be more inclined to adopt innovations in mobility than other groups. As very limited research and information is present on the exact influential factors on this matter, the adoption of the mobility hub is assumed in this thesis.

Besides, the developed methodology is designed to determine the potential of a mobility hub in the region, while in practice, a network of mobility hubs is often planned. When applying the methodology to find multiple locations for a mobility hub, interaction effects between mobility hubs are not taken into account, leading to an incorrect estimation of the potential. These effects might occur due to traffic to the city passing along multiple mobility hub locations, so the same traffic can not simply be taken into account for every hub in case of the implementation of multiple hubs. When placed at a larger distance from each other and in different directions from the city center, the methodology is capable of correctly identifying the high-potential locations.

The maximum possible score from the methodology is 1, as all individual attributes have a value scaled from 0 to 1, and weights are assigned to the attributes such that the sum of all scaled attribute values is 1. What is not taken into account in the methodology, is the actual difference in potential induced by a difference in value on a certain attribute. No meaning is given to the actual (non-scaled) value of the attribute. For some attributes, the value is solely determined by the presence of a facility, like a train station, with a correction for the distance from the area to that facility. For the number of users within the range of the mobility hub, this is more complex. A scaling is applied to give the highest value within the region a value of 1 on this attribute. When applying the methodology to another region, this scaling factor will change, as the highest value is different for another region. The weight assigned to the attribute within the criterion, and the weight of the criterion as determined by the trade-offs remains the same, leading to a different score for areas with an equal number of reached users, in different regions. This is visually explained in Figure 6.1.

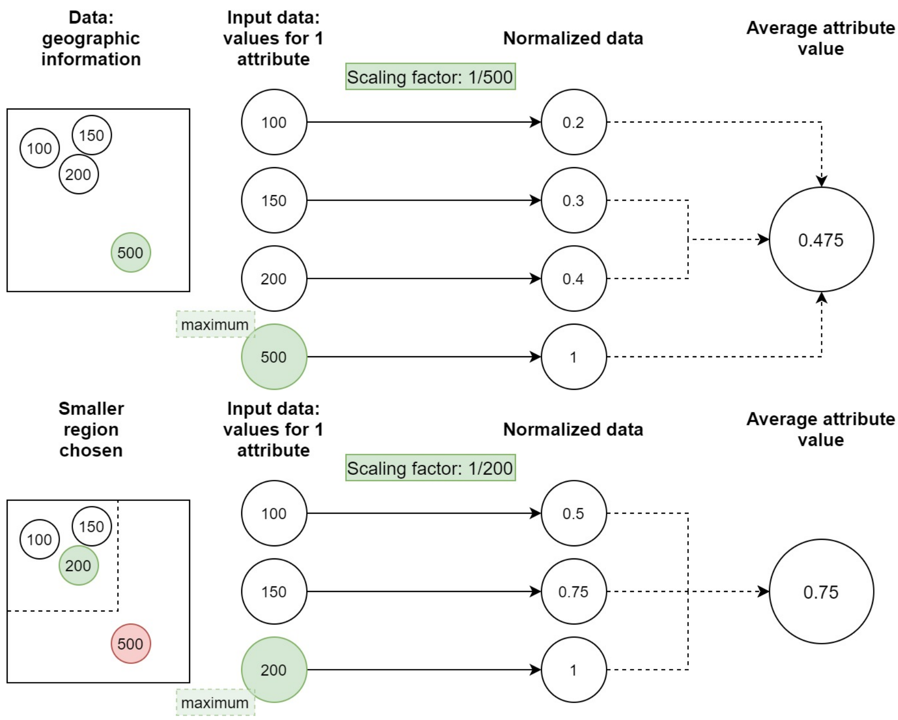

Figure 6.1: Result of the normalization method used in this thesis. In the lower diagram, the size of the region is reduced, leading to a higher average attribute value.

Another way of looking at the impact of the mobility hub, which is not further applied in this methodology, is the current deprivation of (public) transportation in a region. Mobility deprived areas, in which public transport infrastructure is currently not present, would score higher on the impact criterion, because compared to a well-connected area, a mobility hub can provide a greater increase in accessibility. As the mobility hub would also involve higher costs, since infrastructure is not yet present, the choice is made to not further incorporate this attribute in the thesis. Furthermore, mobility deprivation is only important from the government perspective and for a (small) number of end users. The methodology developed in this thesis takes all perspectives into account, the deprivation approach is therefore not suitable for answering the main research question.

Another factor that can come forward is the potential generated by the mobility hub itself. A mobility hub can lead to organizations relocating towards the mobility hub, in order to be well-connected to the public transport system. Just like in past transit-oriented development projects, real estate projects can even be integrated with the development of the mobility hub. This insight drastically changes the mobility hub potential of the areas in a region, because it becomes less important how a mobility hub can be placed looking at the current situation, and it becomes more important how the mobility hub can generate a future demand, given a future situation. A general methodology for determining the potential of areas for regional mobility hubs would then be very difficult to establish, as case specific factors will be dominant in the location choice.

6.3 Weight determination and expert interviews

On the weight determination process, three comments are made. The lack of response from the government perspective, omission of small-scale organizations and lack of explicit information on the trade-offs are described in this section.

In total, 9 experts have been interviewed to obtain information on the view of mobility-related organizations on the mobility hub. Due to time constraints and the absence of a reaction of some organizations, one perspective is not highlighted to the desired extent. This is the government perspective, as the only interviewed organization is the municipality of Rotterdam. Nevertheless, a large number of documents written by governmental organizations have been consulted in the literature review, so this partially makes up for the lack of interviews from the government perspective.

A lot of organizations currently focus on mobility hubs and shared mobility, usually small-scale companies like Felyx, Hely or Mobike. The selection in this thesis is made to only interview organizations from the operator perspective with an established public transport network. Including small-scale companies could provide additional insights and possibly different trade-offs with regard to the criteria in the Multi-Criteria Analysis.

In the adopted method to determine the weights of the criteria, the Analytic Hierarchy Process (AHP), trade-offs between every set of criteria are made by the experts. As the interviews were conducted in an alternative format in this thesis, these trade-offs were not made by the experts. Instead, the interests of the stakeholders were extracted from the interviews, and using this information, the trade-offs were made. This deviation of the standard method can be seen as a weakness of the method application, and could have been prevented by directly asking for the trade-offs in the interviews. However, as not all experts have sufficient knowledge on the trade-offs, the method used in this thesis offers a good alternative to the regular AHP method.

6.4 Limitations of the used data

The used datasets have several limitations. The land use categories of the TOP10NL dataset are very coarse, as grassland and other land usage are not further specified. For example, an empty piece of land can be suitable for the construction of a mobility hub, which could be designated as grassland or other land usage in the topographic dataset. However, land without buildings in the category other land usage can also indicate a backyard, which is a less suitable area for placing a mobility hub. Differences between the dataset and satellite images are revealed by Figure 6.2, it can be clearly seen that both the unused areas and a yard belonging to a house are marked as other land usage. By incorporating the presence of functional areas to determine the land suitability, this problem is partially addressed, by making sure that for example allotments, sports fields and marinas lead to a lower value on the land usage attribute. The exact usage of every single piece of land is unfortunately not registered in an openly available data source.

Figure 6.2: Comparison of the used topographic data (left) with satellite images (right) provided by Google, Aerodata International Surveys, and Maxar Technologies (2021). On the left image, white areas represent other land usage, black areas indicate the presence of buildings and green areas indicate grassland.

What currently lacks in the used input data, is the incorporation of future developments when determining the potential of mobility hub locations. Both real estate development in the vicinity of a mobility hub location, and road network developments can influence the potential of an evaluated area. Furthermore, what followed from a comparison with a proposed hub network is that railway/metro stations might be planned, increasing the potential for a mobility hub in the vicinity of those new stations. Related to this, development projects that are currently being carried out are not taken into account either, because information on these projects is not integrated yet into the data used in this thesis.

A limitation of the traffic model is that it is a model, implying that it is based on assumptions and calculations for the region, so it is not an exact representation of the reality. Future scenarios are developed using growth estimations, so the used 2020 scenario does not contain real data on the number of inhabitants, workplaces etc. in 2020, but interpolated data from a base year. Furthermore, the traffic assignment in the traffic model is not an exact representation of the real traffic flows in the area, so the loads at the links will not exactly match reality. More precise data is unfortunately not available.

A further critical process which is not included in the elaborated method application, is the recalculation of the traffic model, with the regional mobility hub placed in a selected area. The placement of a hub will alter the traffic flows in the region, and to evaluate the impacts of this alteration, the traffic model should be recalculated. For measuring the actual improvement in the region's accessibility due to the mobility hub, this recalculation is necessary too. Nevertheless, the method application provides a good alternative to estimate the concerned attribute values.

Additional data provided by the Mobiliteitsscan was available for usage in this thesis, however as there was no export option possible in this tool, this data was not of further use in this methodology. Additionally, importing the used traffic model (V-MRDH) was very time-consuming, and existing traffic models in the tool do not have the accuracy required for this application. In the Mobiliteitsscan, the accessibility index, that shows the directions in which congestion occurs from/to a certain zone and to what extent, could have been used in the method, but manual insertion would be necessary. As this process is very time consuming, this is not executed in this thesis.

6.5 Limitations in the method application

One of the main limitations of the actual method application is the incomplete inclusion of the costs. All attributes used to measure the costs are a proxy to indicate the differences in costs to build a mobility hub, comparing all areas in the region. A quantitative approximation of the costs is not given. A lot of characteristics of an area should be taken into account when costs are to be incorporated, and this data is not always easily available. Land could also become cheaper as the urbanization degree decreases, as land in low density areas is less desirable than land in high density areas. This factor is not taken into account in this thesis, even though it can lead to a different outcome, with a higher regional mobility hub potential in less urbanized areas.

The potential demand of the mobility hub is based on traffic to and from the city center, as the mobility hub is proposed as alternative to traffic problems to/from/in the city. However, other (local/interregional) traffic might also use the hub. The potential demand caused by these passenger flows will differ throughout the region, an effect which is left untouched in the application. This analysis can be performed after selecting a location, but this is very time-consuming to do for every alternative (location) in the studied region, as described in the previous section on the recalculation of the traffic model. Besides, only road users are taken into account when looking at the trip production/attraction and traffic from/to the city, while the mobility hub might also be a better alternative to people that currently use public transport and cyclists. As the road users are the largest target group, this simplification is justified, but for the full picture, all trips from/to the city should be taken into account. Public transport is frequently used for transportation from/to the city center at present times, as congestion and parking in the city center make a car trip expensive and time-consuming.

Taking the I/C-ratio of a road in the direct vicinity of the area into account is an extreme simplification of the impact of the mobility hub. This basically means that a congested road which is close, will lead to a higher potential for a mobility hub. This assumption holds true only partially, as this high I/C-ratio might indicate a road that is highly used by truck traffic, which is not one of the target groups of the researched mobility hub type. A more truthful attribute would be the congestion-free accessibility of the mobility hub, but as this is direction-specific and therefore more complex to estimate, the choice is made to not include this attribute in this thesis. In section 5.7, it appears that the position of the hub compared to the congestion (upstream, downstream or in the middle) is important for the potential of the hub from a transfer mobility point of view.

A bias is visible in the method application, towards the number of inhabitants/workplaces/student places in an area. A higher potential demand is visible in areas with high inhabitant/workplace/student place values, but the impact of a mobility hub is higher too, as more people are reached upon placement of a mobility hub close to such an area. In essence, this is a logical result of the method, but the question arises whether the assigned weights are not excessively high. In Figure 6.3 and Figure 6.4, the socio-economic data from the traffic model and result of the method application are displayed for a part of the region. The very low score (red) can be observed in areas without any traffic model zones, and a very high score (green) is seen close to the traffic model zones with a high total number of inhabitants, workplaces and student places. Nevertheless, as the results of the method application are deemed logical in chapter 5, and Figure 6.3 and Figure 6.4 seem to relate in a logical way, the observed bias is not additionally studied in this research.

Figure 6.3: Socio-economic data around Kralingse Zoom. The green column represents education places, yellow represents workplaces, pink represents inhabitants and blue represents the number of houses in the zone.

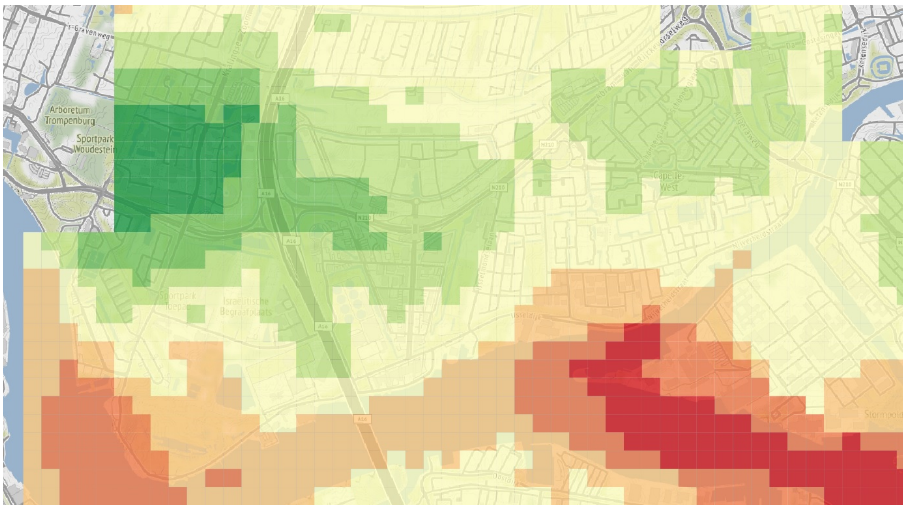

Figure 6.4: Output of the method application in scenario 1 around Kralingse Zoom.

The used value for the distance to a regional cycle route, main road, high-quality public transport link and closest road having a high I/C-ratio or serving traffic from/to the city is set to an arbitrary value of 1000 meter, as described in chapter 4, to be able to make the comparison between areas in the region. A more truthful estimation could be made by further looking into the maximum distance at which one of these links is present, such that it can still positively influence the potential for a regional mobility hub at that location.

A larger value for the catchment area of the mobility hub can be used to incorporate movements by bicycle from/to the hub, which is relevant as the hub facilitates bike sharing. Nonetheless, this would not lead to a satisfactory result, because this would mean that the areas close to the city center have a much higher value looking at the number of reached users. Extremely urbanized areas are not taken into account in the method application, but for the zones from the traffic model are not filtered based on their urban context. As a result, all city center zones from the traffic model, generally having a very high number of inhabitants and workplaces, are included in the catchment area of nearby areas, leading to a very strong bias to locations in a certain range of the city center. To illustrate this, a common value for a cycle catchment area of 3000 meter is drawn around an area close to the city center. The result can be found in Figure 6.5. It becomes clear that such a catchment area would result in the inclusion of the entire city center in the catchment area. The distance is corrected for when determining the number of users of the hub, but the competition of other public transport nodes surrounding the city center will still lead to a much lower potential of this area, compared to the calculated potential with a 3000 meter catchment area. Furthermore, in a city center, the facilities included in a mobility hub might also be offered at a location closer to the user. In less densely populated regions in The Netherlands, this enlargement of the catchment area can be adopted, as less public transport nodes and facilities are present in the catchment area.

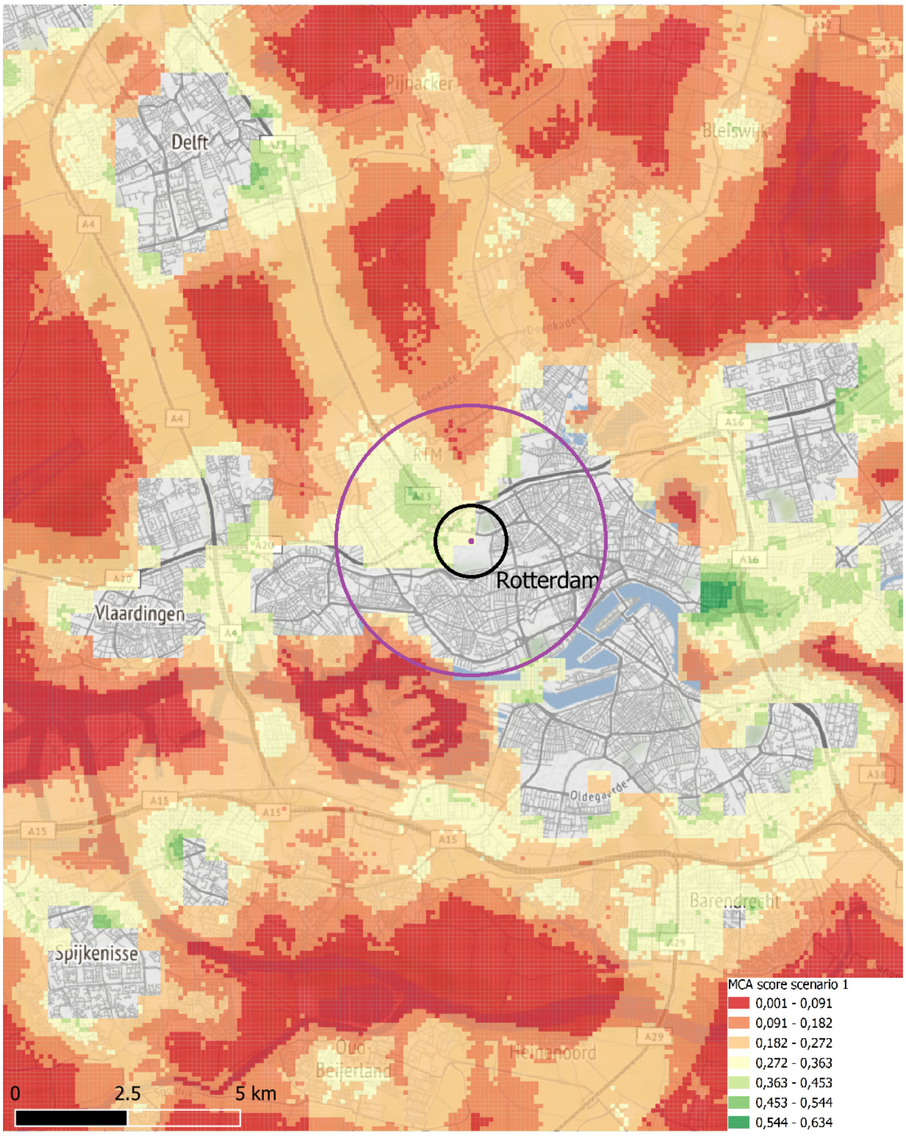

Figure 6.5: Catchment area of 800 meter (black circle) and 3000 meter (purple circle) around an area close to the city center. The output of scenario 1 is used as background.

Chapter 7

Conclusion & recommendations

The conclusion provides the answer to the research questions. It will be elaborated how the potential of areas for a regional mobility hub can be determined, and the reliability of the result will be discussed. Recommendations for policy makers and future research will be given to finalize the report.

7.1 Conclusion

The objective of this thesis is to develop a methodology, which can be applied by an interested company/government to scan a region for areas with a high regional mobility hub potential. In this methodology, three stakeholder groups are incorporated: The government, end user and operator perspective. In developing this methodology, eight sub questions are posed:

1. What is the definition of a mobility hub and which types of hub can be distinguished?
2. Which facilities do the different types of mobility hub include?
3. Which factors affect the potential of a regional mobility hub location?
4. What are the requirements for the methodology to determine the potential for a regional mobility hub?
5. Which elements should be included in this methodology?
6. How can the results from the methodology and its application be interpreted?
7. What can be learned from the application of the methodology to a case?
8. How can the methodology be improved?

These sub questions will be individually answered, where after the answer to the main research question is given. The main research question is: "How can the potential of areas for regional mobility hubs be determined, considering the end user, operator and government perspective?"

7.1.1 Mobility hub definition and typology

In the first sections of this chapter, the concept of the mobility hub is explored. An overview of the relevant information available on the definition, typology and features of the mobility hub is presented. In the literature, multiple definitions have been found, each requiring or omitting one of the elements in the adopted definition. The adopted definition is designed to be global, so all elements from the literature can be included. In this thesis, the adopted definition of the mobility hub is: "The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, possibly including other amenities, ranging from retail, workplaces to parcel pick-up points."

A classification of mobility hubs into three types is done based on the available literature, namely the residential, city and regional mobility hub, their distinctive properties are given in Table 2.1. The city and regional mobility hub differ in the urban context: a limit of 2500 addresses/km^2 is set, based on the definition of extremely urbanized areas by the Dutch national government. The residential mobility hub only targets the residents of a neighborhood and in general, this hub type does not connect to public transport, contrary to the city and regional mobility hub.

7.1.2 Mobility hub facilities

The possible features are then investigated for every hub class, first by examining the existing literature, and then relating the features from the literature to the wishes of the stakeholder groups: the end user perspective, operator perspective and government perspective. It became clear that the selection of features that should be included in a hub strongly depends on the local situation and needs. Therefore, many features in the list are labeled optional. A general overview of the features that are necessary, optional and not required is given per hub class in Table 2.2. The residential mobility hub is generally smaller in size and does not come with additional non-mobility related facilities like retail. The most noteworthy difference between the regional and city mobility hub is the presence of private car facilities like a car parking area at the regional mobility hub. Private car usage is discouraged in city centers, so the city mobility hub does not facilitate private car usage, contrary to the regional mobility hub.

7.1.3 Mobility hub location factors

Subsequently, the choice is made to focus on the regional mobility hub. The factors influencing the potential of a location for a regional mobility hub are examined by means of an extensive literature review. In combination with the interests of the three used perspectives, this leads to the selection of influential factors in Table 2.3, which are input for the methodology developed in the next chapter. In this thesis, an aggregated approach is adopted, so population characteristics, psychological variables and individual trip patterns are left out of the factors.

7.1.4 Method development

With the overview of influential factors, a methodology is developed to determine the potential of locations for a regional mobility hub. This methodology is required to spatially evaluate multiple alternatives, incorporating the interests of the defined stakeholder groups and in the application, the output should be visual, in the style of a heat map. These requirements lead to the selection of the Multi-Criteria Analysis (MCA) to evaluate the problem. The need for explicit incorporation of multiple stakeholder groups lead to the Multi-Actor extension of the MCA, whereas a visual output can be generated using GIS. As a result, the GIS Multi-Actor Multi-Criteria Analysis is proposed to determine the regional mobility hub potential in this thesis. This methodology requires the following steps to be taken:

1. Define alternatives: All areas in the selected region that satisfy the posed constraints are identified as alternatives. The number of areas depends on the selected area size (accuracy) chosen in the method application.
2. Define criteria and weights: The determination of the criteria and weights is done based on the stakeholder objectives. The used methodology for finding the weights is the Analytic Hierarchy Process (AHP). In this methodology, trade-offs between criteria are made by the stakeholders, to establish the weights that will be allocated to the criteria.
3. Criteria, attributes and measurement methods: Attributes are constructed to operationalize the criteria. These indicators should be measurable, and are often quantitative. An overview of criteria and attributes which is used in the developed methodology is presented in Figure 3.3, including the link to the factors from the previous chapter and the stakeholders.
4. Overall analysis and ranking: All areas are evaluated according to the determined weights, criteria and attributes.
5. Results: The regional mobility hub potential for every area in the region is given in a heat map. A sensitivity analysis will be performed, to check the result of changes in the weights. The scoring for every stakeholder group can be found in this stage.

