

# Forecasting Parking Occupancy

Developing a Parking Model Framework Using a Case Study on The Hague

A. J. (Annerieke) Ohm

Delft University of Technology

 **TU Delft**

 **antea<sup>®</sup>group**

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Developing a Parking Model Framework Using  
a Case Study on The Hague

by

A. J. (Annerieke) Ohm

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Thesis committee: Dr. ir. A. J. Pel, TU Delft, supervisory team  
Dr. J. A. Annema, TU Delft, supervisory team  
Ir. J. E. M. van Hoeckel, Antea Group, supervisory team  
Dr. M. Snelder, TU Delft

Cover: <https://unsplash.com/photos/a-row-of-parked-cars-on-a-tree-lined-street-oiYiuaWBrn0>

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# Preface

This thesis forms the final part of my master's in Transport, Infrastructure, and Logistics (TIL) at Delft University of Technology and was performed in collaboration with Antea Group. This research marks the end of my time as a university student and has proved to be the perfect combination of my bachelor's and master's.

I really enjoyed being able to apply my mathematical background to work on a solution in the TIL domain. Since starting my bachelor's in applied mathematics, I have always longed to be able to focus more on the applications of mathematics in everyday situations. This is something my master's, and especially this thesis, have allowed me to do.

I would not have been able to finish this process without the help of my supervisors. Jim, thank you for always being ready to help me brainstorm ideas or ask me difficult questions. I really appreciated our regular check-ins, ensuring that I could always talk about problems I encountered. Adam and Jan Anne, although we may not have seen each other as much, I always knew that I could count on a quick and thorough response whenever I had a question or problem. I want to thank you for your sharp and extensive feedback, steering me back in the right direction.

Furthermore, I want to thank my colleagues at Antea Group for providing me with information and ideas, asking questions, showing me the importance of this topic, and making me feel welcome. I want to extend my appreciation to the municipality of The Hague for their willingness to cooperate. They provided me with information and data I would otherwise not have been able to get. Finally, I want to thank Maaïke Snelder for providing me with additional research papers and for being willing to be part of my final thesis committee.

*A. J. (Annerieke) Ohm  
Delft, August 2025*

# Summary

If one were to park all the cars in the world, they would occupy an area roughly the size of half of the Netherlands. Meanwhile, the number of cars worldwide is steadily increasing each year, all of which need a space to park. This presents a challenge for cities, which are already struggling with limited space as more people move from rural areas to cities and an increased demand for greenery, bicycle parking, and other amenities. There is often little room to expand, forcing municipalities to make difficult choices about how to allocate the scarce space.

Municipalities face several challenges within the parking domain. First, parking is one of the most visible and controversial aspects of urban mobility. Drivers expect to park close to their destination, for an affordable price, without wasting time searching for a parking spot. Local businesses often argue that implementing paid parking or increasing the fees will cost them customers. However, research shows that free parking does not necessarily increase local spending. Instead, it encourages car use, causing more car traffic and congestion. Therefore, municipalities want to communicate and explain the effects of planned policy measures, but these effects are often unknown, presenting the second challenge.

In the Netherlands, municipalities are responsible for the parking supply and policy. Parking policy is important for managing accessibility and quality of life. By controlling supply and implementing regulations, municipalities can influence travel behaviour and reduce the number of car trips. This makes cities more attractive, accessible, and liveable. However, the precise effects of many parking policies remain unknown and depend strongly on the characteristics of the parking location, the driver, and the trip. Therefore, municipalities face a challenge when determining what policies to implement and what their expected impact will be.

The complexity of these first two challenges is increased by the third challenge. Not every car is allowed to park in every space at all times. There are parking spaces specifically for, among others, disabled car users, charging electric vehicles, loading and unloading, car-sharing vehicles, and private driveways. These parking spaces can only serve a specific demand, increasing the difficulty of determining and communicating policy effects.

Additionally, the increasing demand for parking is a challenge for both municipalities and society as a whole. The average car is parked for 95% of the time, occupying space that could be used for housing, greenery, or other public amenities. Excessive parking supply encourages more driving and increases search traffic, reducing the liveability and vitality of cities. Additionally, building and maintaining parking facilities is expensive, which most people are not willing to pay for. These costs are often passed on to society.

Thus, managing parking within a municipality is very complex. This thesis specifically addresses the challenge municipalities face in determining the impact of policy changes. Therefore, it will answer the question: *How can the future parking occupancy in the different areas of a municipality be forecast, while showing the effect of policy measures and area characteristics on this occupancy?* This question was answered in several steps. First, a literature review determined to what extent the effects of parking policy are known and what current models exist to simulate these effects and predict parking occupancy. This was followed by conversations and interviews with consultants and municipality workers, discussing the main problems and possible solutions. The results of both the literature review and the conversations and interviews led to requirements that the designed model should meet. From the gathered information, a conceptual model was designed. The conceptual model was made operational based on the available data and techniques. Finally, this operational model was validated and tested using a case study on the municipality of The Hague.

The scope of the research consists of the following points:

- Only passenger cars and vans are considered. Trucks and buses operate in a different system.

- Parking spaces and drivers are homogeneous. This means that every car is allowed to park everywhere at any time.
- The model framework will consider the peak parking occupancy for a specified part of the day (morning, afternoon, evening, or night), differentiating between a workday and a weekend day.
- The average parking duration will be considered to be the constant parking duration for everyone.
- The model framework is intended to be used for municipalities in the Netherlands.

The literature review revealed that research into the effects of parking policy is scarce and mainly focused on two of the most implemented policies: parking capacity and paid parking. Parking capacity is a delicate balance: an oversupply increases car use, while too few spaces lead to high parking occupancies, long search times, and long walking distances. When occupancy levels exceed 85%, parking demand drops as drivers are discouraged by the difficulty of finding a space. For paid parking, the type of regulation is important, as it determines which user groups are affected by pricing measures. However, determining a general price elasticity of demand is difficult because it depends on the context considered. The literature showed that the effects of many parking policies depend on the specific context, yet no studies were found that focus on the precise way context influences these effects. The implementation of parking policies in an area can often lead to spillover parking, where drivers choose to park in neighbouring areas that are cheaper or more convenient, simply shifting the problem.

Most existing parking models were developed in the past decade, with current developments focusing mainly on machine learning approaches and models that examine underlying parking behaviour and the resulting probabilities of occupancy. Nevertheless, many models still fail to account for the effects of parking capacity, and no commercially available models were identified in the literature. However, some of the available models provide aspects that can be used in the development of a new parking occupancy model.

Conversations and interviews were held with consultants and municipality workers to gain knowledge from their experiences, determine the current practice, and discuss wishes and requirements for a new model. These conversations and interviews confirmed the findings from the literature and added practical perspectives. Municipalities primarily wish to predict and communicate the expected effects of changes in policy or the built environment, such as the construction of new housing. For residents, councillors, and others to trust the results, it is important that a parking model is transparent and explanatory. Moreover, parking problems are very local, which means that an effective model must be capable of working at a small scale and account for the specific characteristics of individual neighbourhoods or streets.

The conversations and interviews, combined with findings from the literature, were used to formulate the following requirements for the model:

- The model must include the effect of the current parking occupancy;
- The model should use a neighbourhood level of detail or smaller;
- The model must be transparent such that the effects of different factors are clear. The model, therefore, cannot use machine learning.

Based on the findings from the literature and the conversations, a conceptual model was designed. The goal of this model is to create a framework that can be used to determine whether the underlying concept can be used to solve the identified problems. The conceptual model shows that the parking system works as a balance between supply and demand. The assignment algorithm assigns the parking demand to the parking supply using the Method of Successive Averages (MSA) until Wardrop's equilibrium is reached. This uses the concept of least resistance, where the resistance depends on parking fees, walking distance, and access time. An overview of the conceptual model is shown in Figure 1.

The conceptual model is operationalised based on the available data and existing techniques.