7.1.5 Method application

The result of the methodology is the potential of a regional mobility hub for every area in the region, in other words: the score of the locations, taking the end user, operator and government perspective into account. Heat maps showing the potential for a regional mobility hub for all non-extremely urbanized areas in the region are presented, separately for every scenario having a distinctive stakeholder configuration. With that output, the application confirms that the methodology can be applied to a case. Differences between the outcomes of the first four scenarios are small, meaning that the method is relatively insensitive to varying stakeholder configurations. The fifth scenario, which considers a higher importance of the costs, leads to a higher number of areas with a high potential. This can be explained by the normalization of the other (non-costs) attributes, leading to relatively higher attribute values in the high-cost scenario.

High-potential areas for a regional mobility hub are found near urban centers, an observation conflicting with the intended urban context of the regional mobility hub. Besides, some assumptions made in the method application negatively influence the reliability of the result. The proposed incorporation of the congestion in the method application leads to a higher potential of areas close to a congested highway, which is not always realistic. Gathering the right data to obtain satisfactory results proved to be difficult.

Multiple analyzes are performed on the results to substantiate the usage of this methodology for answering the main question, the analyzes are summarized in Table 5.6. These analyzes show that the methodology and its application provide logical results, the methodology is robust and relatively insensitive to changes in input. Some irregularities emerged in two analyzes, related to the input data, GIS tool and one major irregularity related to the methodology. This irregularity is the normalization of the input data, leading to a high value on the corresponding attribute for a very small number of areas, whereas more areas would, looking at the values of the input data on the selected attribute, be suitable for a regional mobility hub in reality. After the final analysis, in which the proposed hub locations from a report are checked for their regional mobility hub potential, the conclusion is drawn that the high-cost scenario is best suitable for determining the potential of areas for a regional mobility hub. All in all, the result of the methodology is declared as satisfactory, taking the limitations of the methodology and assumptions in the method application into account.

7.1.6 Main conclusion

The main conclusion of this master's thesis is the answer to the research question: "***How can the potential of areas for regional mobility hubs be determined, considering the end user, operator and government perspective?***"

The potential of areas for a regional mobility hub can be determined using a GIS-Multi-Actor Multi-Criteria Analysis, a methodology combining the GIS-MCA and Multi-Actor MCA. Criteria and attributes are defined to incorporate the factors, resulting from an extensive literature review, influencing the regional mobility hub potential of an area. This methodology is applied on a region by a GIS analysis, the output is visually represented in a heat map for every scenario. Several analysis steps which are carried out on the results show that the developed method is suitable for determining the potential of areas for regional mobility hubs, as the method works as expected, but the assumptions from section 4.6 and limitations from chapter 6 should be taken into account when applying the methodology.

The wishes of the stakeholder groups are reflected in the allocation of weights to the criteria: the regional mobility hub as a solution to quality of life issues and greenhouse gas emissions, as stated in the introduction, is relevant from the government perspective. The number of users and connection to the networks is relevant from the end user and operator perspectives. In finding a successful location for the regional mobility hub, all stakeholders' points of view should be incorporated, which can be done by using this methodology.

7.2 Scientific and societal relevance

This thesis addresses the research gap of determining the potential of an area for a regional mobility hub. As the mobility hub is a relatively new concept, few literature is available on the topic. The mobility hub differs from the conventional public transport node in the integration of shared mobility and an added value to passengers and the neighborhood by providing facilities. A methodology to determine the potential of areas for a mobility hub is not available yet, this research gap is addressed in this thesis.

Three hub classes are identified, each having their own characteristics, so this would potentially result in three separate methodologies. In this thesis, the choice is made to study the regional mobility hub, as a generally applicable methodology is of the highest scientific value for this type of hub. For the residential mobility hub, there is less need for a general methodology, as the location for this type of hub is often known or less difficult to find. Few factors are involved in the location finding process of the residential hub. The difference between the city and regional hub is the available information on the location choice. In the literature, it is mentioned that very little is known on the locations for regional mobility hubs, contrary to the greater amount of information available on city mobility hubs. In short, a methodology to determine the potential of locations for regional mobility hubs has a higher scientific relevance compared to the residential or city mobility hub. By combining the factors from the existing literature into one comprehensive overview, developing a methodology to translate these factors into criteria, and applying the methodology to a case in order to test the suitability, the initial research gap is reduced.

This methodology can support governments, consultancies and potential mobility hub operators in the process of selecting a location for a regional mobility hub. The methodology can be used as a first quick scan to find the highest potential areas in a region, in which the stakeholder influences can be adjusted according to the priorities of the policy maker. The application presented in this thesis can be used as a guideline for applying the methodology to another region. As the mobility hub provides a solution to societal problems, being greenhouse gas emissions, congestion and a reduction in the quality of life in cities, the societal value of this research is well-defined. The mobility hub itself is a unique solution in terms of sustainability, offered modalities, integration of facilities and route planning, although the latter is not explicitly researched in this thesis.

7.3 Recommendations for policy makers

As described in the previous section, this thesis is particularly relevant for policy makers. To increase this relevance, practical recommendations are presented in the following list.

- In finding locations for mobility hubs, all perspectives should be taken into account. Next to the governmental wishes, the operator should be engaged to ensure a continuous operation of the regional mobility hub and related facilities. The vision of the end user is important, as the decision to use the mobility hub is eventually made by the end user.
- To limit the investment costs, a current public transport node can be upgraded by adding shared mobility. This approach, however, will not automatically lead to a reduction in greenhouse gas emissions and an improvement of the quality of life in the city. The developed methodology is only partially based on the existing nodes, but more factors are included in an effort to effectively address the societal issues.
- To be able to incorporate the lack of space in urbanized areas in the methodology, the price of land can be integrated as cost attribute. If available, this data can be a measurement for the scarcity of land in a city and it can replace the urbanization constraint. Instead of excluding extremely urbanized areas, this attribute can reduce the potential of areas which are highly urbanized, as these areas are often characterized by high land prices. This way, the regional mobility hub potential determination methodology can even be extended to a general mobility hub potential determination methodology.
- The best-scoring locations could be inserted in the traffic model, to actually calculate the potential impact, instead of only estimating the attribute by making a simplification. This way, effects which are not included in the methodology, like the detour people have to take to actually use the hub, can be included. Developing a methodology that iterates the methodology using a traffic model would be a worthwhile addition to this thesis.
- As proposed in the MRDH report on the mobility transition (de Kleuver et al., 2020), a combination of mobility hubs with other measures performs best in reducing greenhouse gas emissions and solving quality of life issues in the served city. Other suggested measures to reduce car traffic in a city are congestion charging, reducing the speed limit and increasing the parking fares. These measures are needed in order for the mobility hub to be used.
- Regarding the design of the mobility hub, expert interviews revealed some important considerations. The sense of safety in and around the hub must not be neglected, as this might prevent people from using the facility. Besides, the hub has to offer an added value for the end user in order for it to be used. If this added value is not provided by a gain in travel costs/time/time reliability, it should be provided by additional facilities at the hub. Lastly, the hub should satisfy the basic end user needs, i.e. short walking distances between modalities, a high quality of offered modalities and an integrated tariff for all mobility services.

7.4 Recommendations for future research

Throughout this thesis, uncertainties and inaccuracies came forward, addressing these in a future research can further improve the outcomes of a regional mobility hub location research.

- The sensitivity to a change in the catchment area of the hub, and to a change in the value for the distance to a link could be researched in a following research. This could also provide useful insights into the effects of a change in catchment area on the potential demand.
- This thesis focuses on the mobility hub for passengers. The mobility hub can become even more feasible when the passenger and freight functions are integrated in one facility, as both functions serve a separate target group. This integration can be addressed in a follow-up research, in which the same literature research steps are executed, but with a focus on both passenger and freight transportation.
- In order to obtain a more realistic methodology, fundamental research should also be done on criteria, instead of only taking factors from the literature. For example, the effect of the distance to the city center should be elaborately reviewed to be able to reliably incorporate this factor. In addition, research on the generation of demand for a regional mobility hub due to the presence of various types of facilities (sports, retail, shopping etc.) should be executed. Nevertheless, the most important factor that should be fundamentally researched in order for the mobility hub to be useful, is the change in travel behavior. The shift from the private car to shared mobility and public transportation is assumed in this thesis, but the reality suggests otherwise. It is strongly recommended that this research is executed before planning the implementation of a regional mobility hub. In this future research, the population can be subdivided into multiple population groups with their distinctive mobility patterns, as the adoption of the mobility hub can vary according to the chosen population group.
- Current shared mobility providers might have a rich source of information on the current locations at which shared mobility is highly used. These data sources can be incorporated to fine-tune the methodology, as the current operators already have revealed preference information on the usage of shared mobility. An operator with a service area that stretches outside the extremely urbanized city center should be chosen. In case of a free-floating shared mobility service, in which the start and end of the trip are not fixed locations but large areas, like the city center, the most popular start/end locations reveal the most desired locations for shared mobility. An analysis of these locations can improve the methodology.

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Appendix A

Mobility hub software implementation

The software implementation is not the focus of this Thesis, but will be addressed shortly in this appendix. In order for the mobility hub system to function, and to be used frequently by the traveler, the system should be seamlessly integrated. This integration regarding ticketing and travel planning is very important. Public transport associations were founded over the last decades (Buehler et al., 2019) in Germany, Austria and Switzerland to achieve this integration. The coordination of schedules, integration of tickets and fares and high quality of service are the main characteristics of the established public transport networks. In the six regions researched in the paper, the share of trips by car is reduced significantly since the implementation of the public transport associations.

Literature on the integration of different mobility services in one solution is available on Scopus. The integration of public transportation with car sharing, bike sharing and parking has been researched in a paper by Beutel et al. (2014), where an approach for the integration of the information system, routing system, ticketing and fares is provided. A mobility broker is put into place as joint platform for all mobility services, on which transportation providers can collaborate, and travelers can plan their integrated trip. The system architecture from this paper can be used when designing a mobility hub, as the software implementation is elaborated. Some details are left untouched, like the integration of carpooling (since a different payment method is used there), legal issues and the attitude of the concerned transportation companies.

A lot of research has been done on Mobility as a Service (MaaS), a concept which uses mobility hubs, in which the focus is on mobility-wide integration of ticketing and route planning. In a paper on the literature research concerning MaaS and travel behavior (Durand et al., 2018), four levels of integration are presented: Information, ticketing and payment, service and societal goals integration. It is concluded that "*research reveals that a comprehensive approach combining multiple levels of integration is more likely to encourage passengers to use the integrated modes than solely a lower level of integration. Further, mobility packages could be used to influence travel behavior patterns.*" This emphasizes the importance of software integration for the success of MaaS or mobility hubs.

An example of such a MaaS system can be found in Helsinki, where Whim introduced monthly subscriptions and credit which can be used in public transport, as well as shared mobility services and taxis. Whim offers one app for all transportation modes, in which ticketing and route planning are integrated. The mobility hub requires such a system, as the convenience for the end user determines the adoption and success of the hub.

Appendix B

AHP

In this chapter, the exact AHP methodology is explained, in order to obtain the weights assigned to the criteria in the method application. Several steps have to be taken to convert the trade-offs from the expert interviews into weights. The explanation of these steps is given in (Malczewski and Rinner, 2015, p.38, p.91). Firstly, pairwise comparisons between the criteria are organized in a matrix. All diagonal elements are given the value 1, as the diagonal values represent the trade-offs between equal criteria. The matrix is reciprocal, meaning that all cell values are the inverse value of the opposing element (the element on the other side of the diagonal). To compute the resulting weights, the values on the diagonal are divided by the sum of all values in the column. This leads to a weight factor for each criterion, to be used in the weight calculation. The exact same procedure is executed for the attributes within the criterion.

In this thesis, a step is added to the GIS-MCA weight determination methodology, to incorporate the multi-actor aspect. Criteria are attached to each stakeholder group, as not every criterion is relevant for each perspective. Then, the trade-offs are made by pairwise comparisons between the criteria from every perspective. Subsequently, the weights for every criterion are calculated from all perspectives, and the total weight for each criterion is calculated using the stakeholder influences from the defined scenarios.

In short, using the trade-offs in Table 4.3, Table 4.2 and Table 4.1, the following steps are executed:

1. Calculate the total weight per column, with the value 1 on the diagonal. The resulting sums are found in Table B.1.
2. Normalize weights such that column total is 1. In Table B.2, this calculation is performed. In this table, the resulting criterion weights are calculated per stakeholder group.
3. Combine stakeholder group weights per criterion to a final criterion weight per scenario. The final result is shown in Table 4.4.

Table B.1: Sum of the columns for the AHP weight calculation from the stakeholder perspectives.

Government perspective	**Costs**	**Link to surroundings**	**Impact**
Costs	1	2	0.5
Link to surroundings	0.5	1	0.25
Impact	2	4	1
Sum	**3.5**	**7**	**1.75**

End user perspective	**Generalized costs**	**Link to surroundings**	**Impact**
Generalized costs	1	2	0.5
Link to surroundings	0.5	1	0.25
Impact	2	4	1
Sum	**3.5**	**7**	**1.75**

Operator perspective	**Potential demand**	**Costs**
Potential demand	1	2
Costs	0.5	1
Sum	**1.5**	**3**

Table B.2: Normalized values representing the criterion weights for the AHP weight calculation from the stakeholder perspectives.

Government perspective	**Costs**	**Link to surroundings**	**Impact**
Costs	0.2857		
Link to surroundings		0.1429	
Impact			0.5714
Sum	**1**	**1**	**1**

End user perspective	**Generalized costs**	**Link to surroundings**	**Impact**
Generalized costs	0.1429		
Link to surroundings		0.2857	
Impact			0.5714
Sum	**1**	**1**	**1**

Operator perspective	**Potential demand**	**Costs**
Potential demand	0.6667	
Costs		0.3333
Sum	**1**	**1**

Appendix C

Full expert interviews

In this appendix, the full expert interviews are presented. The interviews are conducted in Dutch and translated to English. The English text has been verified for completeness and correctness at the interviewees. Nine interviews are conducted at eight organizations, whereby the NS section contains two interviews.

C.1 SmartPT Lab

Interview questions

-Is the integration of shared mobility only under investigation at existing public transport stops? Or are new locations with a high demand, and no high-quality public transport stop taken into consideration as well?

Would that be the best solution? Public transport connections must be very quick, for example at stops of HOV (high-quality transit) lines, or line intersections. Infrastructure leading to these stops can be researched to find the connectivity. It can be very advantageous when a stop can be reached by bike easily. A link can be found with TOD here: creating corridors.

-What should a mobility hub (public transport/shared mobility node) comply to, concerning user needs?

The mobility hub should take the following user needs into account: Closeness, availability/certainty of availability, information provision via an application, quality of the shared modalities.

-Which factors play a role when integrating shared mobility with public transport?

The theory of planned behavior affects the success of this integration. A model of access to digital technology addresses another important factor for the adoption of new technologies, namely digital inequality. This model is explained in Figure C.1.

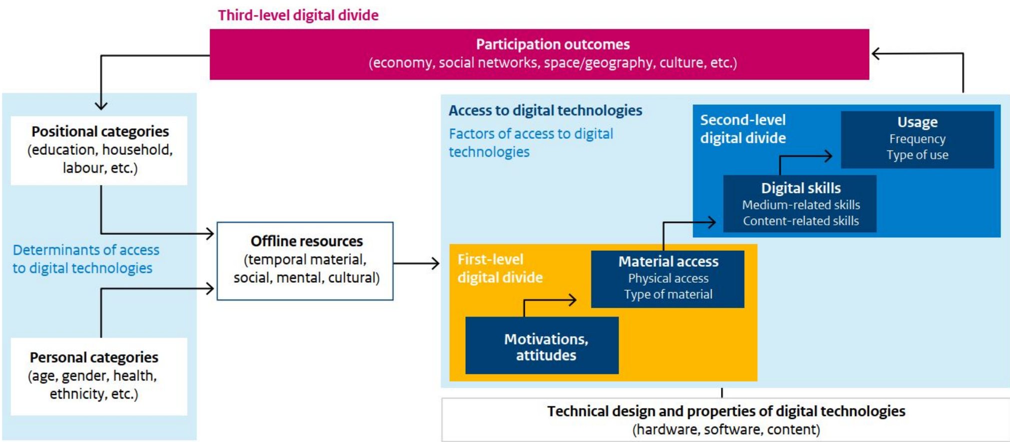

Figure C.1: Digital inequality explanation (Durand and Zijlstra, 2020)

Cycles should be within direct vicinity of the public transport stop, so without crossing five streets before getting to the bicycle stand. The presence of bicycles is necessary, and unlocking should be possible with an application or the OV-Chipkaart (Dutch integrated public transport card).

Digital skills are needed to use this system. MaaS may offer many possibilities, but it should be very user friendly. This leads to very hypothetical problems, because it is unknown how MaaS will look like exactly.

-Which shared modes will play in role in the upcoming years, will that be the shared car and bike, or are there more interesting, innovative modalities?

Researched are the e-bike, e-scooter and e-moped. Other modes are barely used, so there is little added value. The e-bike also offers very little value compared to the regular bike. The e-moped is mostly popular among the youth, and less among elderly. Mostly tourists use those modalities. As it becomes more naturalized, more regular trips will be made using these modalities.

-How can you link the current public transport problems to the upcoming, new modalities?

These new modalities can be offered, but as long as people possess a car, the effect is limited. How will the current car traffic be facilitated in the new plan? My investigation is focussed on the last mile of public transport trips.

-For my research, I will use a Spatial MCA to evaluate every location in a region to certain criteria. Would you have any tips on this methodology, or adding disaggregate data to an aggregate model in general?

In my thesis, one of the models (the aggregated or disaggregated model) can be scaled, which enables one to compare the parameters of the two models. The validity is limited, and it is only applicable in that case-specific context. This thesis is more of a methodology than a specific usage.

-Are Park&Ride facilities under investigation in your research?

The sensitivity to a change in travel time is very limited at the target group of Park&Ride facilities. It is better to cluster all the e-mopeds at a few locations, instead of a lot of e-mopeds spread across the city. Public transport transfer points have the highest potential.

C.2 Arriva

Interview questions

-What is your background and role at Arriva?

After a traffic engineering studies, the interviewee started working at Arriva 6 years ago. One of the interesting projects he collaborated on is the implementation of the transport concession Limburg, in the process of converting the tender to the exact operations in the area. Currently, he fulfills a role as manager transport engineering at the Arriva headquarters, being responsible for the development of the timetable and the mobility strategy of Arriva.

-In my investigation, I am designing a location choice model for regional mobility hubs. Does Arriva have any experience with mobility hubs, or is the topic investigated within the company?

The current tenders for transport concessions are based on static transportation, meaning that they include the operation of fixed public transport services only. Some concessionaires do not achieve a convincing business case for regular public transportation, and therefore think of alternatives, like demand-responsive transportation, or shared modalities. For Arriva, it is interesting to connect shared mobility to the current public transport network, with the goal to increase the number of passenger kilometers traveled on their public transport system.

-What can you tell about finding locations for a new transit/shared mobility hub? To put it differently: do you have experience with choosing the most suitable location to upgrade from existing public transport stops?

Usually, new public transport stops are not proposed without connection to the current public transport system. The placement of a hub is the result of an acceleration of public transport services and tightening of policy, not a new chosen location. The current public transport system forms the basis for determining a mobility hub location.

-I composed a list of criteria determining the potential of a location for the placement of a mobility hub. For the operator, I found the potential demand and connection to the transit network as important factors. In other words: When a choice between two locations should be made, which criterion has a higher influence on the location preference?

The demand is always of high importance in public transportation. If enough volume is available at a location, a higher quality public transport connection can be offered. Therefore, the reach of the public transport service is increased, but this will only be possible in case of a convincing business case, requiring a certain demand.

From the point of view of Arriva, a connection to the transit network is required: shared mobility is seen as an addition to the public transport network. Comparing the two criteria, the demand comes first, but the connection to the transit network should be established as well.

-Would you have any additions on the rest of the criteria from the other perspectives? Or might some of these criteria be relevant for the operator?

The spatial integration is a criterion in which Arriva is not involved. Arriva will probably not operate the hub itself, so the acquisition of the ground is not dealt with by Arriva.

For the traffic problem as criterion, it is important to mention that a transfer to high-quality public transport should be offered, with separate infrastructure to avoid encountering the same road congestion on a bus route.

-Do you have any further tips for my investigation?

To determine the success of a mobility hub, it is highly important to look at it from the user perspective. What is the added value of a mobility hub for the end user? This is something very significant to understand. To continue with the expert interviews from the end user perspective, information might be gathered from a traveler's panel.

Furthermore, the Public Transport Vision 2040 (OV Toekomstbeeld) is an important document to dive into, as this is the guideline for the Dutch mobility strategy written by the government. This document contains a section on trip chains and public transport nodes, relevant for a mobility hub investigation.

C.3 NS

Interview questions

-What is your background and role at NS?

The interviewee finalized her PhD at TU Delft last year September. Since December, she works at both TU Delft and NS, with a role as researcher on first and last mile transportation at NS, where she focuses on both the supply and demand side, her topics include bike parking and car parking. At the TU Delft, she works as a postdoc, linked to projects on first and last mile transportation, cycling and mobility hubs.

At NS Stations, she is a researcher, which actually means that she is business consultant, data analyst, and supports projects, like the realization of a new bicycle parking facility at a station. She provides information to support decision making processes at NS. Not every decision NS makes is currently based on data, so there is room for improvement.

Findings from the interviewee's PhD are incorporated by the municipality of Amsterdam to improve models for first and last mile transportation. Knowledge and insights from this investigation are of further use at NS, but the PhD results could not directly be applied at NS.

-In my investigation, I am designing a location choice model for regional mobility hubs (outside of the city center). Does NS have any experience with mobility hubs, or is the topic investigated within the company?

NS Stations has been struggling with the definition of a mobility hub. The definition in this thesis would imply that NS Stations is the largest operator of mobility hubs in The Netherlands. But a mobility hub isn't necessarily placed at a train station. Within the company, an internal vision and strategy on mobility hubs is developed.

Important for the mobility hub is that the quality of the mobility service should be incorporated. A bus stop with a single bus line operating once an hour/bi-hourly would not be suitable for a mobility hub, whereas a high-quality public transport connection can be suitable.

Worth mentioning about the OV-Fiets, the shared bike system operated by NS, is that some locations are situated at busy spots in Amsterdam and Rotterdam, not connected to a NS train station.

-What can you tell about finding locations for a new transit/shared mobility hub? How is the most interesting location to upgrade from existing public transport stop to shared mobility hub determined?

As an example, the placement of an OV-Fiets facility is determined by the number of passengers using the station. This model is currently not very advanced, as the demand is the only criterion. Within the company, we are improving this model.

-What is the role of NS in the establishment of mobility hubs? Will NS possibly operate these hubs?