The parking supply in an area consists of on-street parking, off-street parking, parking garages, illegal parking, residential parking on private property, and company parking on private property. No data on the amount and location of free off-street parking, illegal parking, and company parking on private

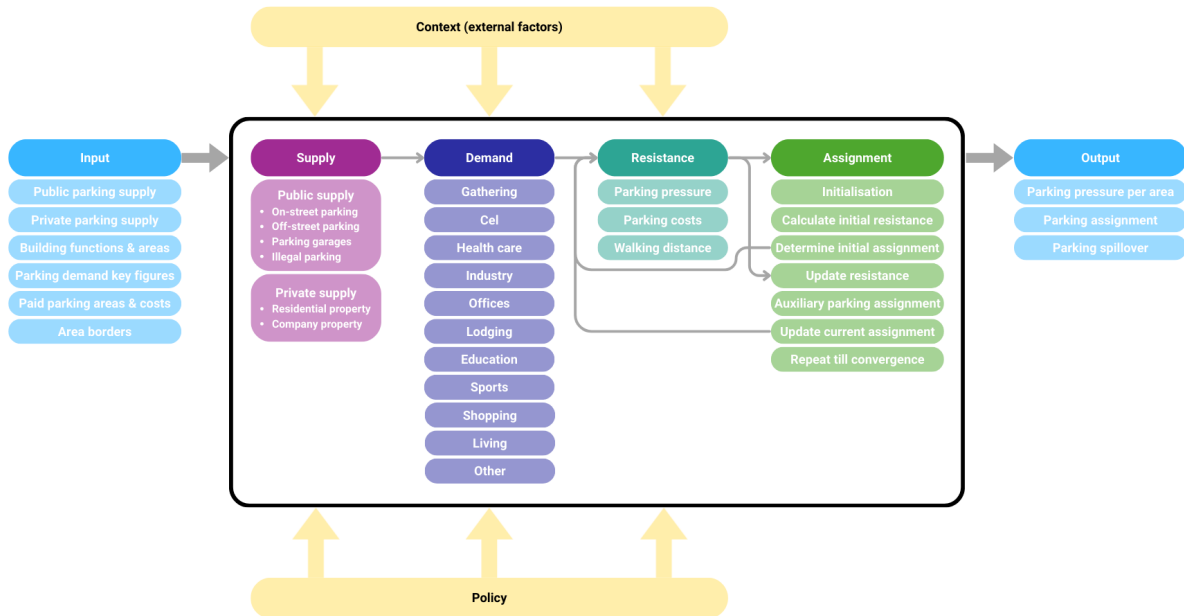


Figure 1: Conceptual model overview

property were found. These categories were therefore excluded from the model. On-street parking, parking garages, and paid off-street parking can best be estimated using regional datasets from the relevant municipality. For residential parking on private property, the supply is estimated to be 20% of the number of residential properties in the area.

The parking demand per area is divided into two categories: residential demand and non-residential demand. The maximum residential demand is assumed to be equal to the total car ownership in the area. The maximum non-residential demand is estimated using the key figures published by the knowledge centre CROW, combined with the buildings' functions and surface areas according to the Basisregistratie Adressen en Gebouwen (BAG). Depending on the time of day considered, this maximum demand is reduced using the attendance percentages also published by the CROW. These attendance percentages indicate the part of the maximum demand per category that is expected to be present at that time of day. Additionally, since the parking supply does not include parking at office buildings, parking demand generated by office buildings was also left out.

The next step involves the definition of the resistance function. The resistance of an area depends on the average parking fee per parking spot, the average walking distance from the parking area to the destination area, and the access time, which depends on the parking occupancy in the area. These were all defined in minutes of time lost, using the Value of Travel Time (VTT) to convert the parking fees and an average walking speed to convert the walking distance.

These all form the input for the MSA. In each iteration, the demand is assigned to the parking supply according to least resistance. The current assignment is then determined by averaging this auxiliary assignment with the previous assignments. The resistance values are updated, and a new iteration is started. This continues until Wardrop's equilibrium is reached.

The operational model was tested and validated using a case study on The Hague. To validate the model, two scenarios were tested: the situation in The Hague on a workday evening and the situation in The Hague on a workday morning. The key figures used to determine the demand are known to overestimate the demand. Additionally, not all supply could be taken into account, amplifying this overestimation. Therefore, the estimated demand in the case study was lowered by 10%.

The case study showed that the model can be used to determine the expected parking occupancies for each neighbourhood, with the predictions for a workday evening being more accurate than the predictions for a workday morning. For The Hague, the completeness of on-street parking supply data was found to vary considerably between neighbourhoods. Nevertheless, in both scenarios, the

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resulting parking occupancies were generally close to the observed values, especially for the areas with accurate on-street parking supply data. Neighbourhoods with incomplete supply data were filtered out, improving the overall predictive accuracy for both scenarios. The case study also showed that the model can be applied to illustrate the expected effects of removing parking spaces. More broadly, the model is likely to be suitable for assessing other aspects of parking policy as well, such as changes in supply, both the addition and removal of parking spaces, and changes in demand, whether due to new housing developments or measures to reduce car use, such as limiting the number of parking permits. In addition, the model can be used to assess the impact of changes in parking fees.

The model presented in this thesis is intended as a framework for a parking model, leaving significant scope for further development and improvement. The scope used in this research results in skewed parking occupancies for some areas. However, the precise extent to which these occupancies are skewed cannot be determined. An example of this is that the current model assumes homogeneity within both supply and demand, even though, in practice, differences exist between types of parking spaces, user groups, and trip purposes. Including this heterogeneity would likely provide more insights into the precise effects of different factors. Additionally, it would allow for the use of heterogeneous resistance factors, further improving the explanatory nature of the model. One clear area for refinement is the completeness of the supply data. Future applications should aim to include all relevant categories that were left out in this version. In addition, while the CROW key figures provide a useful starting point, they are generally known to overestimate actual parking demand. Developing a separate demand model that accounts for local area characteristics, such as proximity to public transport or the socio-economic characteristics of a neighbourhood, would likely increase the accuracy. Moreover, the resistance function could be improved by recognising that perceived time lost and actual time lost are not necessarily the same for all factors. Finally, since parking problems are highly localised, working with smaller areas could provide a more detailed and realistic representation of the parking occupancy distribution.

To conclude, there are many ways to improve the framework developed in this thesis. However, this thesis shows that the underlying concept is able to accurately describe the balance between parking supply and demand and predict the resulting parking occupancies based on this balance. Existing techniques and data sources were combined to create a framework that forms the basis for a full parking occupancy model. This is something municipalities and consultants request. Additionally, in the literature, most models focus on one aspect of parking. Thus, this framework fills both a scientific and societal gap by providing a working concept in an area where this was not yet freely available.

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# 1

## Introduction

According to recent data estimates, the worldwide fleet of cars has passed the 1.6 billion (Hedges & Company, 2025). With a world population of more than 8 billion people (World Bank Group, 2024), this is almost one car for every five people. All of these cars are parked 95% of the time (Mingardo, 2016), taking up a total area of almost 20.000 km<sup>2</sup> (Slagmaat, 2021), approximately half the size of the Netherlands. In the Netherlands alone, there are more than 9.2 million cars (CBS, 2025b), that is one car for every two people (CBS, 2025a). Both the worldwide fleet and the Dutch fleet are steadily increasing every year, requiring more and more space to park. At the same time, people are moving from the countryside to the cities (CBS, 2024), further increasing the demand for space for parking, living, and other amenities in these cities. However, many cities, especially in the Netherlands, do not have a lot of space to grow, neither on the outskirts, nor within the city. The lack of space is amplified by the demand for more greenery, bicycle parking, and other amenities, which is growing regardless of the city's population. This presents a challenge for cities, forcing them to make difficult decisions about allocating the scarce space.

Within the parking domain alone, there are several challenges to tackle. First, parking is one of the most visible and controversial aspects of urban mobility. Many cars are used almost daily, with drivers expecting to be able to park close to their destination, for free or at an affordable price, without having to waste time searching for a parking spot. Similarly, whenever paid parking is introduced somewhere, or the fees are increased, local businesses often argue that the resulting parking costs will result in fewer customers. However, based on the literature reviewed in chapter 2, paid parking does not decrease local spending, nor does free parking increase it. Instead, free parking often increases car traffic, because travellers choose the car over other transport alternatives. This leads to more car traffic and congestion in the area, lowering the liveability. Municipalities aim to prevent parking problems within their boundaries and, therefore, often introduce paid parking zones in areas with high parking demand. To combat the arguments presented by residents and businesses, municipalities want to communicate and explain the expected effects of implementing paid parking or other measures. However, these effects are often unknown or difficult to quantify.