It is important to see the difference between NS and NS stations in this context. NS Stations operates the train stations in the Netherlands, and offers the same services to all carriers (NS, regional transportation companies Arriva, Keolis etc.). Concerning mobility hubs, this distinction should be considered.

NS Stations operates OV-Fiets, while NS offers subscription services to use this service. NS decides whether Felyx or Mobike can integrate a hub at a selected station. For mobility hubs not placed at a train station, NS (Stations) will not play a role, since they do not own the station.

-I composed a list of criteria determining the potential of a location for the placement of a mobility hub. For the operator, I found the potential demand and connection to the transit network as important factors. In other words: When a choice between two locations should be made, which criterion has a higher influence on the location preference?

There has been some discussion with municipalities on the concept of a mobility hub without a public transport connection. In Amsterdam for example, the Bike&Ride concept is explored, a mobility hub where only car and bike are the offered modalities. According to the definition in this thesis, this would not be a mobility hub, since public transportation is not included.

The interviewee is currently working on a research proposal on mobility hubs. The definition she took for mobility hub is a location where multiple traffic flows come together, walking excluded. The manager station development works on the strategic vision (with a role for mobility hubs) within the company, it might be relevant to ask for a call with him.

-Would you have any additions on the rest of the criteria from the other perspectives? Or might some of these criteria be relevant for the operator?

Usually, the main station is examined in a city, that is where the main services are located. The operator considers every train station individually, while an approach taking multiple stations into account could be more realistic. For example in Delft, where the station of Delft Zuid has more potential looking at the bigger picture. Some users might prefer to travel via Delft Zuid instead of Delft due to bike parking difficulties at the main station. Other users prefer Delft because of the available facilities. The offered facilities usually depend on the number of users of the station, but providing facilities at a station like Delft Zuid might attract new travelers.

-Do you have any further tips for my investigation?

Relevant for your investigation would be a talk with a transport developer from HTM, as this organization has been investigating the placement of shared bikes at their tram stops, and the drop zones of these bikes. The deployment of this system is also investigated outside of the city center, so this could be relevant for this thesis on regional mobility hubs.

Interview questions

Following the advice of the previous interviewee at NS Stations, a follow-up with the manager station development is planned. He is able to elaborate on the strategic vision on mobility hubs written by NS Stations.

-What is your background and role at NS?

The interviewee has a background in architecture, followed by a studies on management in the built environment. His main occupation has been real estate since the completion of his studies, working a lot on urban challenges, for example the reconstruction of Alphen aan den Rijn.

At NS Stations, the interviewee is responsible for all station development projects, and the accompanied investments. He makes the plans for these projects, in cooperation with ProRail and often with local partners. In this station development, the biggest challenges are faced just outside of the station. Crucial is the connection between the train station and its surroundings. Some decades ago, big train stations were relatively safe, while the surrounding station environments were criminal hotspots.

The station increasingly became a place to stay over the past years, it became the epicenter of the city. The station and the direct surroundings became a destination by itself, as urban development expanded to the station area.

We should not forget, however, that mobility is the most important function of a train station. On top of the railway tracks, building is possible, but creating borders for station development by placing buildings right next to tracks is not desirable. That takes away the possibility to expand the mobility function.

A key difference between the city and the region is that in the cities, there is a lack of space, and in the regions, there is a lack of facilities.

NS aspires to make The Netherlands accessible for everyone, also for disabled users or mobility deprived users. The challenge is to attract everyone for public transport, the sustainability challenge, which is needed because there is no space left for the private car in cities.

The government is occupied with challenges on quality in the built environment by means of the NOVI, the National Strategy on Spatial Planning and the Environment by the government. The regional implementation plan is the RIA (regional investment agenda), in which the government explores together with market players how the area development can be tackled.

-I'm interested in the vision of NS Stations on mobility hubs. Could you tell me more on the definition of a mobility hub, the connected modalities and offered facilities at the hub from this vision?

NS Stations has approximately 400 'mobility hubs'. For the total number of employees, a distinction should be made between the mobility and station facilities. NS Stations provides a lot of jobs to staff facilities and stores in stations.

Concerning first and last mile transportation, the vision of NS is that muscle power comes before fossil fuel, the goal is to let people walk to the station. This concerns sustainability and healthy urbanization. Of the new attracted train users in the last decades, a large part reached the station by foot. In the strategy, it is further determined that small comes before large, so a small electric scooter (E-Step) is prioritized over a cargo bike.

A common mistake on the topic of mobility hubs is building a hub at a highway/railway intersection, with the goal to let people switch to public transport at that location. This will not happen, as there is often no reason for road users to make this switch, so there is no point in developing a mobility hub. Only 5% of the train users takes the car to the train station. This percentage is slightly higher at 'double name' train stations like Lage Zwaluwe or Driebergen-Zeist, maybe 15%.

The current Park&Ride facilities cannot remain free of charge, as the space is simply not available in cities or at city borders. The modal shift should take place, where users decide at home to cycle or walk to the station and take the train.

NS decides to focus on the widespread continuation and improvement of OV-Fiets, their bike sharing system. The system will gain market share by providing a more intelligent system, in which users can drop the bike at every system location (one-way rental) without a fee. The success of the OV-Fiets is built on the availability and spread of the system, as the user will think of the OV-Fiets as an option when traveling to any random station in The Netherlands.

Looking at the expansion of the system with different vehicle types, NS is a bit reluctant, as there is no other vehicle sharing system in the country with such a large volume as OV-Fiets. An electric version of the bike is considered, as this might be useful when cycling in the dunes, or for seniors. This decision is to be made by NS.

In the city, there should be place for all parties, NS is non-discriminatory. The municipality should take on the management of all shared mobility providers, but NS offers help. The e-moped, for example, poses a spatial problem, as these vehicles do not fit in a regular bicycle parking. Drop zones should be assigned for those vehicles in a city. From the vision of NS, sharing comes before private possession. Shared vehicles should be situated right at the entrance of a station, not somewhere in the back.

-Concerning the mobility hub location choice, how is such a location currently determined?

For now, vehicle sharing systems will be introduced at train stations and other large mobility nodes with a high demand. 95% of the mobility hubs is very unprofitable, as the demand is too low. The loss on mobility hubs is one of the reasons NS is not committing to this development. Besides, the added value NS can provide is limited at locations without a train station, compared to other potential mobility hub providers.

What helps in the introduction of a shared bike system, is the presence of a staffed bicycle parking. This way, bike repairs and surveillance are already offered, leading to lower operating costs for the system. Making substantial investments in supervised bicycle parking facilities is essential for the introduction of the mobility hub. The quality will increase significantly because of the socially safe, supervised environment.

Many parties underestimate the organization of a shared vehicle system. For example, a provincial government decided to implement shared bikes in the concession, but this system was not wind resistant. At NS, countless employees are occupied with recovering non-returned OV-Fiets vehicles.

The experience of NS is that station-based vehicle sharing works better than a free-floating system. OV-Fiets has been introduced years ago as a replacement for public transport in poorly connected areas, therefore the price should be comparable to a public transport ticket. With a free floating system, offering this price is not achievable.

Shared mobility can be a solution to parking problems in real estate development projects. But the question remains who will pay for the facility and the shared mobility. The electric vehicle is becoming cheaper, with an attractive leasing rate, while train tickets are relatively expensive. The sustainability and cost incentives for using mobility hubs are therefore less relevant, high inner-city parking fares form the main stimulus.

Breukelen was promoted as the ultimate hub, with a large parking area. Private vehicles have a large space requirement, so the question is whether this solution really keeps the country connected. It should be considered what percentage of cars can be captured from the highway, and what amount of space is needed for storing these vehicles. This type of hub is often proposed by policy makers, like the projected station of Dordrecht Amstelwijck, which would facilitate the car/train transfer.

-Do you have any further tips for my investigation?

NS produced a vision, called the Journey, on mobility of the future, seen from the perspective of the passenger. This might be interesting to consult for the thesis.

C.4 RET

Interview questions

-What is your background and role at RET?

The interviewee is transport developer for the metro of Rotterdam. He is policy maker, engaged in the development of the strategy: the timetable, planning of the lines and public transport nodes in the metro system are his responsibilities. He has worked at RET for over 15 years and has previous experience at another Dutch regional transportation company.

The Rotterdam metro system is a very dynamic system to manage, as the frequency and timetable need yearly evaluation. To give an indication of the passenger volume of the metro in Rotterdam: the main transfer station Beurs is the sixth largest Dutch rail station.

-In my investigation, I am designing a location choice model for regional mobility hubs (outside of the city center). Does RET have any experience with mobility hubs, or is the topic investigated within the company?

RET is a public transportation company, with the metro as core business. Shared mobility is seen by RET as a first/last mile solution for metro/bus/tram transportation, not as a replacement. The interviewee has some colleagues working on the topic of shared mobility. The comparison with the transport company in The Hague (HTM) is made, as that company operates their own shared bike system.

RET did some effort in expanding the number of metro stations that offer the Dutch OV-Fiets shared bike, which is already offered at several important metro stops (Kralingse Zoom, Slinge). Sometimes, OV-Fiets was not willing to cooperate on this project. RET tries to make arrangements with Felyx, one of the shared e-scooter companies in Rotterdam, to set metro stops as drop-off point for the vehicles.

-What can you tell about finding locations for a new transit/shared mobility hub? How is the most interesting location to upgrade from existing public transport stop to shared mobility hub determined?

In finding new locations, RET depends on external organizations because the company does not own any shared vehicles by itself. The most important factor is the potential demand, metro stations with a higher number of travelers are interesting locations for the placement of a mobility hub.

Tram and bus stops are a lot smaller in size and passenger numbers, but shared mobility can play a role at these locations. For example, at the bus stops of the high-quality bus line through Lansingerland, large bike parking facilities are placed for inhabitants of the influence area. These facilities have a high utilization. For visitors of this region, a shared bike or car can be a solution for their last mile.

Looking at small neighbourhood hubs, the success is often questionable, since the target groups should be willing to use shared vehicles instead of their own (second) vehicle. The availability of these shared vehicles has to be very high, this is related to the available space for a mobility hub.

-I composed a list of criteria determining the potential of a location for the placement of a mobility hub. For the operator, I found the potential demand and connection to the transit network as important factors. In other words: When a choice between two locations should be made, which criterion has a higher influence on the location preference?

Essentially, a public transport line is situated at a location with a high demand. Those two factors correlate with each other, so a clear prioritization can not be given. An extra detail to take into account, is the use of space by shared vehicles at the activity side of the trip. The user should be able to park a shared car close to the destination.

-Would you have any additions on the rest of the criteria from the other perspectives? Or might some of these criteria be relevant for the operator?

The spatial integration is important to include, the space available for shared and private bikes should be considered. At a city center hub, there is hardly any space available for shared cars.

Shared mobility can be suitable for areas in which public transportation links are not present. In this way, shared mobility is a nice addition to the public transport network. For example, at recreation areas and lakes around Rotterdam, the bus/tram network is not well developed, while cycle paths are omnipresent. Shared bikes can complement the network at those places, therefore the connection to the cycle network is a relevant criterion.

High-quality, high-frequency public transport lines can indicate a high demand, thus supply for shared mobility, so they might provide attractive locations for a mobility hub. In addition, neighbourhoods lacking a decent public transport connection can be interesting areas for shared mobility. The passenger numbers are often too low for a fixed bus line, so a bike sharing system at a nearby bus stop can provide a mobility solution for this area.

-Do you have any further tips for my investigation?

Try to develop a formula for shared transportation. There are a lot of shared mobility providers in Rotterdam, so a new system should feature a clear, recognizable formula with logo. A certain quality standard can be offered and expected by customers due to this formula. The locations of a shared mobility system should be planned strategically, just like trailer rental at gas stations, or providing shared electric cars at EV charging points.

What might be difficult is the involvement of all necessary organizations (shared mobility, parcel pick-up point, grocery stores etc.) at a certain location. For example, OV-Fiets was not interested in providing their services at metro stops, because the passenger numbers were too low in their vision.

C.5 Gemeente Rotterdam

Interview questions

-What is your background and role at Gemeente Rotterdam?

The interviewee is senior advisor mobility at the municipality of Rotterdam (Gemeente Rotterdam), city development division. He is responsible for traffic models, monitoring and data at the municipality. With a background in traffic models, he did calculations on traffic models in the past, and is now occupied with best practices in using traffic models, and the link with data and policy.

-In my investigation, I am designing a location choice model for regional mobility hubs (outside of the city center). Does Gemeente Rotterdam have any experience with mobility hubs, or is the topic investigated within the company?

In internal policy documents, the term mobility hub appears regularly. A few colleagues of the interviewee are working on the policy implementation of the mobility hub, which are potentially interesting to interview. They also come up with interesting locations to experiment with the mobility hub.

-What can you tell about finding locations for a new transit/shared mobility hub? How is the most interesting location to upgrade from existing public transport stop to shared mobility hub determined?

As a municipality, we work at two levels, namely investigating the neighbourhood hub, and looking from a higher, strategic level.

For the neighbourhood hub, the municipality explores local initiatives. In some neighbourhoods, a group of enthusiasts comes up with the idea of establishing a small mobility hub with multiple shared cars and bikes. These initiatives are supported by the municipality.

The strategic level is more difficult, since a lot of factors and organizations are involved. The current Park&Ride facilities already serve as a mobility hub. Interesting is the establishment of Park&Bike facilities, for directions from which the public transport connection is not of high quality. The last mile can be replaced by cycling to the city in that case.

To appeal to people ready to transfer to bike for the last mile, the transfer facility should be situated close to the city. This way, cycle distances can remain limited to a comfortable length. The problem arising in this situation is the traffic using the mobility hub, driving their vehicles relatively deep into the city.

At the convention center Ahoy, in the southern part of Rotterdam, there is a huge vacant parking place, because no events are organized there due to the current COVID-19 pandemic. Shared mobility providers launched an initiative to encourage people to park there, and continue by using shared mobility to the city center. This also meets the needs of travelers not willing to use public transport due to the pandemic.

The upcoming year, the municipality of Rotterdam will make a plan and vision document on the position of mobility hubs in the future.

-I composed a list of criteria determining the potential of a location for the placement of a mobility hub. For the government, I found that all criteria are relevant. I need some help in prioritizing the criteria though, could you assist me in arranging the criteria, where the following question is posed: 'Which criterion has the highest/lowest influence on the location choice?'

From the traffic engineering point of view, the potential demand and existing traffic problems are the most relevant criteria. These should have the highest priority. Nonetheless, the spatial integration of a mobility hub can make or break the potential of a location. A perfect location from traffic point of view, with no space available, may be not suitable at all. The connectivity and link to the surroundings facilities are less important for a location's potential.

-Do you have any further tips for my investigation?

Studio Bereikbaar is a traffic consultancy in Rotterdam. The company did an investigation on the mobility transition, where the concept of the mobility hub is studied as well. Four types of mobility hub are distinguished, with corresponding examples from The Hague and Rotterdam.

The company 4cast did calculations on traffic models, in which a mobility hub has been added. Sweco has contact with employees at 4cast, so they might explain the process of including the mobility hub in a model.

C.6 VZR

Interview questions

-What is your background, and role at VZR?

The interviewee has been board member at VZR for 7 years now, and is active in the field of mobility for more than 35 years. He is originally a jurist, and has been occupied with car transshipment in the harbour of Rotterdam, fulfilled a function as director of a large inspection firm in the field of mobility, director of a leasing company and of a car dealer. Afterwards, he started up on his own, with VZR as one of his side activities.

VZR is an organization with 33.000 members, which are the business drivers (potential mobility hub users), and 78 affiliated companies, mostly large leasing companies and importers. Other companies associated with mobility, like Hertz and Parkmobile, are connected to VZR as well.

Since the organization reached a member count of 20.000, it has been fully involved in the Dutch politics, not only to serve their member's interests, but also to be engaged in the mobility of the future. The constructive way of working adopted by VZR ensures that available knowledge can be optimally used.

-In my investigation, I am designing a location choice model for regional mobility hubs (outside of the city center). Does VZR have any experience with or ideas on the mobility hub?

Concerning sustainability, the interviewee established the first sustainable leasing company in The Netherlands, Greenlease.

VZR believes that sustainability is the future. Therefore, VZR is involved in the Dutch mobility alliance. Fact is that the private car is unused for 96% of the time, which implies that the resources are not used optimally. The organization has two ongoing projects on sustainability, firstly a pilot for a varying additional tax liability for using the company car privately. The idea is that a financial incentive would cause a behavioral change among these car users. Demanding to explain the necessity of all traveled kilometers can make a large difference in travel behavior.

The second project is the mobility hub. Upon introduction of this idea, VZR has been fighting for involvement of the end user in the project. For the end user, an unconventional approach is often needed, as there is not only right or wrong, but all values in between are considered by an individual as well. Their preferences and developments should be taken into account when designing such a system.

-What can you tell about finding locations for a new mobility hub? How are the most interesting locations for a mobility hub determined from the user perspective?

There is a document on mobility hubs by the mobility alliance. A differentiation is made in that document, with many different passenger and cargo hub types. It can be useful to consult this document.

-I composed a list of criteria determining the potential of a location for the placement of a mobility hub. For the end user, I found the connection to the road/cycle network, traffic problems and link to the surrounding facilities (supermarket/parcel pick-up point etc.) to be relevant. How can these criteria be prioritized from the end user point of view?

From the business driver point of view, life should be simplified. The hubs should bring an advantage to the user. This translates to a gain in preferably time or money.

An example from practice is Utrecht Science Park, which was a fantastic proposition for the end user, offering an integrated tariff for parking and using public transport. The facility became crowded within a short period of time, as this was a very attractive facility for the end user, directly next to the highway, with a public transport stop situated within the building. The facility relieved the roads in and around Utrecht significantly. Unfortunately, someone reconsidered the facility from the traditional (non-user) perspective and separated parking and public transport tickets. Consequently, the demand faded away. The effort of using the hub is increased, as the ease and financial incentive disappeared for the end user.

Concerning Utrecht Science Park, this facility is close to perfect, but the addition of facilities like a parcel pick-up point or meeting rooms would be desirable. Nonetheless, the financial incentive is needed to reach out to the public at large. Only by that means, the obstacle (additional transfer) of multimodal transportation can be overcome.

Reliability of the journey time is more important than the travel time, because the end user should be able to rely on the schedule. MaaS solutions are active in providing a highly (over 95%) reliable schedule, in order to meet the scheduled appointments. This reliability is of paramount importance to the end user.

-Do you have any further tips for my investigation?

This psychological aspect of the end user is important, and should be incorporated in the research. As an example, being stuck in a traffic jam just before the destination will cause a lot of frustration at the user.

An investigation was conducted on factors inducing the business driver. These factors become increasingly important, this effect was visible at the introduction of electric vehicles as well. After a while, this psychological hurdle is resolved, leading to a high increase in demand for electric vehicles.

Of further interest for the research could be some user input, which can be collected via a poll at the website of VZR, among business drivers. This poll generally has a very high participation rate, within a very short time period.

C.7 ANWB

Interview questions

-What is your background, and current position at ANWB?

The interviewee is team manager mobility and traffic safety at ANWB, where he is the manager of a group of lobbyists, concerned with mobility and traffic safety. Public transport is less represented by ANWB, as the organization Rover picked up on that topic.

The interviewee has a background in business administration and marketing, and has a lot of knowledge on and experience with the various government layers. Previously, he has been employee for the municipal and national government, posted partially outside of the Netherlands. He has worked at ANWB for 5 years now, without a previous background in mobility.

-In my investigation, I am designing a location choice model for regional mobility hubs (outside of the city center). Does ANWB have any experience with or a vision of the mobility hub concept?

ANWB has been co-writing the documents for the mobility alliance, in which the mobility hub appears. ANWB is a member organization, so ANWB lobbies in the members' interests. The members are no pioneers concerning innovations in mobility. The basis is often the private vehicle, and sometimes the bicycle, as ANWB also represents cyclists. For this reason, the ANWB receives very few member questions on the topic of mobility hubs.

ANWB is engaged in the mobility hub from the future perspective, and the role of the hub in achieving the objectives set by the municipalities. ANWB did not develop a mobility hub strategy by itself. As for the strategy on P&R, ANWB developed a vision document on Park&Ride facilities, which disappeared in a drawer.

-What can you tell about finding locations for a new mobility hub? How are the most interesting locations for a mobility hub determined from the user perspective?

Finding a suitable location is slightly easier in a regional setting, at the city borders a hub is often placed at vacant spaces.

The best place for a hub is a valuable place in the city, but a hub is not given a priority such that space is allocated to a mobility hub. In Den Haag for example, a hub is placed in the Binckhorst industrial zone, which is not very well connected to the network.

Another example is the Park&Ride facility in Rijswijk, which is well connected to public transport, but socially not very safe. The hub should be a worthwhile addition to the trip, otherwise it will simply remain unused.

In Den Haag, a Park&Ride has been constructed years ago in an attempt to reduce congestion on the road to Scheveningen. A dedicated bus lane was put into service as the alternative to congestion. The enthusiasm for this service was very little, as people preferred the traffic jam over using public transport. Visitors wanted to be sure of reaching their vehicle quickly on the return trip. This demonstrates that the mobility hub should be an enrichment of the trip, whereas an extra transfer is rarely an enrichment. This added value can be found in offering facilities at the hub, for example a parcel pick-up point, grocery store or childcare. Furthermore, the hub must be a socially safe, comfortable place.

-To pick up on the criteria in my investigation, what is (not) relevant for ANWB to take into account in the process of a mobility hub placement? I marked the following criteria as relevant from the user perspective: network connectivity, presence of traffic problems and the link to the surroundings/facilities. I need some help in prioritizing the criteria though, could you assist me in arranging the criteria, where the following question is posed: 'Which criterion has the highest/lowest influence on the location choice?'

Congestion is presented as a very big problem. But in reality, the traffic jam is not a huge problem for road users. People will simply anticipate to the congestion. This anticipated travel time loss is not a big issue, but unanticipated travel time loss can lead to bigger problems. The certainty of travel time, and in the case of hubs, the certainty of an available shared vehicle, is paramount. This certainty of a vehicle which is always available leads to a high car possession in The Netherlands, which results in the irrationality of a vehicle in front of the house remaining unused for 90% of the time.

The hub should be a means, not an end in itself. Therefore, the added value of a hub must be clear. It should offer additional comfort, or additional certainty (of travel time).

With the population growth and increasing densities in cities, the private car possession can be critically appraised. In cities, search traffic generates a lot of useless vehicle kilometers. With a perspective on a sustainable future and zero traffic casualties, zero emission or zero vehicle zones are introduced in cities. An alternative to the private car is needed, and can be valuable.

A change in behavior is very hard to establish. Interesting things happen during the current COVID-19 pandemic in this respect, current developments can be accelerated. A major impulse is still needed to achieve such a change in behavior.

Currently, there is momentum for traveling more sustainable. In 15 years, electric vehicles will be widespread and this momentum is less. The current transition to low-traffic city centers can be used to implement certain changes.

The mobility transition can be achieved best at places where a densification currently takes place. The choice should be made to build a new car-free neighborhood, instead of removing the cars from an existing neighborhood. People deciding to reside in that neighborhood will deliberately choose to live without a private car, so their mindset towards the transition is positive. That is exactly where the transition to different mobility behavior should take place, where there is a change in a person's life.

Two developments can be seen these days: the densification of cities, and an increasing demand for mobility. More private cars are not the solution, but there is no direct space issue to remove the cars which are present.

In Amsterdam, the proposal is to limit car traffic in the area within the A10 ring road, which is a very profound measure to introduce for the citizens. In Utrecht, it was proposed to relocate cars in the city to parking lots at the ring roads, which would lead to dozens of square kilometers of parking decks.

Even bicycle parking is sometimes a problem in dense cities. Parking all private bicycles in one place at a high-rise building already causes a mess sometimes. The bicycle is often mentioned as a solution, but actually creates a new problem in cities. The space requirement should be taken into account for every modality.

For mobility hubs in the suburbs, it is simple: if it's not possible or allowed to reach the city center by car, the car should be parked somewhere else. The mobility hub can be a good alternative. City visitors should be addressed, as their behavior is the easiest to change.

The hub is an extra obstacle in the trip, a transfer moment, which is undesirable. A metro stop close to your home is perfect, this avoids the extra transfer, but this is sometimes different for a mobility hub. The added value should be figured out, and the groups for which this added value is provided. An ageing takes place, the people from that generation experience difficulties in traveling by public transport. Multimodal traveling can be even more difficult for this group, active mobility can be one of the solutions to this problem. However, this group is not always able to walk or bike. In a member survey, the added value of a mobility hub was investigated. People expect convenience, a social environment and facilities like a parcel pick-up point at such a hub.

-Do you have any further tips for my investigation?

The mobility alliance has a document on which PON co-wrote. One of the interviewee's contacts at PON is occupied with new mobility, and is very knowledgeable about hubs, also on the business side of the mobility hub. Someone needs to pay for the hub, this is frequently the end user. The challenge is to organize the hub in such a way that the trip price will not increase. A mobility hub will be funded partly by the private sector, and partly by the public sector. NS has a lot of experience with these conflicting interests, which poses a complicated situation. At hubs, there will be the issue of the provider of the shared mobility. Is the investor the only operator of the mobility hub, or can all providers place their shared bicycle at the facility?

Good spots for a mobility hub are very expensive, and residences generate a higher profit for the municipality. It is important to prevent the relocation of hubs to a less attractive place, because the societal value of hubs is relevant to take into account. This societal value is needed for a good hub location.

C.8 OV-Consumentenplatform Drenthe

Interview questions

-What is your background and role at Consumentenplatform Drenthe?

The interviewee did a study in philosophy and theology, and has been member of traveler organization Rover for 50 years. Besides, she has a fascination for public transportation, for the operations of trains and buses. Furthermore, she uses the regional bus connections (including international services) in Drenthe on a daily basis.

On behalf of Rover, she is involved in the Consumentenplatform Drenthe, already since the founding of the organization about 20 years ago. For approximately 7 years, she has been board member in the organization, being representative in the Dutch northern rail consultation (a consultation of multiple operators, regional and local governments). Furthermore, she is active in task force timetables.

-In my investigation, I am designing a location choice model for regional mobility hubs (outside of the city center). To what owe the existing hubs in Groningen/Drenthe their success?

To take the example of Gieten, the regional bus connections lead to the success of the node, already before the re-branding as a hub. Multiple frequently used bus lines operate to this node, and offer seamless connections. The hubs in Groningen and Drenthe generally offer at least two bus lines, so these hubs are all transfer points.

The transfer quality between bus/train lines is of high importance for the end user. A low transfer time between connecting services can strongly improve the potential of a hub. Of further relevance are the protection against the elements, and the presence of services like a cafe, or bicycle lockers with charging facilities. These facilities make the trip via the hub attractive for the end user.

-What can you tell about finding locations for a new transit/shared mobility hub, how is the location determined? Is it always an existing stop being upgraded?

Until now, the interviewee has not experienced the introduction of a mobility hub at a not yet existing public transport node.

-What is the role of Consumentenplatform in the establishment of the mobility hubs?

In the first phase of the mobility hub plan, Consumentenplatform was not incorporated in the process. The hub locations were found by the OV-Bureau looking at the network, such that the maximum cycle/car distance to reach a hub is limited to 15 kilometers. Furthermore, most train stations are marked as hub. The failure to incorporate Consumentenplatform lead to mistakes in the hub design, like the lack of a changing table for babies in toilets.

At the mobility hub in Zweeloo, Consumentenplatform is involved in the first step, which leads to a better result for the hub. Currently, Zweeloo has a simple bus station with an undersized bicycle parking and no facilities. At the start of next year, this project is initiated.

-I composed a list of criteria determining the potential of a location for the placement of a mobility hub. For the end user, I found the connection to the road/cycle network, traffic problems and link to the surrounding facilities (supermarket/parcel pick-up point etc.) to be relevant. How can these criteria be prioritized from the traveler point of view?

Most hubs have been public transport nodes already before the conversion to mobility hub. A choice was made on the nodes to transform, a process in which the presence of facilities is important. When facilities are present, this leads to lower costs, so the responsible government (municipal/provincial) might decide to invest in upgrading that node. Some municipalities focus less on public transport, like Emmen, so the chances of establishing a mobility hub there are less.

Furthermore, the integration with other facilities is advantageous for end users. A mobility hub in front of a library, like in Roden, is ideal. But the hub should be connected to the current public transport network, no rerouting should be needed. This is a requirement for the mobility hub.

The idea of the hubs emerged to reduce the vehicle mileage, so the greenhouse gas emissions would be reduced. This creates the demand for high-quality public transport. The hub taxi is developed as complement to the network, but the system is not functioning well. The theory behind the concept is good, but it does not work. Reasons are a high fare (2.5-5x the public transport fare), and the requirement to call at least 1 hour ahead.

The public transport system can not always be expanded, because the demand should be there. When the demand is low, the connections to other bus/train lines at a node should be of high quality. That makes it doable to use public transportation.

The connection to the car and cycle network is relevant, as people will need to reach the hub by their private transportation. The hub in Zweeloo is not equipped with a parking facility, this can be seen as a disadvantage of this hub.

A hub can also operate as a Park&Ride facility, like the hub in Rolde (located at a major road intersection) for the city of Assen, or the network of hubs around Groningen. Especially around Groningen, a city where driving around in the city center is not attractive, this type of hub is very popular. The existence of parking problems in a city increases the need for hubs around that city.

When designing a hub, the sense of safety should be taken into consideration. This aspect is crucial, especially in rural area in the dark, as a low sense of safety may lead to the decision to not use the hub.

-Do you have any further tips for my investigation?

Get a day ticket for the public transport in Drenthe, and travel along a few mobility hubs. This way, you can see the differences between the various hubs for yourself.

A good idea is to talk with a municipal road authority. Try to call the municipality of Coevorden, and ask for the person responsible for the mobility hubs. This might provide interesting input for your investigation!

Appendix D

Method execution

In this appendix, the used workflow to successfully apply the methodology is elaborated. The workflow consists of transformers and connections. Transformers are the building blocks of the workflow, every transformer has a unique function, like evaluating which areas pass a certain test. The connections form the link between the transformers, and make sure the data is routed through the network of transformers, to ensure that the output contains all required data.

D.1 Data transformers

Aggregator: Aggregates all list items belonging to the same area, with the option to sum or average all list values for every area into one attribute.

Attribute filter: Splits the areas into multiple outputs, based on the (text) value of an attribute. By using this transformer, train, metro and light rail stations can be filtered out of the large topographic dataset that contains all spatial elements.

Attribute manager: Creates new attributes and deletes superfluous attributes from the areas. New attributes can be created with a value that is calculated from existing attribute values. This is used to calculate the MCA score in the final step of the method application.

Attribute range filter: Splits the areas into multiple outputs, based on ranges of the values of an attribute. For example, only the roads with an I/C-ratio of higher than 0.6 are filtered out by the algorithm.

Attribute value mapper: Alters the values of a certain attribute to a different value, given a test equation. By using this transformer, text values can be converted into numerical values.

Feature Color Setter: The feature color setter is used in the verification, to be able to clearly distinguish the areas scoring above a certain value. A striking color like red is used in the verification, but this transformer is capable of assigning every possible color to the input data.

Feature Joiner: The feature joiner joins the features which have an attribute in common, like the column and row. Using this transformer, all layers containing data on one of the attributes are joined into one all-encompassing layer, in which every area contains information on all researched attributes.

Feature Merger: Merges the attributes of one layer onto another layer. The layers are joined based on the value of a specified attribute. This transformer is used to merge all links with a high I/C-ratio in the afternoon rush with all links having a high I/C-ratio in the morning rush, to obtain a layer with all links congested in either the morning rush, afternoon rush or both.

List Exploder: Explodes all list values, found by the neighbor finder, into individual elements, to allow for calculations with these list items' values.

List Range Extractor: Finds the maximum and minimum value from a list. Applied to find the maximum I/C-value to use as critical congestion occurring around an area.

Mapnik Rasterizer: Generates a raster, based on the input polygons. The raster is set to areas of 100x100 meter, the transformer calculates the membership of the input in every area. The area is colored white if there is not input present, and red if the area is 100% covered by the input.

Neighbor Finder: Finds a specified maximum number of neighbors for every area, within a specified distance. These neighbors can be lines or polygons, so all links within a distance of 800 meter of an area can be found using this transformer.

Raster Cell Coercer: Coerces the cells of a raster into areas of 100x100m. This is the transformer placed after a rasterizer to force the values into readable areas.

Reprojector: Reprojects data on EPSG:28992 Rijksdriehoekscoördinaten coordinate system. Useful for data which is not in the right coordinate system, like a self-created grid, or the data from the traffic model in OmniTRANS.

Spatial Filter: Filters input based on the spatial relationship with a test criterion. By using this transformer, the created grid can be filtered such that only the part of the grid situated in non-extremely urbanized context is evaluated. The executed test is a filter to check which areas are situated within the 500x500 meter areas in non-extremely urbanized context from the address density dataset.

Statistics Calculator: This transformer selects the largest value from a list, and presents the output grouped by the column and row, so the maximum value from the list per area. By using this transformer, the maximum value for the distance*load from/to the city can be calculated, instead of only the distance to the nearest link from/to the city multiplied by the corresponding load.

Tester: The tester checks whether an attribute value satisfies a constraint. The tester is applied at, for example, Public transport/Bike links to extract the Public transport links only.

2DGridCreator: This transformer creates a grid of areas, sized 100x100 meter in this research, using specified origin coordinates. Each area comes with a row and column attribute, indicating its position in the grid.

D.2 Workflow

The first step in the model execution is the creation of areas, sized 100x100 meter, covering the extents of the selected region. The extents are determined by the size of the topographic dataset encompassing the region, covering x coordinates 80.000 to 100.000 and y coordinates 425.000 to 450.000 in EPSG:28992, the Dutch Rijksdriehoekscoördinaten coordinate system. Using an AttributeRangeFilter, areas with an address density of more than 2500 addresses/km² are filtered out of the address density dataset. By spatially filtering the created grid of 100x100 meter areas that are within the areas in non-extremely urbanized context, a grid of 41.550 100x100 meter areas results. This grid is further used for all calculations. The workflow for this first part is given in Figure D.1.

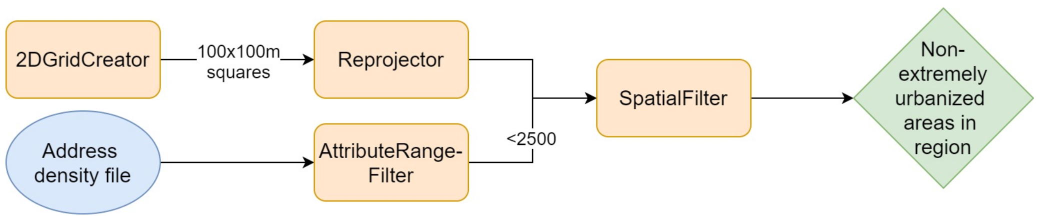

Figure D.1: First step in the method execution, in which the grid of areas situated in non-extremely urbanized context is created.

Data from all other data sources can be added to the created areas. The most complex part is the determination of the physical land suitability, as multiple object classes of the topographic dataset are used for the calculation. The Terrein object class is the initial determinant for the suitability, where after this value is corrected for the presence of a functional area that reduces the land suitability score and for the presence of buildings. In the final step of this calculation, the attribute manager calculates the total value on the physical land suitability attribute. In this calculation, the percentage of the three land usage classes (25%, 75% and 100% suitability) in every area is calculated, where after this percentage is corrected for the reduction in suitability due to the presence of a functional area or buildings. Subsequently, the total value in every area is calculated, by multiplying the values 0.25, 0.75 and 1 to the percentage of corresponding land usage in every area. The workflow for calculating this attribute value in FME is shown in Figure D.2. The workflows used to process the other attributes is shown in Figure D.3. In the end, an AttributeManager is placed after all FeatureJoiner transformers to calculate the final MCA score, by multiplying the weights from Table 4.4 with the respective attribute values in the area, for every scenario.

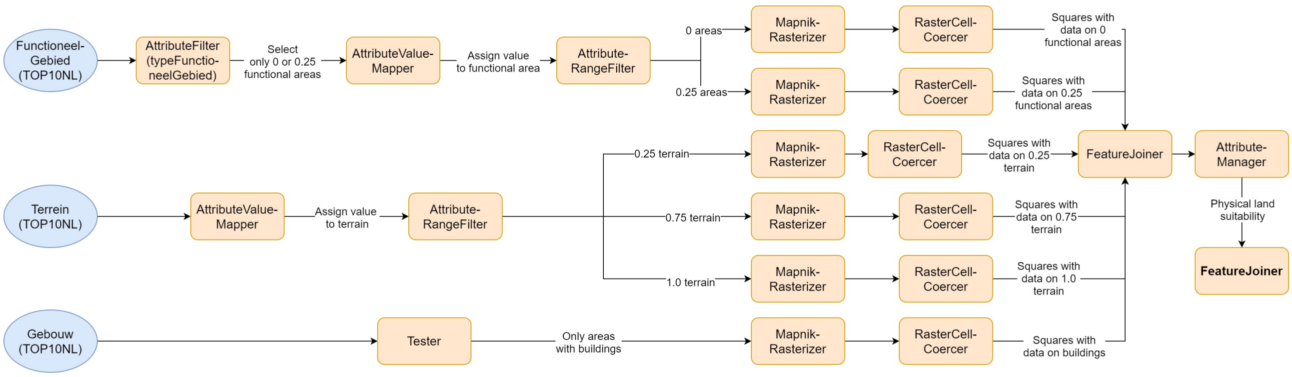

Figure D.2: Method application steps to assign a value for the land suitability to each area.

For the traffic model, multiple steps have to be taken before the data is in the right format, and before the right data is selected for further processing in the GIS tool. The traffic model .7z file can be opened in OmniTRANS, after which a run of the model for the 2020 traffic simulation is performed, for both car and bike/public transport traffic. Several distinct attributes are described by data from the traffic model, therefore multiple exports are carried out. The number of retail workplaces and reached users (SEGs) are found in the zonal data, defined for every zone, which was exported by separately exporting a .csv file with the zonal data, and a Shapefile using the export module in the OmniTRANS application. In this Shapefile, the zones (and their identifier) are linked to the geographical location, and in the .csv file, the zonal data is linked to the zones by a column containing the unique zone identifier. These files are separately loaded into the GIS tool and joined on the zone identifier.

With regard to the links, the public transport and road links are separately exported using the OmniTRANS export module, whereby car and truck traffic loads (based on all-or-nothing assignment, assuming that congestion does not affect the user's route choice) are exported to separate Shapefiles. The files containing the road links are then joined to calculate the maximum I/C-ratio (by comparing morning and afternoon rush data) of every road segment. Truck traffic is included by applying the factor 1.75, meaning that a truck is treated as 1.75 car. This factor originates from a report compiled for the government (Bakker, 2010). Subsequently, only congested road segments, in either the morning, evening or both the morning and evening rush, are passed through a filter.

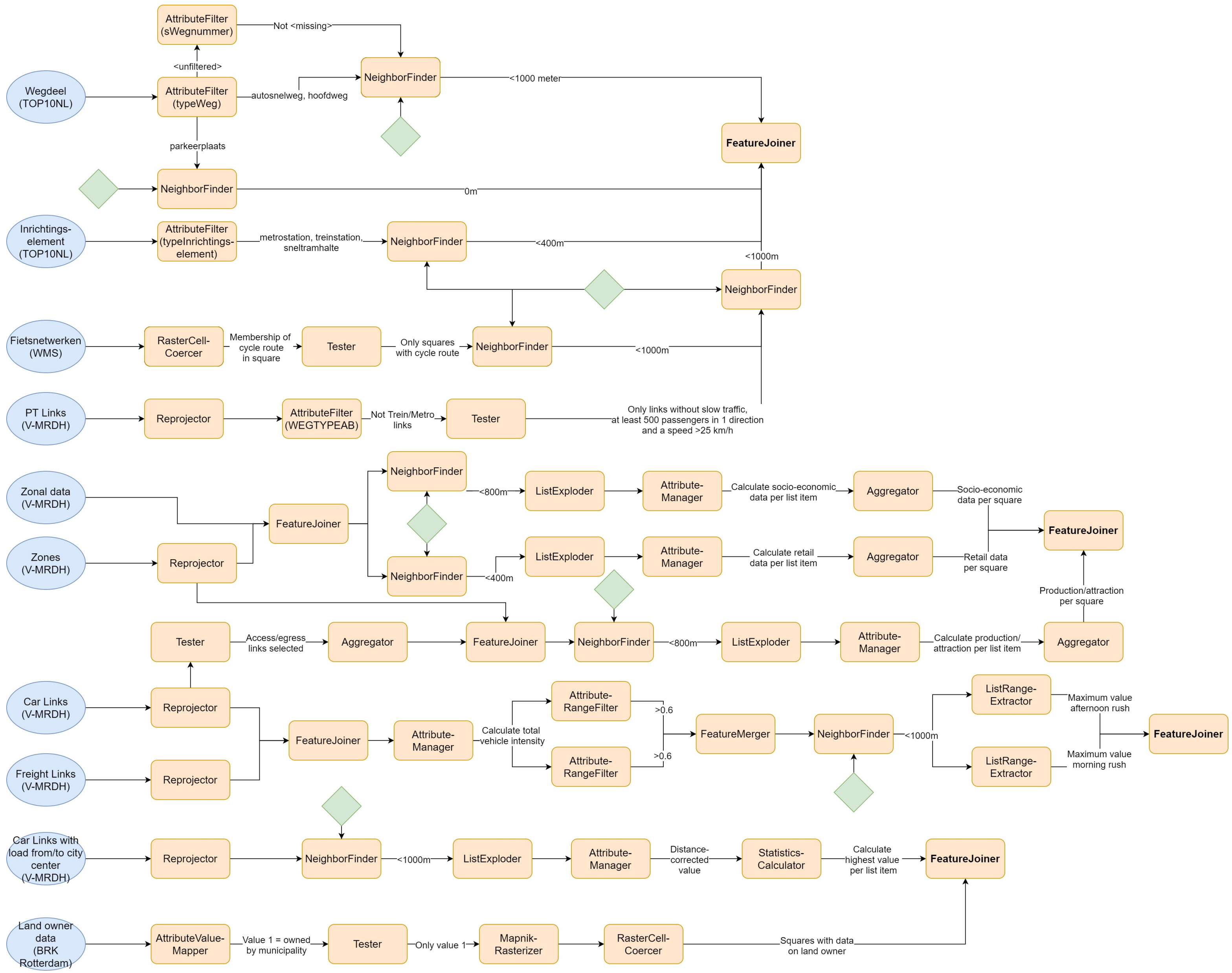

Figure D.3: Method application steps to include all other attributes for every area. The green diamond represents the non-extremely urbanized areas layer created in the first method execution step.

Appendix E

Verification of the method application

In this appendix, every individual attribute of the method application will be verified, to make sure the application functions as expected and the data is not erroneous. Scenario 1, with all stakeholder groups equally weighted, is used as base scenario. In the verification, the following process is executed for every attribute:

1. The weight of the investigated attribute is set to 1 in the MCA score calculation.
2. An attribute range filter filters out all areas with a score on the MCA score of more than 1.
3. An expectation of high scoring areas is given, based on a reliable data source in which areas that should score high on this attribute are identified.
4. If the data is correctly processed in the method application, the high-scoring areas from FME should match the areas containing a high value of the attribute from the other data source.

E.1 Production/Attraction

The data source for this verification is the Mobiliteitsscan, in which the module 'Number of car trips' calculates the total number of car trips departing and arriving in each zone in the area. Note that the zones in the Mobiliteitsscan differ from the zones used in the traffic model. The input data is the NRM West, the strategic traffic model of the Western part of The Netherlands, provided by the national government. The output of both data sources is shown in Figure E.1 and Figure E.2.

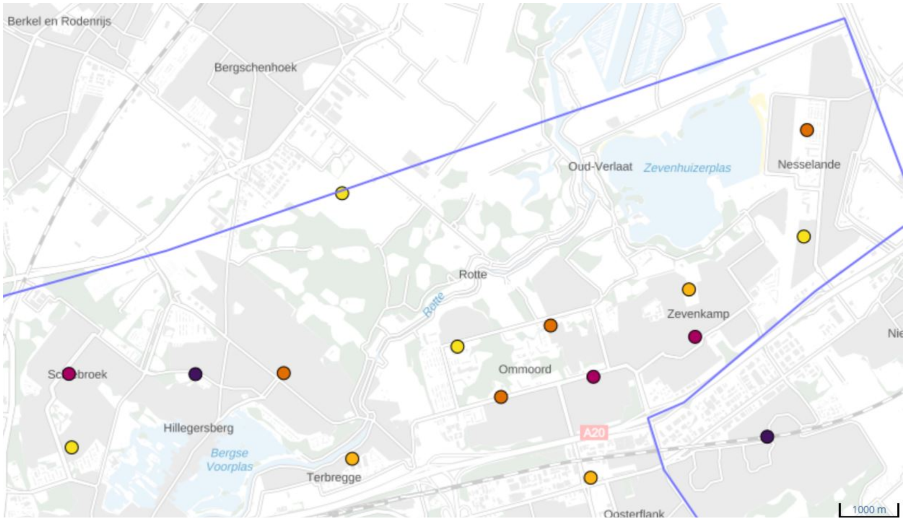

Figure E.1: Output of the high scoring Production/Attraction areas in the Mobiliteitsscan. The darker red color indicates a zone with a high car trip production/attraction, the lighter yellow color a zone with a low car trip production/attraction.