This presents the second challenge: the implementation of parking policy. In the Netherlands, municipalities are responsible for the parking supply and parking policy within their borders. Parking policy is essential for managing accessibility and quality of life in the city. Too much parking supply leads to increased car traffic, bringing congestion, pollution, and sound disturbance. Too little supply or too high fees cause increased search traffic and reduced accessibility, especially when there may not be an alternative mode of transport. By controlling the parking supply and implementing regulations, municipalities can influence travel behaviour and decrease the number of car trips. This makes cities more attractive, accessible, and liveable. However, it is a delicate balance, which is made more difficult by the fact that the precise effects of many parking policies are unknown and very context dependent. As will be shown in chapter 2, even for parking fees, the most researched policy, no single price elasticity of demand can be determined. The price elasticity depends on many factors, such as the specific city, the trip purpose, and the driver. Therefore, municipalities face a challenge when determining what

policies to implement and predicting their impact on parking demand and occupancy.

The third challenge introduces an increased complexity to the first two challenges. Not every car is allowed to park in every parking space. Private driveways can generally only be used by the house's residents, meaning that when they are away from home, this place sits empty and unused. Another example is parking spaces for disabled car users, both license plate-specific ones, making it similar to a private driveway, and general ones, which can also only serve a specific demand. Offices often have their own car parks, only accessible to their employees and visitors. The number of electric and hybrid vehicles is increasing. This causes more and more parking spaces to be turned into car charging spaces, which can only be used while the car is charging, decreasing the general parking supply. Additionally, some garages do not allow electric or hybrid cars to park inside, requiring another split when studying parking demand. Many more specific types of parking spaces can be identified, such as spaces specifically for car sharing, spaces only available during specific time frames, or spaces only available for short-term parking. All of these increase the complexity of determining and communicating the effect of policy measures.

The final challenge is one for both municipalities and society as a whole. The average car is parked 95% of the time, taking up a parking space of 2.5 by 5 m (Slagmaat, 2021). This space can therefore not be used for housing, greenery, or other public amenities. Additionally, building and maintaining parking spaces is expensive. Parking fees or permit fees do not generally cover these costs, because most people would not be willing to pay them. Therefore, the costs have to be paid by society. The additional effect is that car travel seems cheaper than it actually is, leading to increased car use.

Managing parking within a municipality is thus very complex, with many people only noticing the final effects. This forms the motivation for this thesis, which specifically addresses the second challenge identified: determining the effects of planned policy changes. Therefore, this thesis aims to determine a way for municipalities to predict the impact of possible policy changes on the parking occupancy levels within the municipality's borders. The research question guiding this process is: *How can the future parking occupancy in the different areas of a municipality be forecast, while showing the effect of policy measures and area characteristics on this occupancy?*

This research question is supported by several sub-questions. Once an answer has been found to all sub-questions, it should also be possible to answer the main research question. The sub-questions supporting the main research questions are:

1. What are possible policy measures and what is known about their effect on parking behaviour?
2. What techniques and models are currently used to predict future parking demand?
3. What should a new model provide that is not yet captured by existing (publicly available) models?
4. What is a conceptual parking occupancy model, and how can it be operationalised to match these requirements?
5. How does the model perform when applied to a real situation?

Answering sub-questions 1 and 2 provides an overview of the current situation. It determines what is already known and what is still missing. Sub-question 2 also identifies possible existing models and techniques that may provide an initial base or work as inspiration for the design process. Sub-question 3 aims to determine the requirements a new model should meet according to municipality workers and consultants, the people who may benefit from a new model. The answers to these sub-questions are combined to conceptualise how a new model should work. This conceptual model is made operational based on the possibilities within the current data and method availability. This forms the answer to sub-question 4. The operational model is finalised by applying it to a case study on the municipality of The Hague. The case study aims to determine and demonstrate how the model works and how it can be applied in a real situation, answering sub-question 5.

## 1.1. Methodology

Several methodologies are applied to answer the research question and the sub-questions. The following paragraphs provide a short overview of each of the applied methods. The literature review is used to answer sub-questions 1, 2, 3, and 4. Sub-question 3 is further answered using informal conversations and semi-structured interviews. Answering sub-question 4 further requires design, and data acquisition and processing, the latter of which is also used in the answer to sub-question 5. Finally, sub-question 5 is answered with the help of a case study.

### Literature review

Sub-questions 1 and 2 are answered using a literature review. The literature review also forms part of the methodology used to answer sub-questions 3 and 4. Therefore, it has several goals. First, it aims to determine the current state-of-the-art in parking policy and parking modelling research. Thereto, the review provides an overview of the possible parking policies that can be implemented and their corresponding effects on parking behaviour and distribution. Similarly, existing parking models are discussed, grouped based on the aims of the models and the modelling techniques used. Together, these define the current situation and the existing research gaps. The second goal is to determine what aspects are included in existing parking models and what aspects are not included in existing parking models. This provides input for answering sub-question 3. The final goal is to find existing modelling techniques that can be used for designing a new parking model in sub-question 4. These modelling techniques may come from existing parking models and from other transport modelling disciplines.

The literature used in the review was found using Scopus and Google Scholar. As search terms, combinations of the following terms were used: 'parking', 'policy', 'demand', 'forecasting', 'predict', 'model', 'pressure', 'supply', 'Netherlands', 'Europe', 'pricing', and 'strategies'. Some example search queries are: TITLE-ABS-KEY((forecast OR predict) AND (parking AND demand)), and TITLE-ABS-KEY(parking AND policy AND demand). Additional literature was received from Antea Group and lecturers. Using the resulting papers, forward and backwards snowballing were applied to find further sources.

### Informal conversations

This research was conducted in collaboration with engineering agency Antea Group. They expressed the need for a solution that can help determine the effect of planned policy changes on the parking occupancy. Therefore, their experiences with and wishes for a parking model are important to include in the design of such a model. Since the research was conducted collaboratively, many of these experiences and wishes were expressed during informal encounters.

Information gathered from these conversations was used throughout the process, but mainly in the definition of the model requirements and the design of the conceptual model. The conversations provided guidance on application situations and techniques currently being applied. This information was combined and used to answer sub-question 3.

### Semi-structured interviews

Besides informal conversations, semi-structured interviews were conducted to determine the requirements for a new model, answering sub-question 3. As mentioned above, Antea Group expressed the need for a parking occupancy model. The situations in which they would use it are usually questions posed by Dutch municipalities, since in the Netherlands, municipalities are responsible for the parking policy and supply within their borders. Therefore, the experiences and wishes of municipalities should also be included in the design of a new model. Using the contact network of Antea Group, three people working at the municipality of The Hague in the Netherlands were interviewed.

These interviews were conducted using the semi-structured interview technique. This technique combines pre-prepared questions with the possibility of asking follow-up questions based on the interviewee's answers. While semi-structured interviews are much more time-intensive than regular surveys, they can be valuable depending on the research goal. According to Adams (2015), one of the situations in which this technique is useful is to determine potential stakeholders' thoughts on and problems with an issue or idea. Since this aligns with the goal of the interviews in this research, semi-structured interviews are applicable in this situation.

As outlined in the advice given by Adams (2015), questions and topics were prepared and printed out. The interviews were recorded to prevent loss of information and allow full focus on conducting the interview. All interviews started with some general questions. This was followed by a short explanation of the motivation to design a parking model. Using figures based on fictitious data, the interviewees were given an idea of what the output of a parking model could look like and how differences between two scenarios could be compared. Finally, the interviewees were asked additional questions regarding the possible applications of such a model.

## Design

Using the requirements set by answering sub-question 3 and combining this with the information from the literature review and the informal conversations, a conceptual model is designed. Aspects of the model are inspired by other transport and parking models discussed in the literature review in chapter 2. These aspects are adjusted to incorporate parking, and the different parts are combined. This forms the conceptual model, answering part of sub-question 4.

## Data acquisition and processing

The conceptual model is transformed to an operational model based on the available data and existing techniques, answering the second part of sub-question 4. The data is acquired in several ways. First, a search is conducted to open-source data. This is mainly done by searching in Dutch databanks such as <https://opendata.rdw.nl/> and <https://data.overheid.nl/>. Additionally, many of the large municipalities in the Netherlands, such as Amsterdam, The Hague, and Eindhoven, publish datasets on their website. These websites were also searched to determine what data municipalities collect themselves. Additional data was found by following the advice of others. Any data needed for the operationalisation that was still missing after these initial searches was acquired by specific searching in Google.

The acquired datasets are analysed to determine exactly what they include. Possibilities for combining datasets to obtain the exact data needed are investigated. For some model aspects, multiple datasets are available. In those cases, the choice between options is made based on factors such as completeness, general availability, accuracy, and ease of processing. The importance of each of these factors depends on the considered aspect.

## Case study

Chapter 4 shows that the availability and data type in part depend on the specific municipality considered. Therefore, a case study is conducted on the municipality of The Hague to determine the validity and demonstrate the use of the designed model. The Hague was chosen for the case study for the following reasons:

- The Hague is among the largest municipalities in the Netherlands. This means it has a complex network, so if the designed model can be used for The Hague, it is more likely to also work for smaller municipalities.
- The Hague has an extensive open database that can be used. Additionally, they have parking-related data available that has not been published.
- Due to earlier collaborations between Antea Group and The Hague, it was known that they would likely be interested, and the contact information was available.

To conduct the case study, the operationalised model was worked out with the data available for The Hague. Some additional data was received from the municipality, which was also incorporated. The model was tested for two times of day: a workday evening and a workday morning. The results of both scenarios were used to validate the model using real data received from The Hague. Additionally, a model application is demonstrated by showing how the model can be used to determine the effect of the removal of parking spaces on the parking occupancies in the target neighbourhood and the surrounding neighbourhoods.

## 1.2. Scope

As described above, the parking domain is complex, with many factors influencing parking demand and behaviour. Therefore, this thesis will focus on the creation of a model framework. If the designed model framework can be used to solve the challenge municipalities face in determining the effect of planned policy changes or building projects, it can later be further expanded to a complete parking occupancy model. One of the main challenges in developing the model framework is the limited availability of data around parking. Whether it is parking supply, parking demand, or policy effects, the available data is scarce, and it is often difficult or time-consuming to determine its accuracy. Therefore, the created framework must be simplified enough to work with the available data sources. However, to determine if the framework's underlying concept works to solve the challenge, the framework has to be complex enough to include the main dynamics influencing parking occupancy. This leads to the following decisions that determine the scope of this research:

- Only passenger cars and vans will be considered. Trucks and buses usually have their own designated parking areas and abide by different rules. Additionally, their behaviour differs from the average passenger car or van due to the general different trip purposes. Therefore, they are not directly part of the system described above.
- The third challenge mentioned, described the complexity caused by not all cars being allowed to park everywhere. Incorporating this complexity in a model, requires data on the supply and demand of the various categories. Most of the available data does not differentiate these categories; if it does, it is often inaccurate or incomplete. Therefore, the developed framework will not differentiate between different types of parking spaces, such as disabled, private, public, or only for certain cars, nor will it differentiate between different types of drivers or trip purposes. This means every parking space is available for every passenger car at every point in time. By not differentiating between different types of spaces or drivers, some of the inaccuracies from missing data are compensated for by the inaccuracies of other categories.
- The model framework will consider the peak parking occupancy for a specified part of the day (morning, afternoon, evening, or night), differentiating between a workday (Monday - Friday) and a weekend day (Saturday or Sunday). Available data sources on parking demand do not specify further than these categories. Cars that stay parked during multiple time blocks are also part of the demand of the new time block. If a model is used that determines the behaviour of every single car individually, this may cause problems because these cars would choose parking spots multiple times. However, the model framework studies the parking behaviour of the system as a whole, eliminating this problem. The peak parking moments are when parking problems are most likely to happen. Therefore, these are the times municipalities want to influence by implementing policies.
- The average parking duration will be considered to be the constant parking duration for everyone. Most available data sources do not specify further with regard to time, making this the maximum complexity that can be used with the existing datasets. This means that parking costs will be based on the average parking duration.
- This research is performed in collaboration with the engineering agency Antea Group. Additionally, discussion took place with and data was received from the municipality of The Hague. Therefore, the model framework developed in this research is intended to be used for municipalities in the Netherlands.

These decisions were discussed with Antea Group and the municipality of The Hague to ensure that the resulting model framework meets their requirements in terms of complexity and applicability. Additional requirements for the model are determined while answering sub-question 3 and are discussed in chapter 3. The possible effects this scoping has on the model results will be discussed in section 6.2

## 1.3. Terminology definition

The organisation of governing bodies varies per country. With this variation also come differences in responsibilities and the ways in which a country or city is subdivided. The result is that different languages use different terminology to describe these subdivisions, and a direct translation is not always possible. The model developed in this research is intended to be used in the Netherlands. Therefore,

in this thesis, the Dutch division and terminology are used, translated to the closest English translation. To ensure that all readers understand what division is meant by each term, they are clarified below. For each English term used, the Dutch term it is based on and a short description are given. Additionally, all terms are visualised on the city of The Hague.

**Municipality (Dutch: *gemeente*):** This is the largest body used in this research. The model developed focuses on parking within one municipality. Anything happening outside the municipality's borders is ignored. The municipality is responsible for the parking supply and parking policies within its borders. This way, the municipality has (some) influence on parking behaviour. The municipality borders of The Hague are shown in Figure 1.1a.

**Boroughs (Dutch: *stadsdelen*):** The municipality of The Hague is divided into eight boroughs. This is the largest division within municipality lines. Each borough is linked to an alderman and a director within the council. The division in boroughs is included in Figure 1.1b.

**Districts (Dutch: *wijken*):** Every borough is further divided into several districts. The Hague has 44 districts in total. These can be found in Figure 1.1c. Together with neighbourhoods, the district level is one of the levels at which many policies are made. It is also a level to which characteristics of an area are often attributed.

**Neighbourhoods (Dutch: *buurten*):** Most districts are further divided into neighbourhoods. This is the smallest division used in this research. Neighbourhoods within and close to the city centre are often smaller than neighbourhoods near the edge of the city. For most statistical data, this is the smallest level at which it is collected. The Hague is divided into 114 neighbourhoods, which are included in Figure 1.1d.

**Area:** The term area is used in this research as a general term, when the level of detail is either undetermined or irrelevant, meaning that it would work the same for the different levels of detail. This can also mean areas of a different shape or size than those outlined above.



**Figure 1.1:** Visualisation of area terminology

## 1.4. Document structure

After this introduction, this thesis starts in chapter 2 with a review of the existing literature, giving an overview of the existing research on parking policy and parking modelling, and providing related literature to form the basis for the remainder of the study. Chapter 3 starts with determining the model requirements, which are based on conversations and interviews with relevant parties. Based on these conversations, interviews, and requirements, a conceptual model is defined, showing how the different aspects are conceptually intertwined. This is followed by chapter 4, in which the conceptual model is operationalised. For all aspects of the conceptual model, the available datasets and techniques are considered, and the assumptions and choices made are described. The operational model is then tested using a case study on The Hague in chapter 5. In the operational model, some aspects depend on the specific municipality considered. The way these aspects are handled and any additional data sources, assumptions, and choices are described. The resulting model is validated by comparing the predicted parking occupancies of two main scenarios to the real parking occupancies, based on counts performed by the municipality. Additionally, the case study demonstrates how the model can be used to determine the expected effects of a change in the parking supply. Finally, chapter 6 contains the conclusions and recommendations resulting from this research.

# 2

## Literature Review

This chapter provides an overview of existing research and related literature, providing a basis for this thesis. It starts with an overview of the possible parking policies that can be implemented and, where known, their effect on parking behaviour. This both shows the necessity for parking research and provides the necessary information for the incorporation of policy options and effects into a parking model. This is followed by a discussion on the existing parking models in research, showing the differences in approach between different types of models, as well as their joint focus on specific policy effects. This discussion aims to show the need for a parking occupancy model as designed in this research. Next, the parking policy and parking models are brought together by some studies on general factors influencing parking behaviour. Additionally, it describes aspects of existing models that can be incorporated into the new parking model. The chapter ends with an explanation of some aspects of the 4-stage transport model that are used in the design of the parking occupancy model. This should provide the reader with the required knowledge for the remainder of this research.