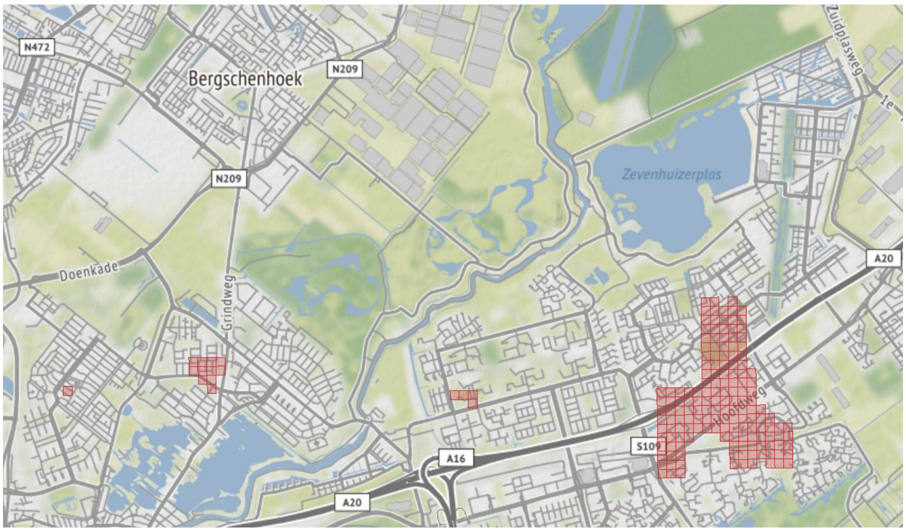

Figure E.2: Output of the high scoring 'Production/Attraction' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

All zones with a high production/attraction from the Mobiliteitsscan match the FME method application output, except for one zone which is situated within an extremely urbanized area, so not taken into account by the method application. This is the area just right of 'Ommoord'. There is one more peculiarity, which is the area just left of 'Ommoord' that has a high MCA score. From the source data of the method application, it appears that this area has a relatively high production/attraction (matching to the orange color of the closest zone). Due to the presence of a parking area in the areas, and a station near the areas, the high score of these areas is justified.

E.2 Traffic along road from/to city center

The data source for this verification is the Mobiliteitsscan, in which all traffic from the city center in the afternoon rush can be visualized. From the Mobiliteitsscan, it appears that there is a very small number of roads for which the MCA score would be high, as only a few roads handle a large part of the traffic volume from the city center. This is verified by FME, as there is only a low number of areas left after the filter. From Figure E.4, it appears that outside of the extremely urbanized city center, areas along only two roads score high. This corresponds to the image extracted from the Mobiliteitsscan (Figure E.3), in which it appears that the road on the left lower side of the image and the road from the center to the bottom process the largest traffic volumes, as the thickness of the line scales to the traffic volume. As the method scales to the largest value of traffic volume present in the region, very few areas will obtain a total MCA score of higher than 1, therefore the areas surrounding the A16 highway in Figure E.4 are not colored. Due to the urbanization constraint, areas in the city center are not evaluated, so not shown in the figure.

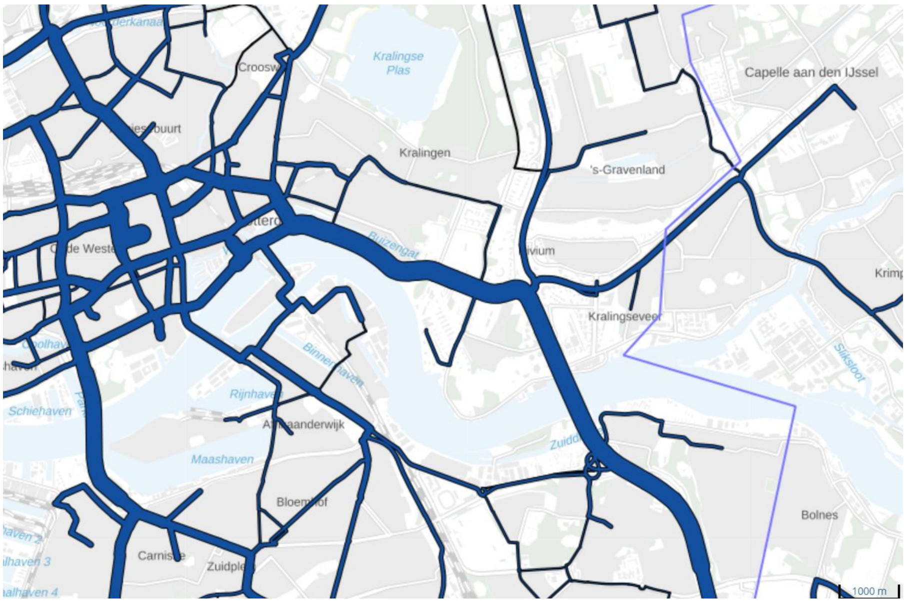

Figure E.3: The allocation of traffic flows from the city center in the afternoon rush from the city center in the Mobiliteitsscan. The thickness of a line indicates the allocated traffic volume in the peak hour, a thicker line represents a higher traffic volume.

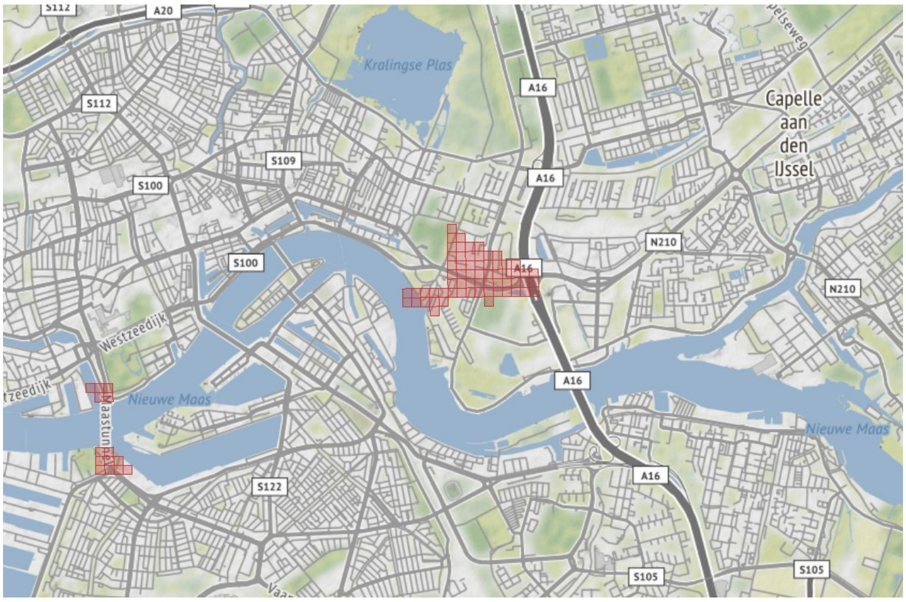

Figure E.4: Output of the high scoring 'Traffic along road from/to city center' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.3 Presence of parking area

To verify this attribute, a visual inspection of satellite images is executed, in which the parking areas in a part of the region are identified. For this analysis, parking areas with at least ten parking spaces are taken into account. Ten is an arbitrary value, used to separate a few adjoining parking spaces from an actual parking area. These parking areas are marked in the image, and this image is compared to the result from the method application. The images are found in Figure E.5 and Figure E.6. From this image, it appears that the input data lacks some parking areas in the region. The smaller parking areas, especially in the top part of the selected area, are not present in the source data for the method application. Reflecting on the reason for including the presence of parking areas as attribute in the methodology, the exclusion of small parking areas is not necessarily seen as a limitation of the data, because the size of an available parking area influences the potential of an area for a regional mobility hub. Small parking areas do not necessarily increase the potential, as a regional mobility hub has a space requirement exceeding the size of a small parking area due to the inclusion of a public transport stop, comfortable waiting facilities and retail.

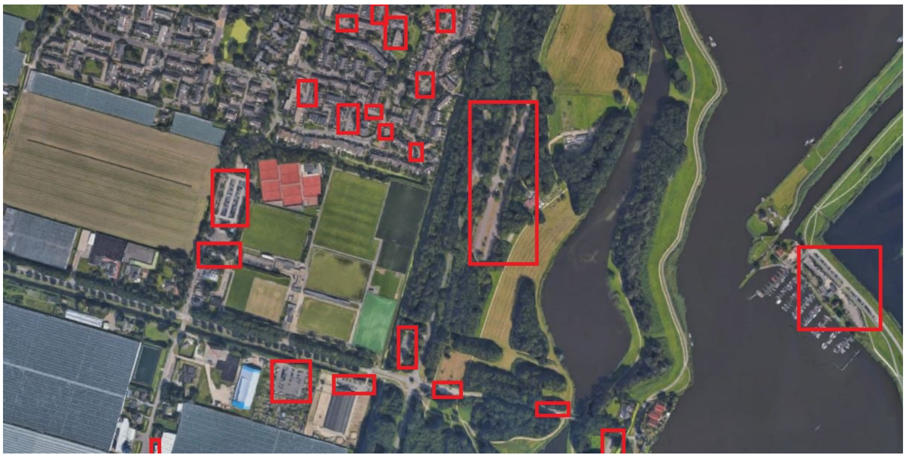

Figure E.5: Satellite images of a selected part of the region by (Google, Aerodata International Surveys, and Maxar Technologies, 2021). The red rectangles represent parking areas in this region.

Figure E.6: Output of the high scoring 'Presence of parking area' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.4 Physical land suitability

To verify this criterion, satellite images will not provide enough detail to make statements on the correctness of the method application. As other data sources to verify the land suitability are not openly available, the original data source is used. By doing so, the method application is verified, without verifying the data source. In Figure E.7 and Figure E.8, it can be seen that areas with the land use 'other' result in a high score in the method application. The area on the right is part of the airport and therefore given a low suitability score. The red area in the lower center part of Figure E.8 corresponds to a green area (grass) in the topographic map, and since this land use leads to a score of 0.75 on the suitability attribute, this may lead to a total MCA score of more than 1. As a percentage of land suitability is calculated for the 100x100m square areas, some white parts of the topographic map do not score over 1 in the method application.

Figure E.7: Topographic source data for determining the land suitability for a mobility hub. The white areas represent 'other' land use, leading to the highest suitability.

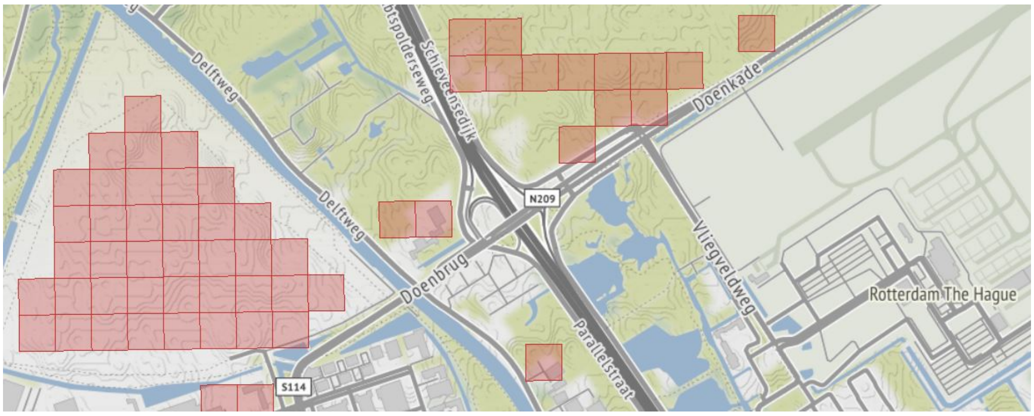

Figure E.8: Output of the high scoring 'Physical land suitability' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.5 Land owner

For the land owner, no other data source is available apart from the data provided by the municipality of Rotterdam. Therefore, the only possible check is the accordance of the high scoring areas with land owned by the government. For the check, a part of the region is chosen with relatively large parcels, in the harbour of Rotterdam. The data is filtered such that only the parcels owned by the municipality are shown in Figure E.9. Comparing this with the result from the method application for the same part of the region in Figure E.10, a limitation of the method application becomes clear. It can be seen that the squares do not exactly match the source data, which is due to the used transformer in FME. This transformer can only take one parcel into account for the determination of the land owner of a square. For squares at the border of adjacent parcels that are both owned by the municipality, only one of the parcels is taken into account for determining the land owner score of each area. As a result, the score on this attribute is sometimes lower than expected.

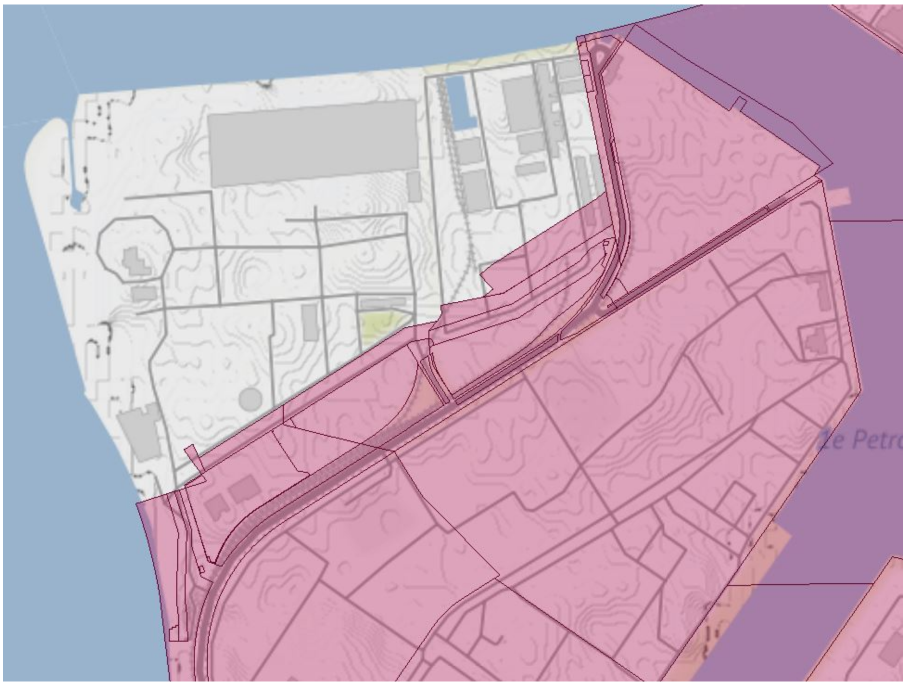

Figure E.9: Source data of the land owner in FME, in which only areas owned by the municipality are passed through the filter.

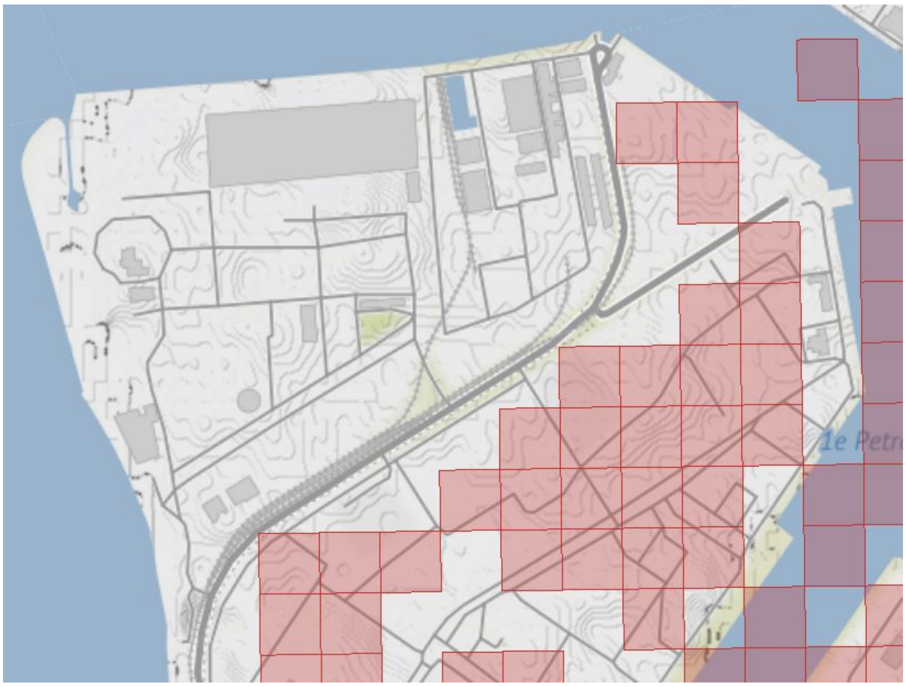

Figure E.10: Output of the high scoring 'Land owner' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.6 Presence of high-quality bus/tram link

To verify this attribute, a high-quality bus/tram link in the Rotterdam region is selected, and it is tested whether these links are correctly identified in the method application. A part of a high-quality public transport map of the Zuid-Holland province is used to verify this, as shown in Figure E.11. Comparing the image with Figure E.12, which shows the high scoring areas in the method application when increasing the weight of the public transport link attribute to 1, it seems that some areas are incorrectly marked as close to a high-quality bus/tram line, and some areas close to the actual line are not marked as high potential areas. In the method application, the high-quality bus/tram links are filtered out of all public transport links by passing through three testers, discarding the links with mixed traffic, a load lower than 500 passengers per day in both directions, and a speed lower than 25 km/h in both directions. When inspecting the links, the right orange line is not identified as high-quality public transport link due to the low loads in both directions (less than 500 passengers per day). For the orange line passing through the center of the image, investigating satellite images shows that the bus-only lane is situated next to a cycle path. These infrastructures are combined into one link in the traffic model and incorrectly labeled as mixed traffic link. Concluding, the verification of this attribute shows incorrect simplifications in the source data and an assumption in the method application leading to the unjustified omission of some high-quality public transport links.

Figure E.11: A snippet of the map showing the high-quality public transport lines in the Dutch province of Zuid-Holland, indicated by the orange lines (Provincie Zuid-Holland, 2018).

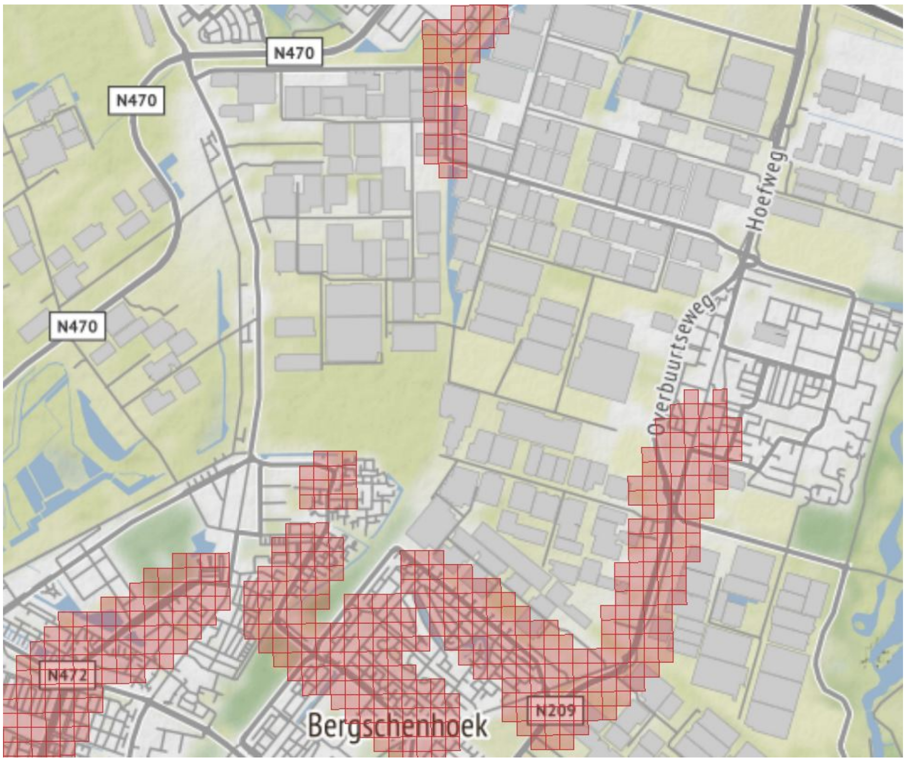

Figure E.12: Output of the high scoring 'Presence of high-quality bus/tram link' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.7 Presence of light rail/metro/train station

As most rail stations are situated in extremely urbanized context, this attribute is more difficult to verify. A solution is found in only selecting the northern part of region, in which both metro and light rail stations are present. In the comparison between Figure E.13 and Figure E.14, it is found that all squares surrounding the stations in the method application match the metro/light rail stops from the network map. Besides, a manual inspection shows that squares around all train stations in less urbanized areas in the region are identified as high scoring in this verification, and no areas which are not close to a station score higher than 1.

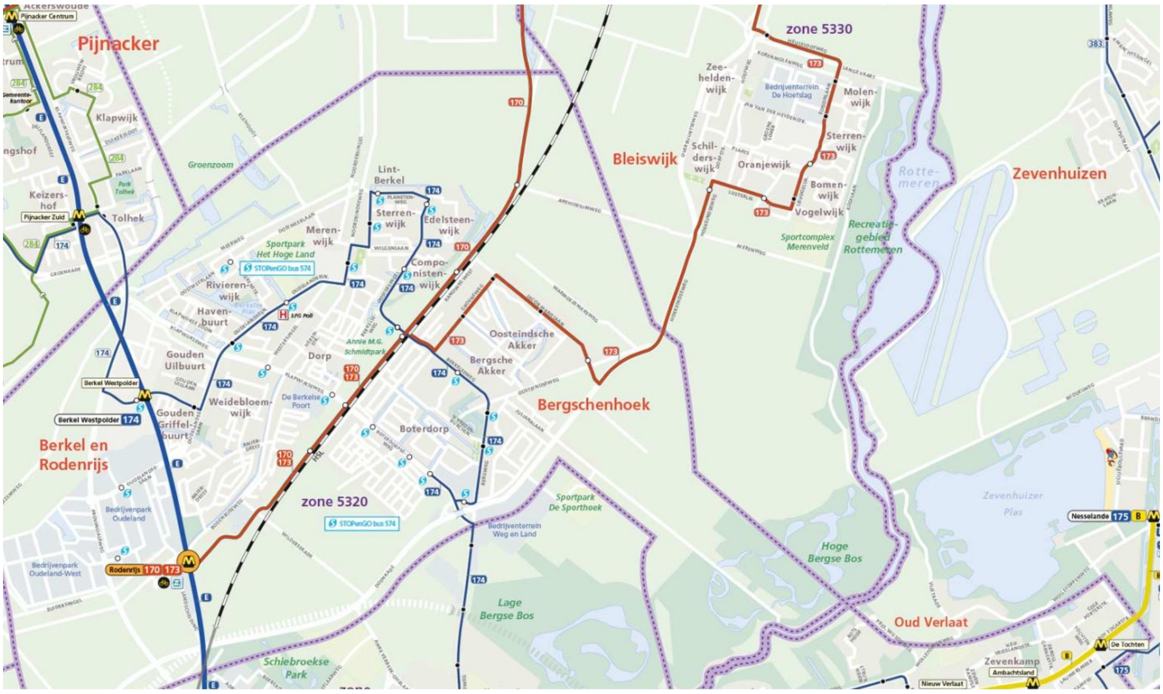

Figure E.13: A part of the public transport network map of the Rotterdam-The Hague region (RET, 2020), in which the yellow M icons along the yellow and blue line indicate the presence of a light rail/metro stop.

Figure E.14: Output of the high scoring 'Presence of light rail/metro/train station' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.8 Presence of regional cycle route

To verify the functioning of the method application with regard to the regional cycle route attribute, a map of the Dutch cyclists' federation is used. This map contains reliable information on the cycle routes in The Netherlands (Kadaster and Fietsersbond, 2021). Comparing this map (Figure E.15) with the result from the method application in Figure E.16, the squares surrounding the long-distance cycle routes are correctly identified as high scoring, so close to a cycle route. One cycle route, between the numbers 6 and 12 in Figure E.15, lacks in the method application, probably because of a recent change in this cycle route. In the method application, this cycle route is situated at the top of the image.

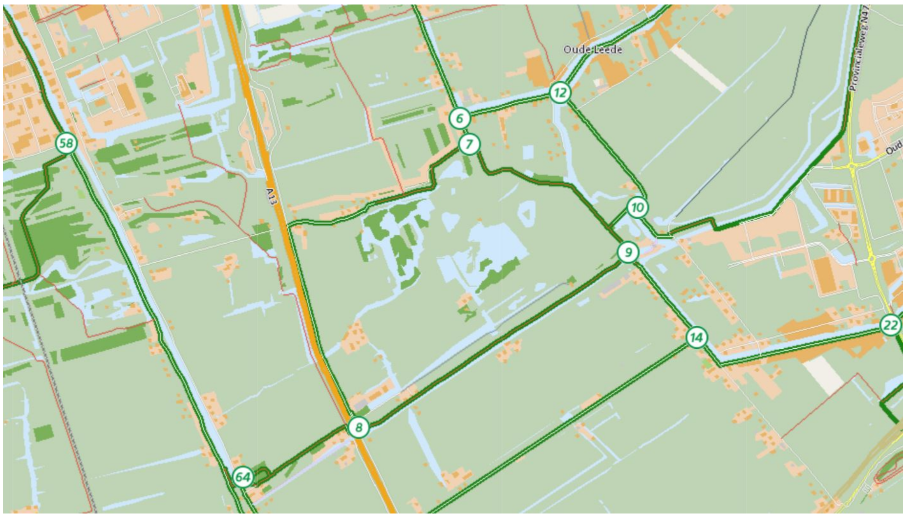

Figure E.15: A map of the Dutch cyclists' federation (Kadaster and Fietsersbond, 2021) showing all long-distance cycle routes in the region. The green lines are the cycle routes.

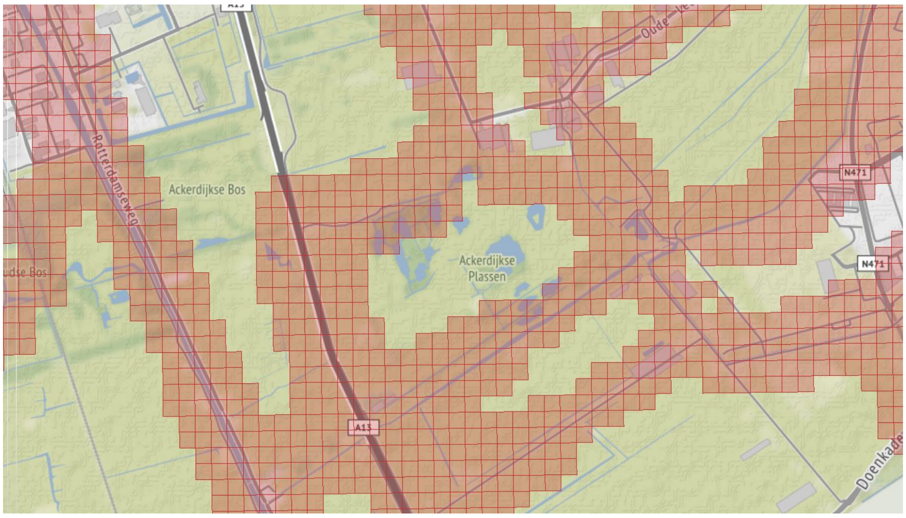

Figure E.16: Output of the high scoring 'Presence of regional cycle route' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.9 Presence of main road

As the background image in FME shows the presence of a main road (A, N or S-road), this data source is used to verify the method application. In Figure E.17, the result of assigning a high weight to the main road attribute in the final score is visualized. It appears that the method application functions as expected by assigning a score higher than 1 to areas very close to the main road, except for areas around the N472, scoring below 1. This is due to the category of that road in the topographic dataset, being regional road instead of main road. For that reason, this road is less suitable to connect the mobility hub to the main road network, so the omission of this road is justified. In short, not every N-road is classified as main road, so not every N-road is taken into account by the method application.

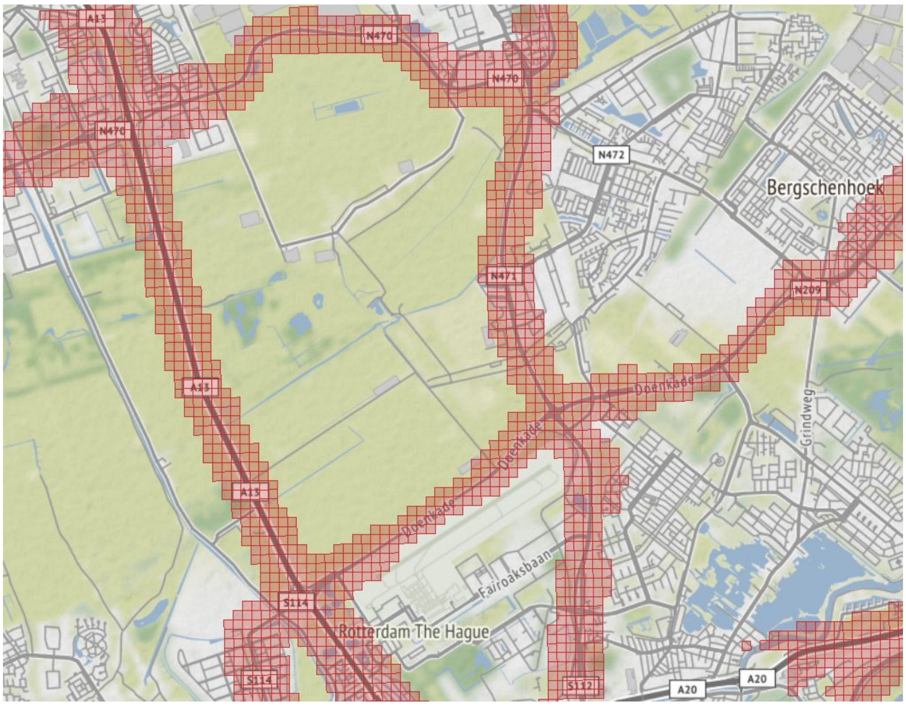

Figure E.17: Output of the high scoring 'Presence of main road' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.10 Number of retail workplaces

The retail workplaces attribute aims to measure the possible link of the selected area with the surrounding facilities. As a result of the normalization of the data, only a few areas actually score above 1 when assigning a high weight to this attribute in the MCA. These areas are grouped in 6 clusters of high-scoring areas, of which 1 is in Delft at the IKEA, a large furniture store, and the other 5 clusters are situated in dense shopping districts in regional urban centers. The three clusters in the southern part of the region are shown in Figure E.18. As the presence of a dense shopping district improves the potential for a mobility hub by offering a possibility to integrate the mobility and economic function, the identification as high potential area is justified. For the IKEA, this high score is not justified, so a limitation of the data source is revealed.

Figure E.18: Output of the high scoring 'Number of retail workplaces' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.11 Maximum I/C-ratio in vicinity

To verify the maximum intensity/capacity ratio attribute, the Mobiliteitsscan can be used again. The data source of this scan is the governmental strategic traffic model (NRM) for the Western part of The Netherlands.

By comparing Figure E.19 and Figure E.20, it is remarkable that the data from the Regional traffic model differs from the data in the Rotterdam-The Hague traffic model. The A29 highway in the middle of the image is not identified as congested link in the traffic model. Because of the higher level of detail in the Rotterdam-The Hague traffic model, this data source is generally more reliable than the Regional traffic model. The high scoring areas in the method application are situated around heavily congested roads according to the Regional traffic model, so the method application works as expected.

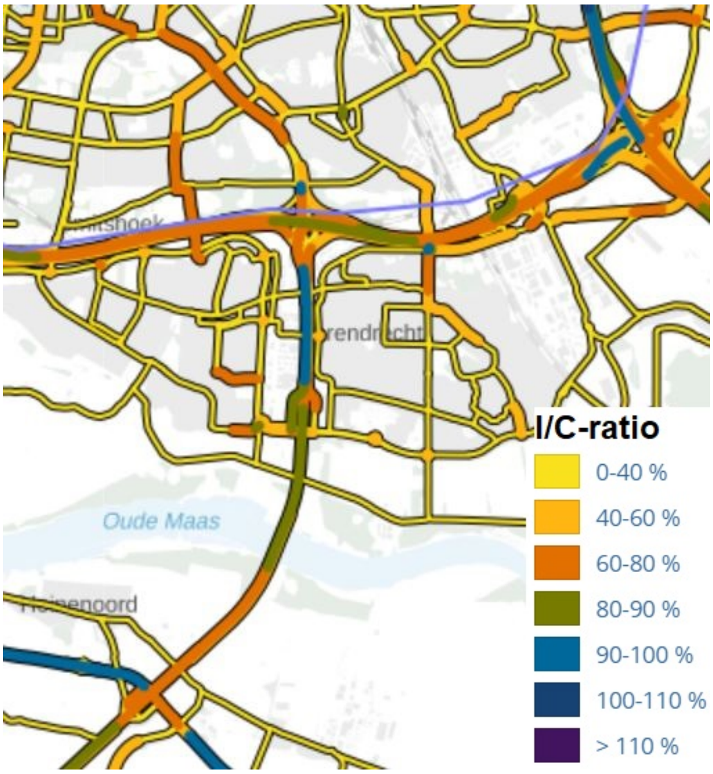

Figure E.19: The I/C-ratio on roads in the afternoon rush from the Mobiliteitsscan.

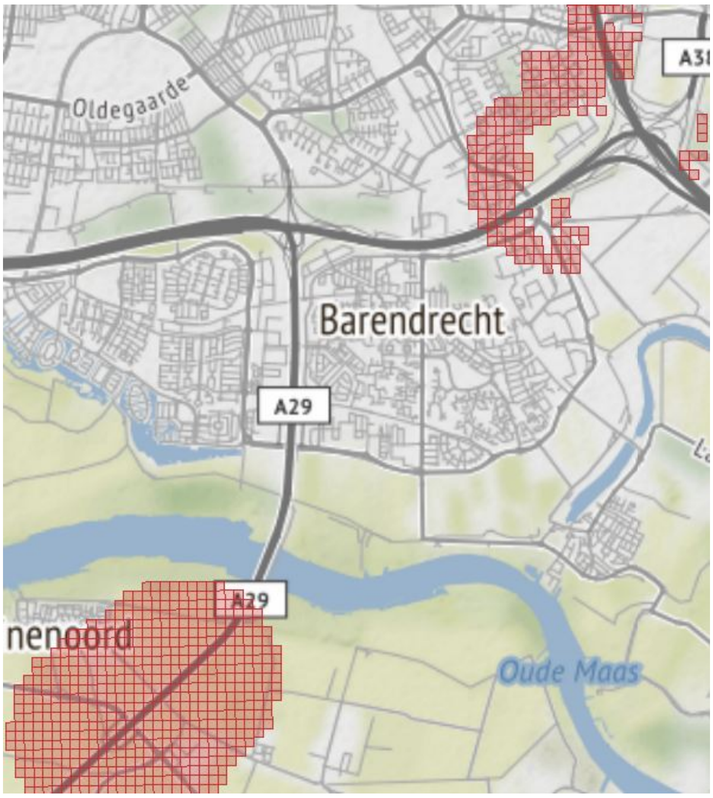

Figure E.20: Output of the high scoring 'Maximum I/C-ratio in vicinity' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

E.12 Reached users (SEGs)

For this attribute, the method application can be verified by comparing the highest scoring areas to source data in the traffic model. In Figure E.21 and Figure E.22, the source data and resulting high scoring areas in the method application for this verification are shown in the area around the university campus of Rotterdam. Because of the normalization, only areas around the university of Delft and Rotterdam score above 1 in this verification. Apparently, the number of student places in these areas is a lot higher than the maximum number of workplaces/inhabitants per area outside of the extremely urbanized city center. The method application works as expected, as the highest score is given to the areas with a high number of reached users.

Figure E.21: Socio-economic data in a selected region just east of the city center. The green column represents education places, yellow represents workplaces, pink represents inhabitants and blue represents the houses in the zone.

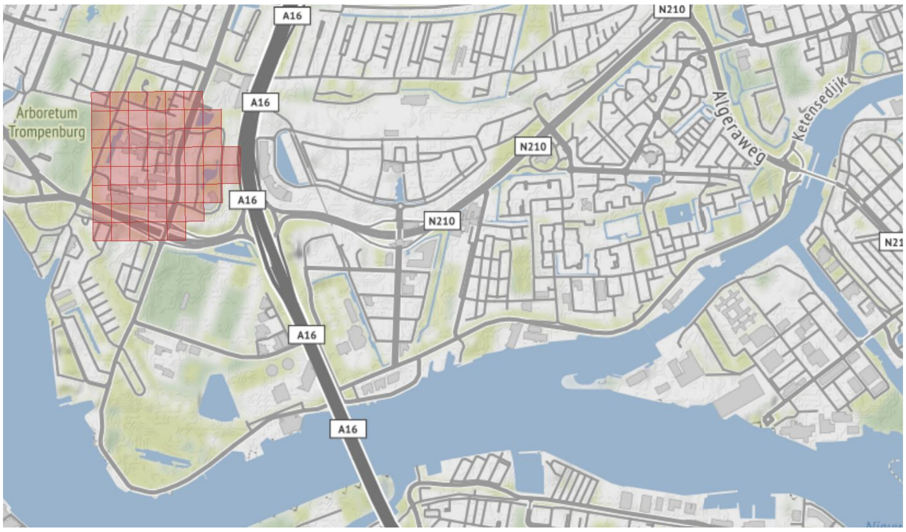

Figure E.22: Output of the high scoring 'Reached users (SEGs)' attribute areas in FME. The red squares are the areas with a MCA score of more than 1.

Appendix F

Sensitivity analysis

All weights used in the sensitivity analysis are listed in this appendix. The sensitivity analysis is split up in two parts. The sensitivity of the method application for a change in perspective weight is analyzed first, followed by the sensitivity for a change in the weights allocated to the attributes. Both sensitivity analyses are executed based on scenario 1, in which the three considered perspectives are assumed to have an equal influence on the mobility hub potential.

F.1 Sensitivity for change in perspective weight

The criteria weights used in the sensitivity analysis are presented in Table F.1, the corresponding attribute weights in Table F.2.

Table F.1: The weights allocated to the criteria following a change in perspective weights.

Perspective weight change	**-5% Government**	**+5% Government**	**-5% End user**	**+5% End user**	**-5% Operator**	**+5% Operator**
Potential demand	0.2278	0.2167	0.2278	0.2167	0.2111	0.2333
Costs	0.2044	0.2083	0.2115	0.2012	0.2032	0.2095
Generalized travel costs	0.0488	0.0464	0.0452	0.05	0.0488	0.0464
Link to surroundings	0.1429	0.1429	0.1393	0.1464	0.1464	0.1393
Impact	0.3762	0.3857	0.3762	0.3857	0.3905	0.3714

Table F.2: The weights allocated to the attributes following a change in perspective weights.

Perspective weight change	**-5% Government**	**+5% Government**	**-5% End user**	**+5% End user**	**-5% Operator**	**+5% Operator**
Production/Attraction	0.1139	0.1083	0.1139	0.1083	0.1056	0.1167
Traffic along road from/to city center	0.1139	0.1083	0.1139	0.1083	0.1056	0.1167
Presence of parking area	0.0361	0.0368	0.0373	0.0355	0.0359	0.0370
Presence of high-quality bus/tram link	0.0180	0.0184	0.0187	0.0178	0.0179	0.0185
Presence of light rail/ metro/train station	0.0180	0.0184	0.0187	0.0178	0.0179	0.0185
Physical land suitability	0.0721	0.0735	0.0746	0.0710	0.0717	0.0739
Land owner	0.0361	0.0368	0.0373	0.0355	0.0359	0.0370
Presence of regional cycle route (costs)	0.0060	0.0061	0.0062	0.0059	0.0060	0.0062
Presence of main road (costs)	0.0180	0.0184	0.0187	0.0178	0.0179	0.0185
Presence of regional cycle route (generalized costs)	0.0163	0.0155	0.0151	0.0167	0.0163	0.0155
Presence of main road (generalized costs)	0.0325	0.0310	0.0302	0.0333	0.0325	0.0310
Number of retail workplaces	0.1429	0.1429	0.1393	0.1464	0.1464	0.1393
Maximum I/C-ratio in vicinity	0.1254	0.1286	0.1254	0.1286	0.1302	0.1238
Reached users (SEGs)	0.2508	0.2571	0.2508	0.2571	0.2603	0.2476

F.2 Sensitivity for change in attribute weight

The attribute weights resulting from the sensitivity analysis in which the weights allocated to the attributes are varied can be found in Table F.3.

Table F.3: The weights allocated to the attributes following a change in perspective weights.

Attribute weight change	+5% Production /Attraction	-5% Production /Attraction	+5% Presence of parking area	-5% Presence of parking area	+5% Presence of high-quality bus/tram link	-5% Presence of high-quality bus/tram link	+5% Presence of light rail/metro/ train station	-5% Presence of light rail/metro/ train station	+5% Physical land suitability	-5% Physical land suitability
Production/Attraction	0.1138	0.1083	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111
Traffic along road from/to city center	0.1084	0.1140	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111
Presence of parking area	0.0364	0.0364	0.0379	0.0349	0.0363	0.0366	0.0363	0.0366	0.0358	0.0371
Presence of high-quality bus/tram link	0.0182	0.0182	0.0180	0.0184	0.0190	0.0174	0.0181	0.0183	0.0179	0.0185
Presence of light rail/ metro/train station	0.0182	0.0182	0.0180	0.0184	0.0181	0.0183	0.0190	0.0174	0.0179	0.0185
Physical land suitability	0.0728	0.0728	0.0722	0.0735	0.0725	0.0732	0.0725	0.0732	0.0751	0.0704
Land owner	0.0364	0.0364	0.0361	0.0367	0.0363	0.0366	0.0363	0.0366	0.0358	0.0371
Presence of regional cycle route (costs)	0.0061	0.0061	0.0060	0.0061	0.0060	0.0061	0.0060	0.0061	0.0060	0.0062
Presence of main road (costs)	0.0182	0.0182	0.0180	0.0184	0.0181	0.0183	0.0181	0.0183	0.0179	0.0185
Presence of regional cycle route (generalized costs)	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159
Presence of main road (generalized costs)	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317
Number of retail workplaces	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429
Maximum I/C-ratio in vicinity	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270
Reached users (SEGs)	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540

Attribute weight change	+5% Land owner	-5% Land owner	+5% Presence of regional cycle route (costs)	-5% Presence of regional cycle route (costs)	+5% Presence of main road (costs)	-5% Presence of main road (costs)	+5% Presence of regional cycle route (generalized costs)	-5% Presence of regional cycle route (generalized costs)	+5% Maximum I/C-ratio in vicinity	-5% Maximum I/C-ratio in vicinity
Production/Attraction	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111
Traffic along road from/to city center	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111	0.1111
Presence of parking area	0.0361	0.0367	0.0364	0.0365	0.0363	0.0366	0.0364	0.0364	0.0364	0.0364
Presence of high-quality bus/tram link	0.0180	0.0184	0.0182	0.0182	0.0181	0.0183	0.0182	0.0182	0.0182	0.0182
Presence of light rail/ metro/train station	0.0180	0.0184	0.0182	0.0182	0.0181	0.0183	0.0182	0.0182	0.0182	0.0182
Physical land suitability	0.0722	0.0735	0.0727	0.0729	0.0725	0.0732	0.0728	0.0728	0.0728	0.0728
Land owner	0.0379	0.0349	0.0364	0.0365	0.0363	0.0366	0.0364	0.0364	0.0364	0.0364
Presence of regional cycle route (costs)	0.0060	0.0061	0.0064	0.0058	0.0060	0.0061	0.0061	0.0061	0.0061	0.0061
Presence of main road (costs)	0.0180	0.0184	0.0182	0.0182	0.0190	0.0174	0.0182	0.0182	0.0182	0.0182
Presence of regional cycle route (generalized costs)	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0164	0.0153	0.0159	0.0159
Presence of main road (generalized costs)	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0312	0.0323	0.0317	0.0317
Number of retail workplaces	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429
Maximum I/C-ratio in vicinity	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1270	0.1311	0.1227
Reached users (SEGs)	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2540	0.2498	0.2583

Appendix G

Scientific Article

Developing a methodology to determine the potential of areas for regional mobility hubs

Koen Blad

Abstract

As a solution to the high greenhouse gas emissions and declining quality of life caused by the private vehicle, the mobility hub is introduced. The mobility hub is a place where multiple modalities come together, including public transport and shared mobility. As the mobility hub is a relatively new innovation, limited research is available on the topic, especially on finding potentially suitable locations for a mobility hub.

In this research, the knowledge gap on the potential of locations for a mobility hub is addressed by developing a globally applicable methodology to determine the potential of locations for a specific mobility hub type: the regional mobility hub. The regional mobility hub is located outside of the city center, and for this type of hub, an area potential determination methodology has the highest added value. The developed methodology is a combination of the GIS-Multi-Criteria Analysis and Multi-Actor Multi-Criteria Analysis available in the literature, leading to all areas in the region being evaluated for their regional mobility hub potential, taking the end user, operator and government perspective into account. The result is presented in multiple heat maps based on scenarios with varying stakeholder influences. The methodology consists of 5 criteria (Potential demand, Costs, Generalized travel costs, Link to surroundings and Impact) measured by 9 attributes to incorporate all relevant influential factors found in the literature. The Analytic Hierarchy Process (AHP) is used to determine the criteria weights.

The developed methodology is applied to the region of Rotterdam, to find out whether the methodology works as expected. From multiple analyzes, it appears that the methodology is suitable for tackling the location potential determination problem, as it works logically. In future research, the focus should be on extending the methodology to incorporate freight transportation. Besides, the methodology can be improved by incorporating revealed preferences of shared mobility users. This information can be collected by analyzing the usage of existing shared mobility systems.

Keywords: mobility hub, multimodal transport, geographic information systems, multi-criteria analysis, multi-actor multi-criteria analysis

1. Introduction

In the Paris Climate agreement, 195 countries agreed on lowering greenhouse gasses in the upcoming years (Government of the Netherlands, 2019). A substantial part of these greenhouse gasses are emitted by passenger transportation, in particular on-road vehicles like cars (European Commission, nd). Together with the declining quality of life in city centers (Harbers and Snellen, 2016), the need for sustainable mobility that uses less space in the city center increases. Improved public transportation, stimulation of active modes (walking, cycling) and the introduction of shared mobility provide a solution to this problem. The mentioned solutions imply a big role for multimodal travel, introducing transfers in the travelers' trips. To provide an attractive transfer between those various modes, and to solve the issue of a lack of space in urbanized areas, the mobility hub is invented. In the mobility hub, all previously named modalities (public transport, walking, cycling, private vehicles and shared mobility) come together in one place.