### 2.1. Parking Policy

Parking policy encompasses all possible policy measures that can be taken in an attempt to influence parking behaviour or parking demand in an area directly. The existence of thorough scientific research depends on the specific measure in question. The body of scientific research is substantial for well-known measures, such as regulated or paid parking, while for other measures, there is no scientific research at all. Therefore, it is challenging to determine what measures to apply to achieve a desired effect. Both CROW (2017) and Mingardo (2016) have created an overview of the existing knowledge on parking policy measures and their effect on parking behaviour and demand. In both reports, the possible policy measures are divided into several main categories. These categories are roughly the same for both, with the CROW considering one additional category, *social environment*, where the effect of social interactions on parking behaviour is discussed.

In their report, the CROW discuss all possible policy measures affecting parking. For each policy, an overview is given on the existing knowledge about the effect of the policy on parking behaviour and how to best apply the policy. This report provides a good basis to determine the state-of-the-art when it comes to policy effects. However, it is important to note that many of the references used by the CROW are not publicly available or have been removed from the websites they refer to. The CROW is the Dutch national entity for research on infrastructure, public space, traffic, and transport (Rijksoverheid, n.d.). Therefore, the information from the CROW report can likely be trusted, but should, where possible, be corroborated with additional sources.

Mingardo (2016) also discusses the existing knowledge about parking policy. Contrary to the CROW, his focus is more on the effect of the main category on parking behaviour rather than the specific policy. His goal is to provide an overview of the development of parking policy over time, resulting in a much more compact discussion of the effects.

Since the CROW provides a more extensive discussion on parking policy and parking behaviour, the

structure of that report will be used to provide a short overview of state-of-the-art parking policy research. This section will be structured based on the categories presented in the CROW report: physical environment, digital environment, parking regimes, marketing, and social environment.

### 2.1.1. Physical Environment

The physical environment category includes any policy that is executed by changes in the built environment. The main policies captured by this category are: capacity measures, using rest capacity, stimulating garages, park & ride, and safety & comfort. Of these policies, capacity measures is most researched.

When applying capacity measures, the supply of parking spaces in an area is either increased or decreased. The effectiveness of an increase or decrease in parking supply depends on the parking occupancy in the area. Inci et al. (2015) showed that the inflow rate, indicating demand, is relatively constant as long as the occupancy rate stays below 85%. Once the occupancy rate crosses this 85% line, the inflow sharply decreases with each additional car. This knowledge can be used to influence demand in an area, but one should pay attention to the possible consequences for neighbouring areas or shops within the area that this higher parking occupancy might cause (CROW, 2017).

This is confirmed by the research of Antonson et al. (2017) showing that a low parking capacity in a Swedish neighbourhood barely changed the parking demand of the neighbourhood. Many of the residents now simply parked in the neighbouring areas rather than their own neighbourhood. This behaviour is known as the *spillover effect* (Mingardo, 2016). The spillover effect is a term describing the behaviour of motorists to park slightly further away if parking close by is either difficult or expensive. When this is not taken into account before implementing policy changes, solving parking problems in one area may lead to new parking problems in its neighbouring areas.

Generally, capacity measures alone are not enough to largely reduce parking demand in an area, but combined with other measures, these effects may change.

### 2.1.2. Digital Environment

The digital environment category includes any policies that require some form of digitalisation to work. The main policies captured by this category are: parking guidance systems, mobile parking, pre- and on-trip information, license plate registration, reservation system, and Airbnb for parking places. These policies have something in common: they make something easier. Some make it easier to find a parking spot (parking guidance systems, pre- and on-trip information, reservation system, and Airbnb), others make it easier to pay and check payment in paid parking areas (mobile parking, and license plate registration). All of these result in less search traffic, which reduces the traffic density in the area. As shown by Chaniotakis and Pel (2015), drivers find it important to find a parking spot within 8 minutes, especially if this is a cheap or free parking spot. The policies in the digital environment can help reduce the search times and therefore increase the number of people finding a spot within 8 minutes. This reduces the amount of search traffic in the area, which can be more than 50% of urban traffic (Arnott & Inci, 2006; Chaniotakis & Pel, 2015; Shoup, 2006). It is important to realise, however, that some of these policies, especially the reservation system and Airbnb, may increase car usage and, with that, increase the demand in the area. Additionally, Van der Waerden et al. (2011) showed that parking guidance systems only really affect the incidental visitors to an area. People who visit an area more often usually already know where the good parking spots are (CROW, 2017). This means that parking guidance systems can best be applied in areas with a lot of tourism to reduce search traffic.

### 2.1.3. Parking Regimes

The category parking regimes includes any policy that sets rules or limits to parking in an area. The main policies within parking regimes are: parking fees, stakeholders, parking norms, shopping regimes, mix parking, time limits, long parking arrangement, and enforcement. This is the category that most people think of when talking about parking policy, and therefore also the category within which most research takes place. Several of the policies within this category have a monetary component, directly linked to the parking demand, which should make it relatively easy to quantify their effect.

Most of the research into parking policy effects involves the effect of parking fees on parking behaviour. This is studied in various ways.

Lehner and Peer (2019) compares the effect of parking fees on parking behaviour as found in 50 different studies. The study shows that the price elasticity of parking demand differs per situation and per research methodology. This is confirmed by looking at several studies. For example, Ostermeijer et al. (2019) focuses on the relationship between parking costs and car ownership. They find a price elasticity of car demand of approximately -0.7, indicating that a 1% increase in car ownership costs leads to a 0.7% decrease in car ownership.

The report of CROW (2017) also suggests that the price elasticity is context dependent, but at the same time, they name an elasticity of -0.3 as being the average. An elasticity of -0.3 indicates that a 1% increase in parking fee leads to a 0.3% decrease in parking demand. This elasticity seems to come from the book from National Academies of Sciences and Medicine (2005), where it is named as the most cited number, rather than the average. In this book, again, it is noted that the elasticity is largely dependent on the parking context, including the reason for the trip. Noteworthy is that the bibliography of the section on parking fees in the CROW report contains the research of Albert and Mahalel (2006) as a source. The text never refers to this study, but in the research a very different price elasticity of parking demand was found, namely one of -1.2.

These are just a couple of examples showing that there does not seem to be one clear price elasticity of parking demand. So even for the most-researched aspect of parking policy effects, the precise effect is not yet entirely clear and likely to be very context-dependent. This is corroborated by the study of Rye and Koglin (2014), which looks at the circumstances in which parking policy is used and especially when it is appropriate to use parking policy as a parking demand management tool. This study shows that not only parking fees, but most parking policies are context-dependent. This suggests that there is not one clear set of rules that can be implemented everywhere to manage parking demand. When implementing paid parking, the spillover effect needs to be taken into account, because, as shown by Mingardo (2016), a small area of paid parking usually evolves to cover most of a city.

Besides paid parking, municipalities sometimes introduce time limits to parking in certain areas. This is either free parking for a maximum number of hours, after which a driver has to leave, or paid parking, but still for a maximum number of hours. According to the CROW, the main effect of this is to relocate long parking vehicles to other areas. This makes it mainly effective in shopping areas, where short parking makes the area more attractive since visitors are more likely to find a parking space nearby (CROW, 2017). These conclusions are corroborated by Mingardo et al. (2022), where three policies are compared: pricing, pricing combined with time limits, and daily tickets. If the goal is to divert long-parking vehicles to other areas, time limits are more effective than parking fees. However, this only really works if it is combined with strict enforcement, making it relatively cost-inefficient (CROW, 2017).

As mentioned in subsection 2.1.1, the supply of parking spaces can also influence the demand for parking spaces in an area. Many places work with parking norms whenever a new construction project takes place. The effects of this can vary, depending on the area and whether minimum or maximum requirements are used.

Setting minimum requirements helps to prevent parking congestion in the new and bordering areas, but also often leads to a higher parking supply than necessary (CROW, 2017; Mingardo, 2016). Shoup (1997) argues that the oversupply of parking spaces due to minimum requirements is a problem for society. He states that the parking norms used, at least in the United States, are not based on enough scientific research to be reliable. Additionally, the studies they are based on, study free parking demand at peak times for locations with no other transport mode alternatives. Shoup argues that this reduces the space available for building, leading to higher prices for houses, goods, and services. Furthermore, he states that the cost of parking somewhere is always lower than the societal cost of the parking space, making driving seem less expensive than it should be. This, in turn, leads to people more often choosing to travel by car rather than an alternative mode.

Maximum requirements have been shown to often lead to lower car usage, but may lead to a higher parking occupancy (CROW, 2017; Mingardo, 2016). Both minimum and maximum requirements have to be carefully constructed to limit the negative effects (Merten & Kuhnimhof, 2024).

The remaining policies in this category, stakeholder parking, regulation long parking and shopping regimes, are all relatively new policies. Due to this, the effects on parking demand are still largely unknown (CROW, 2017).

### 2.1.4. Marketing

This policy category is focused on behavioural change through communication. It involves the following policies: general communication, stimulating alternatives, employer approach, car sharing, target group segmentation, discouraging car ownership, hospitable parking city centres, and valet parking. Many of these policies are usually implemented in combination with policies from the previous three categories. Due to this, the specific effects of the marketing policies are unknown (CROW, 2017).

### 2.1.5. Social Environment

The goal of this category of policies is to involve society in the creation and enforcement of parking regulations. The policies included in this category are: participation, tradeable parking rights, target group checker, reporting system, and use of retail. Most are not a parking regulation on their own, but a way to create societal support for the introduction of other parking regulations. The specific effects are mostly unknown (CROW, 2017).

### 2.1.6. Conclusion

The scientific research into parking policy is scarce. The existing research focuses on some of the common policy measures, with research on other measures being close to non-existent. The effects of policy measures are largely influenced by the context of the parking trip, making it difficult to clearly quantify these effects. This means that even for the most researched parking policy: parking fees, its relation with the parking demand cannot definitively be determined. From the literature, it was shown that for the most-used parking policies, the main effect is generally known, meaning that it is known whether a policy will increase or decrease the demand for parking or the parking occupancy. However, how big the change will be depends on many more factors and remains a question. The next section discusses literature on the possibilities of using different modelling techniques to determine these effects under different circumstances.

## 2.2. Existing parking models

Several attempts at creating parking models to forecast parking demand have been made. Especially in the past decade, the research into parking models has increased. In the past couple of years, most studies were conducted in Asia, with many of them using machine learning models to predict parking demand. Zheng et al. (2023) compared several existing parking models and their strengths and weaknesses. They showed that most existing models use either existing parking demand or land use properties to predict parking demand. Most models ignore parking supply and, with that, the possible influence of parking supply on the parking demand.

This section is divided based on the types of models that were found. First, the machine learning models are discussed. Next, the statistical models are described. The final subsection discusses models that use the underlying behaviour guiding parking choices to predict the parking distribution.

### 2.2.1. Machine learning models

In the past couple of years, several studies have been conducted that use machine learning techniques to model parking demand or behaviour. Various machine learning techniques have been applied. Zeng et al. (2022), L. Chen et al. (2023), and Ma et al. (2023) all used a Long Short Term Memory (LSTM) model to predict short-term parking demand in an area. Zeng et al. (2022) even managed to include multiple factors in the prediction. They showed that including factors such as weekday/weekend day, weather conditions, and parking occupancy improved the predictive accuracy of the model.

Paudel et al. (2024) used a combination of linear regression and Artificial Neural Networks to predict parking demand on a university campus based on the trip generation step of the classic 4-step model used in traffic modelling. This allowed for the possibility of adjusting the teaching schedule to reduce parking peaks. It is, however, not clear how this can be translated for use in a more general setting, since controlling trip generation so specifically is not usually possible.

Tang et al. (2022) uses a combination of multiple machine learning models combined with an index system describing the demand characteristics to predict parking demand in urban areas. This combination of models leads to a higher predictive accuracy than the separate models.

Several more studies into the use of machine learning for predicting parking demand have been conducted, some taking external factors into account, but most looking mainly at historic parking demand. Most machine learning models have one big disadvantage compared to the more 'classic' models: they form a black box. Even if external factors are taken into account, machine learning models usually do not show the effect of any of those factors on the prediction. The accuracy of a machine learning model is tested by comparing its prediction to existing data, but that leaves the possibility for overfitting or illogical things happening.

### 2.2.2. Statistical models

Another common category of models is the mathematical or statistical models. These are models that use existing data combined with mathematical algorithms to predict the resulting future demand in an area.

Hollander et al. (2006) and Ottomanelli et al. (2011) both take into account that drivers' choice for parking places depends on multiple factors. They use an extension of the logit model and discrete choice modelling, respectively, to predict parking behaviour. Both look at parking from the perspective of individual drivers, rather than parking demand as a whole. Additionally, several simplifications of choice behaviour were made, which may influence the results.

H. Chen et al. (2023) used an ARIMA model to short-term forecast parking demand without the need for large datasets. The forecasting is based on parking demand data of 8 days and tested by using the model to predict the demand for the final day. They found a high predictive accuracy when using this model. They suggest further developing this model by adding additional factors such as weather conditions. This model cannot be used in the same way for long-term predictions and, therefore, also not to determine policy effects.

Rietveld and Koetse (2008) used demand forecasting to determine the effect of policy changes, in this case, the effect of parking fees on the retail sector. To do so, a fixed effects model was used. This model allows for the input of several explanatory variables to be used in the forecasting of retail demand. The study showed that shopping behaviour does not necessarily change much when parking fees are introduced, but people are likely to change their parking behaviour or even change their transport mode. In this model, parking demand is not explicitly used. Instead, retail employment is used as an indicator of shopping demand.

### 2.2.3. Behavioural models

Behavioural models focus on the underlying choices and resulting behaviour of individuals in parking situations, rather than the general outcomes of this behaviour. These models provide insights into the decision-making processes of drivers, which can be crucial for understanding and improving parking policy. For instance, the study by Levy et al. (2013) developed an agent-based model to predict cruising behaviour of drivers searching for parking. The study found that higher occupancy rates lead to increased cruising. By examining the problem at an individual level, this model offers new insights compared to those that consider the overall situation.

Similarly, Lim et al. (2017) used an assignment model to predict parking locations based on pricing, land use changes, and parking supply. This model provides a deeper understanding of the trade-offs drivers make between different parking options. Another notable model is the PARKAGENT model introduced by Benenson et al. (2008), which determines parking choice behaviour at the individual driver level. The model predicts where drivers will park as they approach their destination, offering a detailed view of parking decisions.

Leclercq et al. (2017) takes it a step further and created and combined two models: a trip-based formulation of a Macroscopic Fundamental Diagram (MFD) model, which they extend with a distance-to-park model. The MFD model accounts for congested driving by calculating average speeds based on the amount of searching traffic. This is combined with the distance-to-park model, which considers parking occupancy, mean time, and distance to park. Calibrated on Lyon, France, the goal is to investigate the relationship between mean travel distance to park and parking occupancy, considering that parking isn't allowed everywhere.

Expanding the scope to include the transport network, Van der Tuin et al. (2021) describes the Urban

Tools Next II project, which aims to incorporate the effects of parking on the transport network. Special parking and walking links are added to the network, combined with a new travel time function to determine the best route, including parking and walking to the final destination. This model requires knowledge of the location and capacity of parking facilities, but there is no comprehensive database for all parking spaces in Dutch cities. The paper also outlines a method to estimate parking supply based on general datasets, highlighting the challenges of integrating parking data into broader transport models.

Finally, in the Netherlands, the Landelijk Model Systeem Verkeer en Vervoer (LMS) is used to predict transportation behaviour. The documentation PARK (2024) explains how parking choice behaviour is included in the LMS. It assumes parking demand and supply are known for each area, assigning demand to supply using the Method of Successive Averages (MSA) with all-or-nothing assignment. This method considers search time, walking time, and parking fees as costs. Demand can be allocated to any area within 15 minutes walking distance from the destination. Any remaining unassigned demand is allocated to a dummy area. However, since this is documentation of a used programme, rather than a scientific paper, the model's validation and the substantiation of its assumptions are not detailed, making its accuracy uncertain.