The mobility hub is designed to offer the traveler, based on the available information, the optimal route and modality at the time of travel. Public transport plays a central role in these multimodal mobility hubs (Miramontes et al., 2017), supplemented by a shared mobility service, like car sharing or bike sharing. The service is integrated in mulitmodal trip planners, and integrated in terms of pricing and/or access. The convenience offered to the end user by these features aims to make multimodal travel easier for the traveler.

1.1. Research gap

In the existing academic literature, very little is known on the mobility hub. The hub is a very recent innovation in mobility, which is one of the causes for the limited available research. The available research mainly focuses on the facilities and adoption of the mobility hub (Miramontes et al., 2017; Bell, 2019; Aono, 2019). Research on potential locations for mobility hubs is non-existent, whereas Enbel-Yan and Leonard (2012) introduces guidelines for the integration of hubs in the existing networks and urban context. The shared mobility function of the hub is not mentioned in that report.

Available research on multimodal transfer points might partially fill in the gap, as a location finding methodology is described in literature on Park&Ride locations (Faghri et al., 2002). The distinction between a regular public transportation node and a mobility hub is sometimes difficult to see. However, the mobility hub can be seen as a unique facility, because of the sustainability of the transportation modes, integration of shared mobility services, inclusion of additional facilities at the hub and integrated route decision making. The integrated route decision making aims to offer the best possible route to the traveler, given current traffic and public transport conditions, whereas in public transport, this choice should be made by the traveler. The offered modalities use almost exclusively non-polluting power sources, like electricity. The electric bus, train, metro, tram, (shared) electric vehicle and bike can all be connected to a mobility hub. The hub also contributes to sustainable transportation by providing the opportunity of making a trip (partly) by shared electric vehicles instead of a privately-owned gasoline vehicle.

1.2. Research objective & question

The gap in the literature leads to the objective of this thesis, which is to develop a methodology that is able to determine the areas in which a mobility hub has a high potential, incorporating the government, end user and operator perspective. This methodology is intended to contribute to the emergence of innovative, environmentally friendly mobility solutions, that help in reducing the negative impacts of the envisaged increase in demand for mobility. In developing this methodology, a main research question is proposed, which will be answered in this research: "How can the potential of areas for regional mobility hubs be determined, considering the end user, operator and government perspective?"

1.3. Scope

The exact implementation is not elaborated in this thesis. The methodology is developed as a quick scan for the potential of for a regional mobility hub in a region, not a methodology to find the exact implementation of a hub. By deciding to develop a quick scan, a generally applicable framework can be established, suitable for global application.

The focus of the methodology is on passenger hubs only. The factors influencing the potential of a location for a freight mobility hub are different from the passenger hub location factors, as freight has characteristics which will lead to different high potential locations for mobility hubs.

In section 2, a literature review of existing literature on mobility hubs is presented. In section 3, the methodology to evaluate the potential of locations for regional mobility hubs is introduced, based on factors found in section 2. The developed methodology is applied to the region of Rotterdam in section 4, where after the output of this application is discussed and analyzed in section 5. Conclusions and recommendations follow to conclude this paper in section 6.

2. Literature

The first step in answering the research question is defining the mobility hub. The mobility hub is a recent topic, with no well-established definition and typology, whereas a hub definition and typology are needed to determine the potential for a hub. To come to a hub definition and typology, existing literature on the mobility hub is reviewed. An overview of the relevant information available on the definition, typology and features of the mobility hub is presented. The definition is derived from several sources, including Miramontes et al. (2017); Enbel-Yan and Leonard (2012); Li (2020), in which an attempt is made to define the mobility hub. In this research, the literature is combined into one universal definition of the mobility hub: "The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, possibly including other amenities, ranging from retail, workplaces to parcel pick-up points."

A classification of mobility hubs into three types is made based on the urban context and function in the transportation system, using literature by van den Berg (2020); Atkinson et al. (2020); Aono (2019); L. van Gils

	Residential mobility hub	City mobility hub	Regional mobility hub
Urban context	>500 addresses/km²	>2500 addresses/km²	<2500 addresses/km²
Modes offered	Shared mobility	Shared mobility, PT	Shared mobility, PT, car parking
Transportation function	Provide alternative to car possession	Improve city's accessibility	Improve reach PT, provide alternative to car usage
Target groups	Residents	Residents, visitors, commuters	Residents, visitors, commuters

Table 1: The adopted mobility hub classification, required to determine the type of hub investigated in this research.

(2019). A hub only offering shared mobility for residents, lacking a connection to the public transport system, is referred to as a residential mobility hub, whereas the city and regional mobility hub offer public transport and focus on multiple target groups. The main distinction between the city and regional mobility hub is the urban context: the city mobility hub is located in very dense city centers, as opposed to the regional mobility hub. This distinction is important, as the regional mobility hub offers car parking, which alters the used modalities in the user trips. The city mobility hub will not facilitate private car usage, due to the lack of space in a highly urbanized area. An overview of the distinctive properties of the three defined hub classes is presented in Table 1.

To be able to determine the potential for a mobility hub, a certain mobility hub type should be selected, as location factors might differ per hub class. In this research, the choice is made to further investigate the regional mobility hub, as a general framework is of the highest scientific value for this type of hub. For the residential mobility hub, there is less need for a general framework, as the location for this type of hub is often known or less difficult to find. Few factors are involved in the location finding process of the residential hub. The difference between the city and regional hub is the available information on the location choice. In the literature, it is mentioned that very little is known on the locations for regional mobility hubs, contrary to the greater amount of information available on city mobility hubs. In short, a methodology to determine the potential of locations for regional mobility hubs has a higher scientific relevance compared to the residential or city mobility hub.

The factors influencing the potential of a location for a regional mobility hub are examined by means of an extensive literature review. The economic and mobility function of the hub are investigated in separate subsections, in which the literature on the mobility function is split up according to the three mobility functions of the hub (based on the identified target groups): a mobility hub positioned at the activity side of the trip, the home side of the trip, and in between as transfer point. Important detail is that for all three functions, multimodal trips are considered, as the regional mobility hub focuses on multimodal transportation. In combination with the interests of the three used perspectives, this leads to a selection of influential factors, which are input for the methodology developed in the next chapter.

The found criteria are based on numerous studies on a location specifically for a mobility hub or on public transport nodes in general. In an interview with a program manager for the Dutch hub concept in the provinces of Groningen and Drenthe (Taxistop, 2020), it is named that social and economic facilities can give a location a higher potential for a regional mobility hub. This leads to the 'Economic function' criterion to be incorporated in the methodology.

A strategic study on mobility hubs in Scotland by SEStran (2020) provides information on factors influencing the potential of a location. The demand is marked as important factor, measured by the population and workplace population in an area. The level of additional connectivity offered by the mobility hub in a certain area also alters the potential of a regional mobility hub. Besides, it should be kept in mind that the hub is intended to reduce emissions and improve the quality of life in a city, so the extent to which this improvement is realized determines the potential of a certain location for a regional mobility hub.

Additional factors to enhance the methodology are found in other researches. The costs are mentioned as main influential factor for the success of an innovative mobility concept in Talen et al. (2018), whereas the generalized travel costs are important for the traveler, as these costs are a measure for the accessibility change (Koopmans et al., 2013), which is essential in calculating the hub potential of an area. In Atkinson et al. (2020), the generalized travel costs factor is found to be important for the end user, just as the change in travel time reliability induced by using the hub. A complete overview of the included influential factors in this research is given in Table 2.

Factor	Perspective	Explanation of the influence
Demand	Operator	A higher number of users leads to higher earnings for the operator, causing a higher mobility hub potential from that perspective.
Costs	Operator & Government	Costs are a leading factor in deciding on the approval of a project. A convincing business case is needed to execute a transportation project, for both the operator and government. Therefore, lower costs increase the feasibility of the project.
Economic function	Government & End user	An integration with surrounding facilities limits the additional space usage, important for the government. For the end user, the attractiveness of the hub increases due to the economic function.
Added connectivity	Government & End user	The government aims to offer mobility for all inhabitants, the mobility hub can improve on this connectivity. A higher additional connectivity contributes to the inclusiveness induced by the mobility hub, and is therefore desired from the end user perspective as well.
Generalized travel costs of using the hub	End user	A decrease of the generalized costs of the trip due to the usage of a mobility hub increases the attractiveness for the end user.
Increase in travel time reliability	End user	A low travel time reliability means that the current situation is unattractive, due to congestion or parking problems. An increase in reliability of the travel time offered by the mobility hub makes the hub more attractive from the end user perspective.
Impact on quality of life & emissions	Government	A higher reduction of parking problems and congestion induced by the hub will lead to a higher impact on quality of life issues & greenhouse gas emissions.

Table 2: The selection of influential factors to be used in the regional mobility hub location potential determination methodology, along with the involved perspective and explanation of the influence.

3. Methodology

With the overview of influential factors, a methodology is developed to determine the potential of areas for a regional mobility hub. This methodology is required to spatially evaluate multiple alternatives, incorporating the interests of the defined stakeholder groups and in the application, the output should be visual, in the style of a heat map. It should be possible to include both quantitative and qualitative evaluation criteria in the methodology, as both types resulted from the literature review; for example, both the demand (quantitative) and the existing facilities around the location (qualitative) should be taken into account by the methodology. These requirements lead to the selection of the Multi-Criteria Analysis (MCA) to evaluate the problem.

The Multi-Criteria Analysis is a widely used methodology to evaluate decision problems, as this method makes it possible to incorporate quantitative and qualitative criteria in the evaluation of multiple alternatives (Macharis et al., 2009). Two extensions to the MCA are required in order to answer the main research question: multiple perspectives should be incorporated explicitly, as this is an important part of the research question, and the result should be visually presented. The focus on the incorporation of multiple stakeholder groups leads to the Multi-Actor extension of the MCA, in which the stakeholders are explicitly incorporated in the MCA. In addition, the spatial evaluation of the alternatives requires the methodology to incorporate the spatial element in the analysis. This is where GIS comes in, as GIS has the possibility to present the output visually. The GIS-MCA combines the spatial analysis and decision support from GIS with the decision making process of MCA. GIS has the capability to identify a suitable area for a new facility, by performing overlay operations to find a location that satisfies all criteria. In order to include the preferences of the decision makers, Multi-Criteria Decision Analysis can be added into GIS, leading to the GIS-MCA. The exact procedure for the GIS-MCA is presented in Figure 1. The problem, constraints and alternatives are spatially defined, whereas the regular MCA defines the decision maker's preferences and evaluation criteria. In the GIS-MCA methodology, the result of the evaluation of the alternatives is analyzed in a sensitivity analysis, leading to a recommended alternative (location).

Subsequently, the GIS Multi-Actor Multi-Criteria Analysis is proposed to determine the regional mobility hub potential in this thesis. This methodology requires the following steps to be taken:

1. Define alternatives: The alternatives are defined which will be used in the analysis. These alternatives are all areas in the region that satisfy the urbanization constraint posed in Table 1.
2. Define criteria and weights: The determination of the criteria and weights is done based on the stakeholder objectives. The used methodology for finding the weights is the Analytic Hierarchy Process (AHP). In this methodology, trade-offs between criteria are made by the stakeholders, to establish the weights that will be allocated to the criteria.
3. Criteria, attributes and measurement methods: Attributes are constructed to operationalize the criteria. These indicators should be measurable, and are

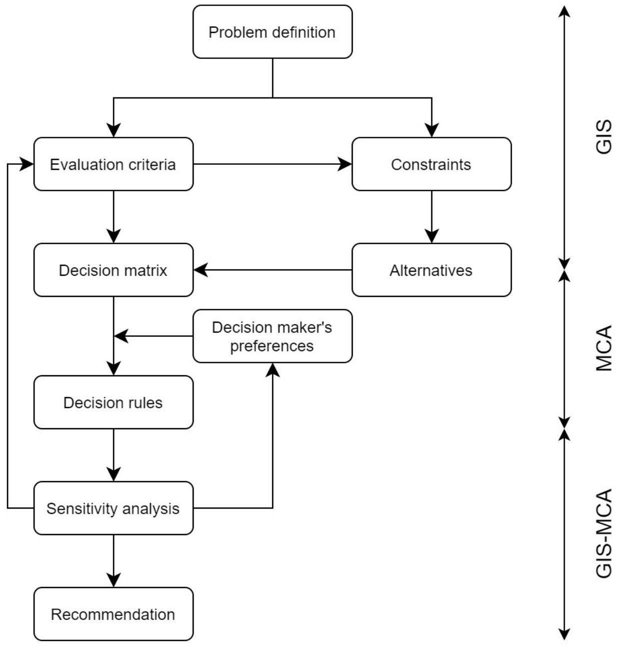

Figure 1: Flowchart for using the GIS-MCA method, adapted from (Malczewski, 1999)

often quantitative.

4. Overall analysis and ranking: All alternatives are evaluated according to the determined weights and criteria.
5. Results: The scores of the various alternatives are given. A sensitivity analysis is performed, to see the results of changes in the weights.

3.1. Computations & Procedures

Within the developed methodology, the computations and procedures required for the correct implementation of the method are firstly explained. Two basic concepts are required to obtain the correct score out of the input data (Malczewski and Rinner, 2015) for the GIS-MAMCA. These concepts are value scaling and criterion weighing.

In order to make sure that the influence of an attribute is not dependent on the actual values of the input data, but on the relative value, the data is scaled. The least preferred attribute value is given the value 0, whereas the most preferred value is given the value 1. This procedure is called normalization, i.e. scaling all data into the range of 0 to 1. The scaling factors are completely dependent on the provided input data, a change in input data will lead to a change in scaling factor.

Weights are assigned to the criteria, measured by the normalized attributes, to indicate that not all criteria are of equal importance. To determine the importance of one criterion compared to another, ranking, rating, entropy-based and pairwise comparison methods are available. For this thesis, the pairwise comparison method seems the most feasible method, as the stakeholders' opinions should be incorporated, more precise than only a ranking, but less specific than exact weights allocated to each criterion by each stakeholder. In the pairwise comparison method, multiple procedures are available, but the most common procedure is adopted in this thesis. This is the Analytic Hierarchy Process (AHP), the most frequently used procedure in GIS-MCA (Al-Shalabi et al., 2006), especially in transportation projects (Macharis and Ampe, 2007). AHP is a logical, well-structured framework which makes complex problems more manageable.

Then, the criteria should be added in the methodology. The criteria are derived from the influential factors for a regional mobility hub location discovered in the literature research. The attributes provide a way of measuring the criteria. These criteria and attributes are described in the upcoming subsections. A full overview of the criteria and attributes, with the link to the influential factors from the literature and the stakeholders is presented in Figure 2.

3.2. Potential demand

The potential demand for a regional mobility hub in an area is of a high importance from the operator perspective, as it determines the passenger numbers of the offered mobility service. From a profit-making point of view, the demand should be as high as possible. The target groups of the mobility hub are taken into consideration, which is necessary to determine which user groups might actually use the mobility hub. A division between the mobility hub as access/egress point for the catchment area, both on the home and activity trip end, and the mobility hub as transfer point in a trip can be made. Consequently, two attributes are introduced to measure the criterion, each referring to one of these trip positions.

Attribute: Trip production/attraction in catchment area

The trip production/attraction is based on the social-economic data (population, workplaces and facilities) of the locations in the region. The trip production/attraction in the catchment area of the mobility hub is used to measure the potential demand from/to this

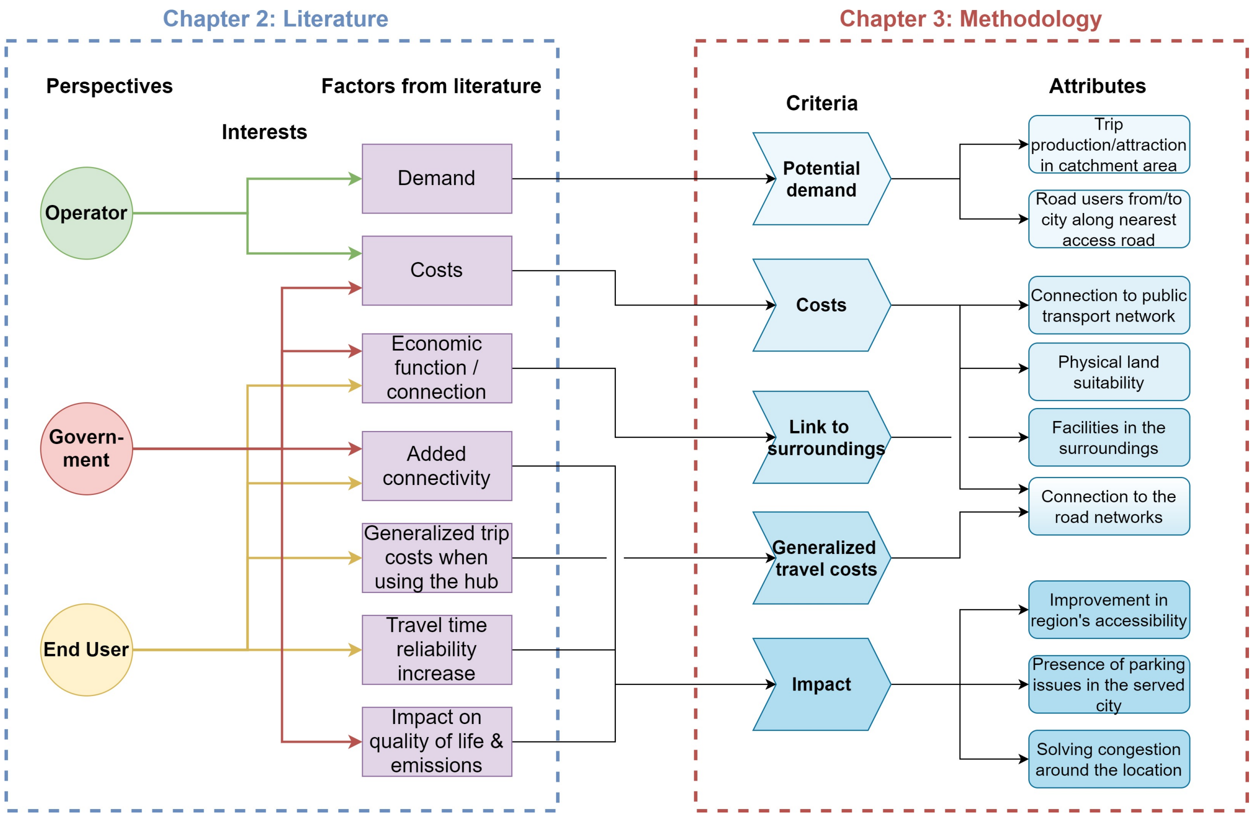

Figure 2: Connection between the stakeholders, literature and methodology

catchment area. The word potential is used here, as not all travelers will make the switch from the currently used modality to using the mobility hub.

Attribute: Road users from/to city along nearest access road

Next to the local demand, the demand for the facility as transfer location should be included. This is operationalized as the vehicle intensity at the nearest access road, usually being a road/highway, from/to the city. This way, traffic with an origin outside of the studied region, headed for the city is also included in the demand. This attribute relates to the transfer mobility function of the mobility hub.

3.3. Costs

From the operator and government perspective, the introduction of a mobility hub is accompanied by costs. Two types of costs are important to take into account: the one-time investment costs and the operating costs of the mobility hub. The investment costs will be mostly relevant for the government, as these costs are mostly covered by a local/regional/national government, while the operating costs are more relevant for the operator. As a proxy for both costs, the connection to the current road and public transport networks and the physical land suitability are the measured attributes.

Attribute: Connection to the road & public transport networks

For the government, the connectivity to the road network relates to the costs. A road should be constructed to connect the mobility hub with the main road network, as road traffic flows may become too high for the local road network to process. As an indication of the length of the road and therefore the costs, the distance to this main road network is used as attribute. The same holds for the connection to the regional cycle route network, as bikesharing will generate traffic that will use this cycle route network.

For the operator, the connectivity to the public transport network is relevant, because costs are involved when adding or rerouting bus lines. This factor is composed of the distance to the public transport network and the presence of a railway station. The rerouting distance of transit lines is a measure for the additional costs involved for the public transport operator due to the rerouting of their lines via the proposed location. Ideally, the exact cost of rerouting and upgrading an existing public transport line (towards the city center) is used as attribute, but simplifications should be made because those costs can not be calculated directly, as these are based on many case-specific characteristics. The best possible approximation is the distance to a high-quality bus/tram line, to give an indication of the additional infrastructure and vehicle hours needed to redirect the service via the mobility hub. Furthermore, the presence of a train/metro/light rail station is added as measurement of the costs, as this can significantly reduce the investment costs.

Attribute: Physical land suitability

With respect to the costs of integrating the mobility hub, the spatial integration is most relevant. For the construction of a regional mobility hub, space is needed to accommodate a public transportation stop, bike and car parking, sharing and additional facilities. Comparing the land usage of these facilities, car parking will require the largest area of land. Therefore, the presence of a car parking facility would ease the integration of the mobility hub significantly. Furthermore, the integration with respect to existing structures should be noted, as relocation of these structures would bring along high costs. The zoning plan should allow for the integration of a mobility hub, so the presence of, for example, an environmental protection area makes it more difficult, and with that more costly to implement the hub.

3.4. Link to surroundings

The economic importance of the mobility hub, as found in the literature, leads to the link to surroundings criterion. The inclusion of other facilities in the mobility hub, like retail, catering and parcel pick-up points, improves the potential of a mobility hub. To incorporate this factor in the location potential, the presence of one of these facilities at the location provides an opportunity to integrate mobility at that location. For example, the presence of a supermarket would lead to a higher potential for a regional mobility hub, as the mobility function can be integrated with the existing economic function in the area.

Attribute: Facilities in the surroundings

A selection of facilities should be made in order to include this criterion in the analysis. Based on the features that can offer an added value for the mobility hub, the following facilities are relevant: a library, healthcare facility, sports center, grocery store, parcel pick-up point and retail facilities. The presence of these facilities at a location provides a higher mobility hub potential, because of a potential collaboration/integration of the mobility function and the economic function at the mobility hub.

3.5. Generalized travel costs

Incorporating the costs for the end user is more difficult. The saved costs/time for using the mobility hub at a specified location is important for the end user, but for the mobility hub location, an aggregation of all these costs/time savings would be relevant. To give an indication of these savings, the connection to the current main road and cycle network is used, which is related to the additional travel time and costs imposed when driving/cycling to the mobility hub.

Attribute: Connection to the road networks

The road network connectivity is the leading factor in determining the additional costs/travel time for users, and this factor is split up in two parts: The distance to a main road/highway and the distance to a regional cycle route.

3.6. Impact

For the traveler, current traffic problems lead to additional travel time and a lower travel time reliability of their trip. Furthermore, for the government, these traffic problems have consequences. The quality of life in the city and around the main roads decreases because of congestion, whereas pollution and nuisance cause problems for the inhabitants of a municipality, and congestion limits the accessibility of a city. These problems can exist in the city which is served by the regional mobility hub, or on the route to/from the city.