#### 2.2.4. Conclusion

Multiple attempts at the creation and development of parking models have been made, with the research increasing over the past decade. Especially machine learning techniques are increasingly applied. However, most of these models focus on one or a few aspects of parking or parking behaviour, usually ignoring the way parking demand may be influenced by parking supply. Some of the models confirmed what the studies on parking policy also showed, namely that parking behaviour is very context-dependent and is influenced by many different factors. Behavioural models can be very useful to try to understand how parking choices are made and, therefore, determine which factors play a role.

### 2.3. Parking behaviour

Both the studies on parking policy, as well as many of the studies on parking models, look at factors influencing parking behaviour. Additionally, several studies have specifically looked at the most important factors that determine this parking behaviour.

Khaliq et al. (2017) specifically studies parking behaviour to improve the aforementioned PARKAGENT model by Benenson et al. (2008). The study assumes that parking behaviour is based on utility maximisation and therefore uses discrete choice modelling to determine the factors influencing this behaviour. They show that the characteristics of a street strongly influence whether or not someone chooses to park there. These characteristics include factors such as occupancy, security, parking fees and walking distance. The choice of characteristics is based on the results of earlier studies into factors influencing parking behaviour. The researchers do not describe how the choice experiment was set up or who the respondents were, making it difficult to determine in what situation the results of the research can be applied.

One of the studies used by Khaliq et al. (2017) to determine what characteristics to include in their choice model, is the study by Chaniotakis and Pel (2015), mentioned before. A follow-up of that research is the research from Pel and Chaniotakis (2017). In this study, the researchers focus on the route taken when searching for parking. The route choice is again based on utility maximisation, which in this case uses the results from the earlier study to determine the utility specification. They show that parking location choice mainly depends on access time, parking fees, and walking distance. Access time refers to the same concept as the earlier discussed search time, the time it takes from arrival at the target destination until a parking spot is found. This confirms some of the factors mentioned by Khaliq et al. (2017). The two studies by Chaniotakis and Pel elaborate more on the method used to find the results and how the results were validated. This makes these studies more reliable than the study from Khaliq et al. (2017). Therefore, these factors will form the basis for the resistance function designed in this thesis.

## 2.4. Transport models

Within the identified existing parking models, no models were identified that can fully solve the challenges experienced by municipalities. Some of the parking models provide aspects that can be applied to solve some of the problems. Similarly, there may be non-parking models within the transport domain that may provide additional applicable aspects. Parts of the model designed in this research are inspired by the concepts used in the classic 4-stage transport model, often used in traffic modelling to determine traffic flows. The relevant parts of this 4-stage transport model will be described below.

### 2.4.1. Classic 4-stage transport model

A regularly used model in transport modelling, is the so-called 4-stage transport model. As the name suggests, this model uses four stages to predict the transport flows in a network. The four stages are: trip generation, trip distribution, modal split and trip assignment. The model allows for the possibility of changing the order of some of the steps or iterating back and forth between some steps. The details and different options of this 4-stage model are outlined in the book by Ortúzar and Willumsen (2011). The input of this model is a network of the roads in the area linking different zones together. It then starts with the trip generation step, where for each zone an estimation is made of the number of trips it generates and attracts based on its characteristics. These characteristics focus on what is present in the zone, such as shopping, housing, or education. Once this stage is complete, the trip distribution stage starts. In the trip distribution stage, the generated trips and attracted trips are linked, forming origin-destination pairs. These origin-destination pairs are brought together in an origin-destination matrix (OD matrix), indicating exactly how many trips go from any zone to any other zone. The trips in the OD matrix are then distributed across the different possible transport modes in the 'modal split' stage. Finally, the assignment stage starts. In the assignment stage, the trips from the OD matrix are assigned to the network. This is usually done based on the principle of least-cost, where the cost of a route may depend on multiple factors such as travel time or travel distance. This stage is the stage most relevant for the model to be developed. Therefore, the process underlying the assignment stage will be discussed more thoroughly.

#### Traffic assignment

The final stage of the 4-stage transport model, traffic assignment, forms the basis for the parking model developed in this thesis. The book by Ortúzar and Willumsen (2011) discusses the assignment step at length, discussing the several options available for execution. The basis for the assignment is the assumption that travellers will always take the best route. There are several possible approaches, depending on what is and what is not taken into account. The choices to be made are:

- with or without a capacity constraint;
- a single user class or multiple user classes, indicating whether there is a difference in objective between travellers;
- including or excluding stochastic effects, indicating whether the travellers all have the same route preferences.

Since this thesis focuses on creating a framework for a parking model with very limited available data, a single user class without stochastic effects will be used. To get the additional accuracy that the other options could provide, more testing and validation are required, which is outside the scope of this research. As will be discussed in section 3.2, the model should be able to take into account and output the parking occupancy in areas. The parking occupancy in an area is an indication of the percentage of parking spaces that are occupied. This requires knowledge about the number of occupied parking spaces, as well as the total number of parking spaces. Additionally, this means that the model should be able to take into account the capacity of each area.

According to Ortúzar and Willumsen (2011), a single user class, without stochastic effects, and with a capacity constraint, is known as the Deterministic User Equilibrium (DUE) assignment. This means that traffic assignment should take place according to Wardrop's equilibrium. Wardrop's equilibrium states the following:

**Definition (Wardrop's Equilibrium).** *All travellers choose their optimal route, such that no traveller can improve their travel time by unilaterally changing routes.*

According to Ortúzar and Willumsen (2011), this equilibrium can be found using an iterative process. In this process, there are several possibilities to determine the current assignment based on the auxiliary assignment in each iteration. It has been shown that the method of successive averages converges to Wardrop's equilibrium. The iterative process using the method of successive averages works as follows:

1. Initialise process. Set all flows to 0 and determine initial costs based on this.
2. Compute the shortest path for every origin-destination pair.
3. Determine auxiliary assignment by assigning the demand all-or-nothing to the shortest paths.
4. Calculate current assignment using method of successive averages:

$$\text{current assignment} = \text{previous assignment} + \frac{1}{n}(\text{auxiliary assignment} - \text{previous assignment}).$$

5. Check against convergence criteria. Either stop or update costs and repeat from step 2.

## 2.5. Conclusion

A brief overview of the existing research in the field of parking policy and parking demand prediction was given. In general, the amount of research in the field has increased a lot in the past few years. However, there are still many aspects in which additional research is required.

In the case of parking policy and its effect on parking demand and parking behaviour, the focus of the literature is mainly on the effects of paid parking on parking behaviour. Even then, the results of these studies vary greatly. Additionally, several studies have been conducted into the effect of parking supply on parking behaviour. For most other parking policies, research is scarce or nonexistent. This provides many possibilities for additional research.

With the increasing development of machine learning models in general, several machine learning models have also been created to forecast parking demand. While many of these have a high predictive accuracy, their process is mostly a black box. This means that even if multiple factors are taken into account, the model makes it impossible to know if and how these factors influence the demand.

Besides machine learning models, several statistical models were studied. Many of these models are based on historical parking data, sometimes combined with some location factors or parking fees. However, even if these factors are included, the models are usually not explanatory, due to which the actual effect of these factors remains unknown.

Finally, some behavioural models were studied. While these models manage to provide more insight into the underlying behaviour guiding parking choices, the factors considered are still the same few that most other research has also focused on. Additionally, most of them ignore many factors that have been shown to influence parking behaviour, creating a simplified version.

The research gap that lies at the centre of this research is the lack of a model that can be used in practice by municipalities or consultants that not only predicts the parking occupancy, but can also be used to explain the effect of policy or area factors on the parking occupancies. Therefore, literature on the underlying factors influencing parking behaviour and related transport models was discussed. In the next chapter, the requirements for a practical model are determined in consultation with consultants and municipality workers. Based on these requirements and the literature just discussed, a new conceptual model is defined.

# 3

## Conceptual Model Development

The goal of this thesis is to design a parking occupancy model that can be used by consultants to answer questions posed by municipalities. In this chapter, the wishes and requirements for such a model are identified using input from consultants and municipality workers. Then, a conceptual model is developed that shows what elements are involved in parking and which elements interact. This conceptual model incorporates these wishes and requirements. First, several conversations and interviews were held with consultants of Antea Group and municipality workers of the municipality of The Hague. These are described in section 3.1, with subsection 3.1.1 discussing the main information from the conversations with consultants, and subsection 3.1.2 discussing the interviews with the municipality of The Hague. This leads to several requirements for the model to be developed, included in section 3.2. The resulting conceptual model is described in section 3.3.