Additionally, the regional mobility hub can have a positive impact on the accessibility of an area. Both the connection between the region and the city center can be improved by placing a hub, and the accessibility of a region itself can be improved by providing shared mobility and a connection to the public transport and road network. To be sure of the impact of the researched hub location on the traffic problems, the occurring congestion and the region's accessibility should be recalculated for every area upon introduction of a mobility hub in that area.

Attribute: Improvement in region's accessibility

The improvement in a region's accessibility can be measured in terms of the increase in facilities and work places that can be reached from the selected location within an arbitrary travel time, caused by the introduction of a mobility hub. This change in accessibility should be determined for every location in the region of choice.

Attribute: Presence of parking issues in the served city
The presence of parking issues in the served city might indicate a need for a mobility hub, as providing a replacement for or transfer of the car to a different modality tackles the lack of space problem in the city. Shared modalities and public transport require less space in a city, so these parking issues are mitigated for the end user when using a mobility hub.

Attribute: Solving congestion around the location
The aim of this attribute is to give a higher score to locations from which the car route to the city center is congested. In this way, it is attempted to improve the score of locations upstream of where the congestion occurs, a location in the middle of or downstream of the congestion is a less favorable location for a mobility hub, as users will encounter congestion before reaching the hub.

4. Application

After defining the methodology, it is tested for its suitability to answer the main research question by means of an application. To be able to apply the methodology to a region, multiple steps have to be taken. These steps are shortly described in this chapter.

Region selection: In the application, the first step is to select a region for which the mobility hub potential will be evaluated. The region is selected on the basis of posed data requirements and current societal issues. Due to the presence of a detailed, up-to-date traffic model and the fact that the highways around this large city are among the most congested highways of The Netherlands, the choice is made to apply the methodology to the Rotterdam region.

Expert interviews: Experts are interviewed to gather information on the weights for the trade-offs between the criteria, and to provide additional insights in the facilities included in a mobility hub. The 9 interviewed experts are part of one of the stakeholder groups, namely Arriva, RET and NS from the operator perspective, Gemeente Rotterdam from the government perspective, OV-Consumentenplatform Drenthe, VZR and ANWB from the end user perspective and one independent expert from a research group linked to the TU Delft. The interviews did not lead to an exact weight determination, but the interests and priorities of the experts are gathered to determine the trade-off values in this thesis.

Scenario formulation: To explicitly incorporate the stakeholder groups, multiple scenarios with varying stakeholder configurations are developed. By doing so, more insight can be gained in the result of uncertain influences of the perspectives. In this research, four scenarios are developed with varying stakeholder influences, and a fifth scenario is formulated to incorporate the uncertainty of the importance attached to the costs from the stakeholders' point of view. The weights from the expert interviews are established for every scenario in Table 3.

1. Scenario 1: All stakeholder groups are equally important: 33.3% operator, 33.3% government, 33.3% end user.
2. Scenario 2: The government is more important than the other stakeholders. This is a realistic scenario, as the government has the largest financial contribution to the project. In most cases, the government makes the final decision whether the hub development can proceed or should be stopped. The stakeholder influence in this scenario: 16.7% operator, 66.7% government, 16.7% end user.
3. Scenario 3: The stakes of the end user are the most important in this scenario. This scenario is realistic when focusing on the interests of the end user, which is an important approach, because the number of end users determines the success of a hub. The stakeholder influence in this scenario: 16.7% operator, 16.7% government, 66.7% end user.
4. Scenario 4: The operator is allocated the highest influence weight in this scenario. This scenario is useful, as the operators are the providers of the services at the mobility hub. A low potential of a location from the operator perspective will lead to a lower willingness of the operator to offer their services at that location. The stakeholder influence in this scenario: 66.7% operator, 16.7% government, 16.7% end user.
5. Scenario 5: In this scenario, the weights are equally distributed over the three stakeholder perspectives. What changes in this scenario is that the

costs criterion is three times more important than the original score from both the operator and government perspective. This scenario is realistic in present times, as governments are currently very hesitant when it comes to funding new projects. Furthermore, the costs criterion has a high level of uncertainty, as no literature on the costs of a mobility hub is consulted, so the costs might be a lot higher than expected.

Based on the defined scenarios, the final weights resulting from the trade-offs from the expert interviews are established by using the Analytic Hierarchy Process. The applied weights for every scenario are found in Table 3.

Criterion	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Potential demand	0.2222	0.1111	0.1111	0.4444	0.1333
Costs	0.2063	0.2460	0.1032	0.2698	0.3818
Generalized travel costs	0.0476	0.0238	0.0952	0.0238	0.0476
Link to surroundings	0.1429	0.1429	0.2143	0.0714	0.1255
Impact	0.3810	0.4762	0.4762	0.1905	0.3117

Table 3: Weights allocated to the criteria for the scenarios used in the method application.

GIS tool selection: A GIS tool is selected that is able to execute the developed methodology in an application. The three GIS tools which are considered are ArcGIS, FME and QGIS. All three tools are suitable for performing a multi-criteria analysis, leading to the choice being made based on the user-friendliness and available knowledge at the company supervising this research, which is Sweco. The decision was made to use FME.

Data gathering: The needed data to operationalize the attributes is gathered from various sources. The region's traffic model, topographic data on the land usage, land owner data from the municipality and the national cycle route database are the used sources to operationalize all attributes of the methodology, except for the presence of parking issues in the served city. This attribute is not included because it does not vary in the region, as the served city is the same for all areas in the Rotterdam region. Some other attributes are slightly changed in the method application, due to the availability of data. An overview of all used attributes in the method application, and the link with the attributes from the methodology is given in Table 4.

Data preparation: The data is prepared for usage in the GIS tool. After having all data ready for use, the preparations for the execution step are made. A size of the areas in the method application is chosen, which is set at 100x100 meter. 100x100 meter is approximately the limit posed by the accuracy of the input data. The zones in the traffic model and accuracy of the topographic data lead to this choice, as a smaller area size will not lead to a large improvement of the method application compared to the additional calculation time.

Then, the urbanization constraint is corrected for, so areas that do not fit the definition of a regional mobility hub are filtered out. Subsequently, the data is prepared for usage in the GIS tool, meaning that the attributes are given a value. For all attributes, the value depends on the presence or quantity of a certain element, corrected for the distance to the area. As final step before the method execution, the data is normalized to a scale from 0 to 1, in which the value 0 is given to a value leading to a low mobility hub preference, and a value 1 leading to a high mobility hub preference.

Method execution: The method application is executed, leading to the results. FME Workbench 2020.2 is used to run the method application, where after the output for every scenario is exported, in order to visualize the data in QGIS Desktop 3.10.10. The figures, including a QGIS background map, are then exported and added to the project.

Some assumptions are made in order to be able to execute the method application using the available input data. These most important assumptions are listed below.

- A simplification is made with regard to the impacts of the regional mobility hub in the method application. The actual impacts of a hub in the area are not calculated as the regional mobility hubs are not inserted in the traffic model. Instead, non-iterative measurements are used to estimate the score of an area on the impact criterion. This means that the improvement in region's accessibility is only measured in the number of users in the catchment area of the hub, and the solving congestion attribute is simplified to the presence of congestion close to the area.

- Future developments are excluded as the method assumes the current situation. Detailed data on future developments is often not easily available.

- For the 'Road users from/to city along nearest access road' attribute, only traffic from or to the main served city is taken into account. This is an underestimation of the actual transfer demand of the

Criterion	Attribute (methodology)	Attribute (method application)	Data source
Potential demand	Trip production/attraction in catchment area	Production/Attraction	Traffic model (V-MRDH 2.6)
	Road users from/to city along nearest access road	Traffic along road from/to city center	Traffic model (V-MRDH 2.6)
Costs	Physical land suitability	Presence of parking area	Topographic file (TOP10NL)
	Physical land suitability	Physical land suitability	Topographic file (TOP10NL)
	Physical land suitability	Land owner	BRK Rotterdam
	Connection to public transport network	Presence of high-quality bus/tram link	Traffic model (V-MRDH 2.6)
	Connection to public transport network	Presence of light rail/metro/train station	Topographic file (TOP10NL)
	Connection to the road networks	Presence of regional cycle route	National cycle route database
	Connection to the road networks	Presence of main road	Topographic file (TOP10NL)
Generalized travel costs	Connection to the road networks	Presence of regional cycle route	National cycle route database
	Connection to the road networks	Presence of main road	Topographic file (TOP10NL)
Link to surroundings	Facilities in the surroundings	Number of retail workplaces	Traffic model (V-MRDH 2.6)
Impact	Solving congestion around the location	Maximum I/C-ratio in vicinity	Traffic model (V-MRDH 2.6)
	Improvement in region's accessibility	Reached users (SEGs)	Traffic model (V-MRDH 2.6)
	Presence of parking issues in the served city	-	-

Table 4: The criteria and attributes from the methodology, with the corresponding attribute and the data source for the method application.

regional mobility hub, as users from/to other cities might also use the hub as Park&Ride facility.

5. Results & Analysis

The next step in this research is introducing and analyzing the results. Each scenario results in a map covering the extents of the region, with the potential for a regional mobility hub evaluated for every area in this region, except for the extremely urbanized areas. The result for the first scenario, with equal influence of every stakeholder group, is given in Figure 3.

The first four scenarios largely resemble each other, differences in scores are found to be small. The fifth scenario, in which the costs are given a three times higher weight, is clearly different. For a selected part of the region, the minor differences in score can be seen in Figure 4. A much higher number of areas score high in this scenario, as 1302 areas score a green score (0.363 or higher), compared to 581-801 high scoring areas in the four other scenarios. To find out more on the reliability of the result, several analysis steps are executed. An overview of the steps with the corresponding outcomes is presented in Table 5.

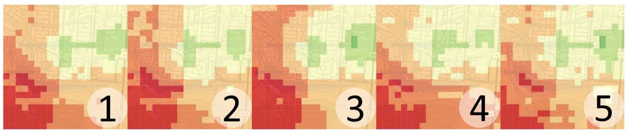

Figure 4: The output of the method application for a selected part of the region, shown for scenario 1 to 5. Green areas have a high hub potential, red areas have a low hub potential.

From Table 5, it appears that the methodology responds logical to the performed analysis steps. Besides, the methodology is relatively insensitive to changes in the input. This insensitivity is found in the scenario comparison as well, as the potential of areas barely changes following a change in scenario.

In the analysis of the high-scoring locations from the method application, very logical results are produced. The largest high-scoring area, which is represented by number 1 in Figure 3, is an area in which all elements possibly leading to a high regional mobility hub potential come together: A congested highway passes the area, large traffic numbers from/to the city center are found on the road crossing the area, a high workplace and student population is found and a metro station with an adjacent parking (Park&Ride) area is present. This high potential is completely in accordance with the usage of the Park&Ride area: the Kralingse Zoom Park&Ride area is the most frequently used Park&Ride area in the entire Rotterdam-The Hague metropolitan area (van de Werken, 2018). This area also seems to be very useful in the transportation networks. Users from the catchment area, being mostly commuters and students of the Erasmus university, can use a regional mobility hub to switch from public transport to a shared bike, in order to accelerate their last mile from the hub to their company/university. With that, public transport is made more attractive due to a decreased total travel time. Besides, car users from both southern and southeastern direction can make the shift at the regional hub from their car to a more space-efficient modality like the metro or a shared bike, to bypass any congestion or parking problems in the city center. As this area is situated along the route to the city center, additional travel time/costs for the end user can be limited to just the transfer time. When making this transfer more attractive by the offering of facilities at the hub, it is very likely that travelers will actually use the hub.

Analysis step	Result	Description
First output analysis	Logical	Rural areas with no roads nearby and water areas have low potential, areas close to the highway have high potential.
Scenario comparison	Insensitive method	The method is relatively insensitive to a change in stakeholder group influence. The various scenarios are only slightly different.
Attribute contribution	Some irregularities	The used scaling factors in the normalization cause unwanted deviations from expected attribute contributions to the final score.
Verification	Some irregularities	Irregularities related to the input data and used GIS tool. Normalization leads to a very small number of areas that score high on certain attributes.
Sensitivity analysis	Insensitive method	This analysis results in a relatively low sensitivity of the method for both a change in perspective weight and attribute weight.
Robustness analysis	Robust method	The outcome is robust for a large part of the high scoring areas in the region, meaning that the spread in MCA scores is low for most areas that score high in one of the scenarios.
Omitting urbanization constraint	Logical	The highest scoring areas can be found in city centers. The lack of space in the centers causes this methodology to be less suitable for application to extremely dense city centers.
Analysis of high-potential locations	Logical	Regional urban centers and suburban centers are identified as high potential areas, along with areas around rail stations and congested roads.
Comparison with MRDH hub network	Logical	The proposed hub locations are an 82% match to the high-cost scenario (scenario 5), the mismatch can be substantiated by future developments and the other criteria used in that report.

Table 5: Result of the steps taken to analyze the performance of the methodology and its application.

The proposed locations for mobility hubs from a document by the Rotterdam-The Hague Metropolitan Region (MRDH) are projected on the output of the method application, leading to the observation that scenario 5 best matches the proposed locations. This is a logical result, as the MRDH report mainly considers the connection to the existing public transport network, which is an attribute to measure the cost criterion in the method application. Scenario 5 is the scenario that allocates a higher weight to the cost criterion, so this should logically be a better fit to the proposed locations. In the MRDH report, 4 hub locations indicate a city mobility hub, due to the very high urban density. Of the remaining 22 proposed locations, 18 are situated in a high-potential area in scenario 5 of the method application. Two of the four low-potential locations are situated at locations at which future developments are planned, the numbers 3 and 5 in Figure 3. As future developments are not taken into account in the method application, it can not be determined what the potential of these proposed locations will be in the future, according to the methodology. The remaining two low-potential locations are further examined.

Number 2 on the map is placed at the Nesselande metro terminus, in a suburb at a distance of 10 km of the city center of Rotterdam. Number 4 is placed at the Vlaardingen-West metro station, at a slightly larger distance from the city center. The contribution of the attributes to the final MCA score in scenario 5 are compared to the average contribution in high scoring areas in Table 6. For both locations, a metro station, parking area and regional cycle route are present, positively influencing the score. The number of users in the catchment area, trip production/attraction and land suitability attributes are approximately equal to the expected value for high-scoring areas. These areas score much lower than expected because of the absence of a main road and facilities close to the location, the absence of a congested road around the location and a very low traffic volume from/to the city. This is remarkable, as the mobility hubs in the MRDH report are proposed with the focus on the transfer function of the mobility hub, so a location near the main roads from/to the city would be expected. A low score of these locations in the method application is justified, as a low potential for a regional mobility hub of the locations is expected in reality.

One important methodological limitation emerges from the analysis steps, which is a result of the normalization of all attributes. The actual attribute values are discarded as a consequence of this process, and normalized on a scale from 0 to 1. Therefore, the highest attribute value in the region is scaled to 1, the lowest attribute value to 0. For the attributes in the demand criterion, this means that the importance of the actual

Attribute	Average % score contribution	Hub 4: Actual contribution	Hub 2: Actual contribution
Production/Attraction	9.33%	12.38%	8.34%
Traffic along road from/to city center	2.77%	0%	0%
Presence of parking area	5.37%	25.06%	21.28%
Presence of high-quality bus/tram link	6.2%	0%	10.30%
Presence of light rail/metro/train station	0.49%	11.96%	10.64%
Physical land suitability	17.84%	20.35%	14.57%
Land owner	6.09%	0%	15.08%
Presence of regional cycle route	5.43%	10.08%	8.56%
Presence of main road	12.91%	0%	0%
Number of retail workplaces	3.17%	2.59%	0%
Maximum I/C-ratio in vicinity	16.93%	0%	0%
Reached users	13.49%	17.54%	11.20%
MCA score	**100%**	**100% / 0.268772476**	**100% / 0.316615053**

Table 6: Percentage contribution of the individual attributes to the MCA score in scenario 5, compared to the average contribution of the attributes in the top scoring areas in the region. A green cell color indicates a relatively high contribution of the attribute, a red cell color a relatively low contribution.

value is ignored, since the scaling factor depends on the maximum value in the region, instead of a scaling that depends on the significance of the value.

6. Recommendations & Conclusions

6.1. Recommendations

In the process of developing and applying the methodology, limitations are discovered, leading to recommendations for both policy makers, which are the potential users of the methodology, and recommendations for further research. Addressing these recommendations can improve both the usability and the quality of the developed methodology.

From the costs point of view, it seems obvious to decide on upgrading an existing public transport node to a regional mobility hub. It should be considered that these locations are not necessarily the highest potential locations for a mobility hub. The cost aspect is only one of the criteria which should be incorporated in deciding on a regional mobility hub location, the other criteria in the methodology can cause an existing public transport node to be less suitable for a hub.

A useful addition to the methodology would be the incorporation of the price of land, to better evaluate areas on the cost criterion. By including this factor as an attribute in the methodology, the methodology might become suitable for extremely urbanized areas as well, as the constraint can be replaced by the attribute.

To better estimate the impacts of the regional mobility hub in selected areas, the highest potential locations can be inserted into a traffic model. This way, the actual impacts can be estimated, leading to better estimation of this criterion. Before implementing the regional mobility hub, this step should always be performed.

Additional research is suggested on two topics. Firstly, the methodology can be extended for usage on regional hubs with both a passenger and freight function. To do so, the same steps can be performed, meaning that all factors influencing the location potential are identified from the literature, where after these factors are converted to criteria in the methodology. Trade-offs between the passenger and freight transport function should be made, which will be difficult, as the characteristics strongly differ among these two transport groups.

Secondly, the methodology can be improved by using revealed preference research on current shared mobility usage. The actual usage of a hub will differ from the projected usage of the hub, due to factors which are very difficult to measure, such as personal characteristics and behavior. By incorporating revealed preferences of the future users of the mobility hub, the methodology can be improved.

6.2. Conclusions

The potential of areas for a regional mobility hub can be determined using a GIS-Multi-Actor Multi-Criteria Analysis, a methodology combining the GIS-MCA and Multi-Actor MCA. Criteria and attributes are defined to incorporate the factors, resulting from an extensive literature review, influencing the regional mobility hub potential of an area. This methodology is applied on a region by a GIS analysis, the output is visually represented in a heat map for every scenario. The assumptions and limitations specified in this thesis should be taken into account when applying the methodology.

The wishes of the stakeholder groups are reflected in the allocation of weights to the criteria: the regional mobility hub as a solution to quality of life issues and greenhouse gas emissions, as stated in the introduction, is relevant from the government perspective. The number of users and connection to the networks is relevant from the other perspectives. In finding a successful location for the regional mobility hub, all stakeholders' points of view should be incorporated, which can be done by using this methodology.

The method is globally applicable to other cases, as the used literature is gathered from multiple countries throughout Europe and North-America. The method can be easily applied to other regions in The Netherlands by using the exact same data, the only requirement is the availability of a traffic model, as the application largely relies on this data.

The developed methodology contributes to the existing literature by providing a generally applicable methodology to determine the potential of areas for a regional mobility hub. The mobility hub distinguishes itself from conventional public transport nodes by the integration of shared mobility and an added value to passengers and the neighborhood by providing facilities. A methodology to determine the potential of areas for a mobility hub is not available yet, this research gap is partially addressed in this thesis, by providing this methodology for a specific hub type, the regional mobility hub.

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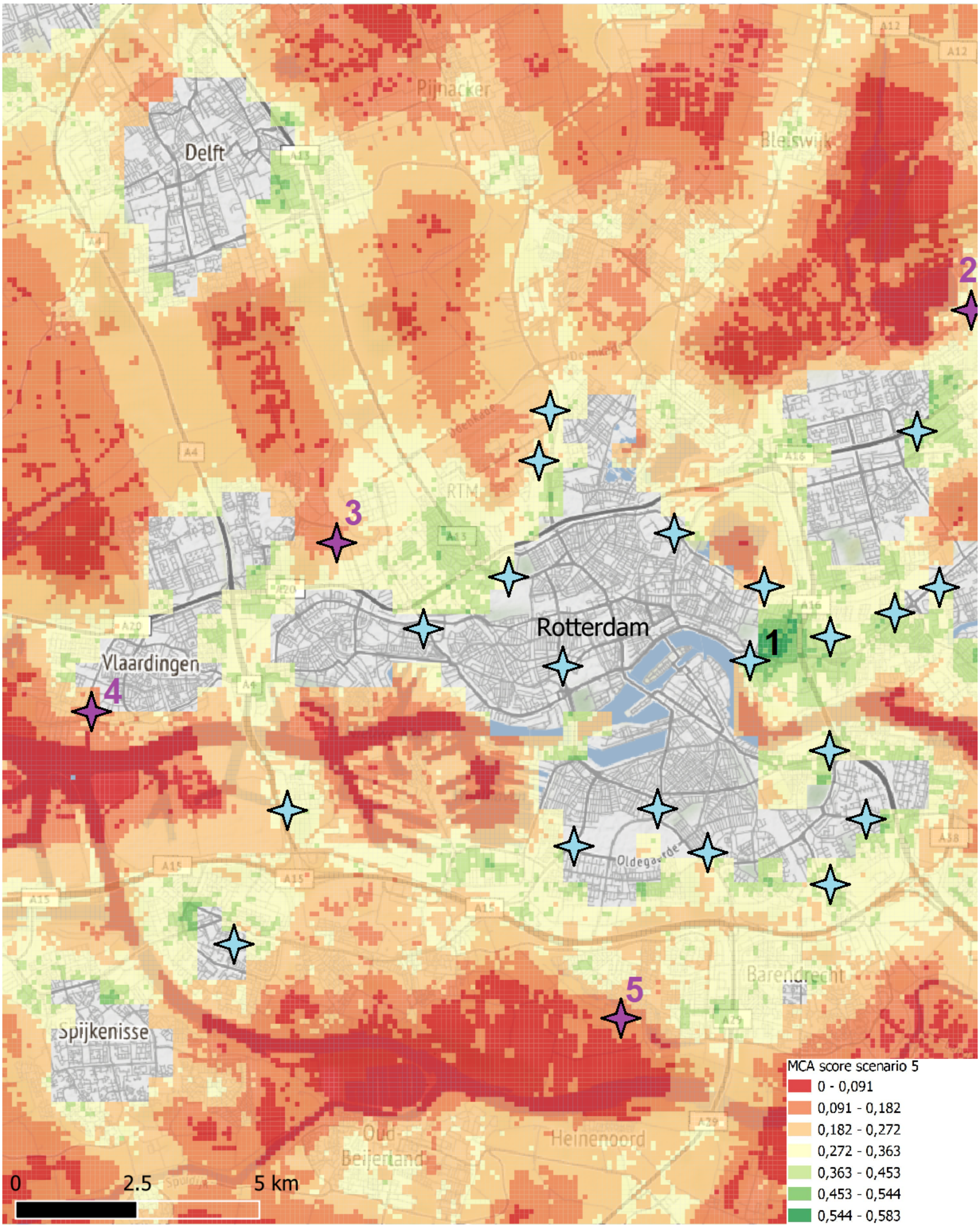

Figure 3: Output of the application of the methodology for the Rotterdam region in scenario 5. The blue and purple stars represent the proposed hub locations from the MRDH study. The number 1 is the highest potential area, numbers 2-5 are the low-potential proposed hub locations, which are discussed in the main text.