### 3.1. Conversations and Interviews

As discussed in section 1.1, the model requirements are determined based on information from conversations with consultants at Antea Group and interviews with municipality workers at the municipality of The Hague. The goal of these conversations and interviews was not only to determine the requirements for a new parking model, but also to discuss current practices, possible applications, and gaps the model would fill. To reach all these goals, people with various backgrounds and expertise have been consulted.

#### 3.1.1. Conversations Antea Group

This research was done in collaboration with Antea Group. Several conversations were had with various consultants providing information on the current practice and problems based on their experience. Most of these conversations were held in informal ways. Therefore, only the main lessons and points are included.

Municipalities regularly ask Antea Group what the expected effect on the parking occupancy will be of a change in the built environment. This often involves the removal of parking spaces in an area to use the public space for another amenity, such as tram rails or underground waste bins. The effect is usually difficult to determine, in part because the parking supply is not generally available, and there is no tool or model that can be used yet.

In regard to current practices, they noted several points. First, policymakers used to apply strict minimum parking norms that were determined in the same way for every location. However, they are starting to move away from this practice to methods where the number of required parking spaces is more situation-dependent. Their main aim is usually to prevent parking disturbance, which is the reason for applying minimum parking norms. In the new methods, this is, for example, achieved by issuing a maximum number of permits. Additionally, developers want to realise as few parking spaces as possible, because parking spaces are usually not profitable. This results in minimum parking norms often being equal to the number of realised parking spaces. Finally, parking is usually viewed per area,

where parking supply, demand, and occupancy are determined by counting their values at different times of the day. This counting can happen by using scanning cars, similar to checking paid parking, by people counting by hand, or a combination of both.

Antea Group answers questions posed by clients. This means they do not have a full overview of the problems municipalities or policymakers face when it comes to parking. However, it is essential that a new model is able to answer the questions important to municipalities. Regardless of the specific problem, when implementing policies, it is important to look at the group it targets. Different groups have different wants and can therefore be deterred in different ways. Additionally, clients want to understand why specific advice is given. Therefore, it is essential that a new model is explanatory and transparent, such that the arguments leading to an answer can be clearly explained and their logic can be checked.

To answer questions posed by municipalities, Antea Group sometimes uses a parking demand multiple regression model. This model predicts the residential parking demand in an area based on the car ownership, combined with some contextual factors such as functional urbanity, income, and public transport. However, since the main indicator for this model is car ownership, it can only predict the residential parking demand at night, when most people are home. This makes it especially applicable during the development of new residential areas when the number of realised parking spaces has to be determined, but it is less applicable for mixed-use areas, where not all parking demand can be explained by car ownership.

### 3.1.2. Interviews municipality The Hague

From the conversations, it follows that it is important that a new model can be used to answer questions posed by municipalities. Since Antea Group does not have a full overview of the problems municipalities face, three people working at the municipality of The Hague in the Netherlands were interviewed. These interviews provide information on the current practices, common problems, and possibilities of applying a new parking model.

As outlined in section 1.1, the interviews were conducted using the semi-structured interview technique. All interviews started with some general questions. This was followed by a short explanation of the motivation to design a parking model. Using figures based on fictitious data, the interviewees were given an idea of what the output of a parking model could look like and how differences between two scenarios could be compared. Finally, the interviewees were asked some additional questions regarding the possible applications of such a model.

The three interviewees all have a different role within the municipality of The Hague. Depending on the interviewee's role, the specific goals and questions for the interview were adjusted to best fit the interviewee. For each interview, the role of the interviewee, the goals of the specific interview, and the most important points from the interview are included in Tables 3.1, 3.2 and 3.3. Additionally, full technical summaries of all interviews are included in Appendix B.

**Table 3.1:** Interview response 1

<b>General interview information</b>	
Interview number	1
Job title	Traffic Modeller
Experience	1 year at municipality of The Hague, before that elsewhere
Short job description	Working with and developing a new version of the traffic model V-MRDH. Answering (internal) questions about traffic flows using forecasts.
Interview goals	Determine situations in which models are applied by the municipality. Determine how a parking model would fit in with the methods and tools currently in use. Get their view on the main elements of the conceptual model (supply-demand-resistance-assignment).
<b>Important points</b>	
Traffic model	Traffic flow mainly determined on the basis of social economic factors.

	<p>Traffic model detail smaller than neighbourhoods.</p> <p>Traffic model is mainly used to determine the effect of a change, mainly the difference between not doing anything and making the change.</p>
Parking	<p>Parking is one of the largest issues and a source of complaints from people.</p> <p>Parking problems are extremely local.</p> <p>Important for parking model: Estimate parking occupancy and whether parking was found close by or further away. Keep it transparent.</p>
General	<p>It is important to be able to explain what happens in a model, especially when the results may not be completely correct.</p> <p>Neighbourhoods is the largest level of detail that is still useful. Ideally, try to separate functions of areas.</p> <p>People accept a lot from models as long as you can explain what happens.</p>

Table 3.2: Interview response 2

<b>General interview information</b>	
Interview number	2
Job title	Mobility Advisor
Experience	1-2 years
Short job description	Advising on safety and the parking standard in construction projects, and making use of data (in this regard). In addition, with regard to reports, complaints, and citizen letters within the parking domain, responsible for the areas where paid parking does not apply (paid parking areas is the responsibility of the enforcement organisation).
Interview goals	<p>Determine general need for a parking model.</p> <p>Determine general wishes and requirements for a full parking model.</p> <p>Determine the most important aspects for a basic parking model.</p>
<b>Important points</b>	
Parking	<p>Parking is always a point of discussion. Developers feel they need to create too many parking spaces. Residents feel there are not enough (though this is also often just a feeling).</p> <p>Parking problems can sometimes be so problematic that residents are happy with regulated or paid parking.</p>
Model	<p>Parking model can be useful in both internal and external communication.</p> <p>Important for full model: allow for multiple criteria (change in supply, differentiate type of resident, parking policy).</p> <p>Important for initial model: what does a change in supply mean for the parking occupancy?</p>
General	Policy is mainly a political choice.

Table 3.3: Interview response 3

<b>General interview information</b>	
Interview number	3
Job title	Parking Policy Officer
Experience	15+ years
Short job description	Work on parking policy within the municipality. When and how to implement or adjust policy. Work on long-term parking strategy.

Interview goals	Determine general need for a parking model. Determine general wishes and requirements for a full parking model. Determine current practices in policy making.
<b>Important points</b>	
Parking	The parking norms in The Hague are at the lower end of the CROW bandwidths. This is based on car ownership and the ambition to reduce parking demand. A permit ceiling has been introduced. However, it will take several years before the permit count is actually below this ceiling. Residents are most affected by too high parking occupancies. Most new developments take place in existing districts. To prevent increased parking problems, most parking is realised on private property. Currently under consideration: using company parking at night for resident parking.
Model	Policy plans are easier to achieve if you can show the effect in advance. Main use for a model would be in communication to the council and residents. It is important to include permit location limits.
General	Car sharing may replace several passenger cars in the demand.

## 3.2. Model Requirements

During the conversations and interviews, several wishes and requirements for a parking model were named. Some of these are outside the scope of this research and focused on a further extension of the model. These requirements are in addition to the points outlined in section 1.2, which were also set using input from these conversations and interviews. The wishes and requirements that were named are combined with information from chapter 2. This leads to the following model requirements:

***The model must include the effect of the current parking occupancy.***

Whether an area has parking problems is determined by the parking occupancy in the area. As shown by several studies discussed in the literature review in chapter 2, a high parking occupancy leads to reduced parking demand. From the conversations and interviews, it follows that municipalities are starting to use this concept in their policymaking. Therefore, it is essential that the parking model is able to incorporate this effect in its prediction.

***The model should use a neighbourhood level of detail or smaller.***

According to the municipality, parking problems are very local, often entailing a couple of streets. Therefore, a model using small areas is most useful for the municipality. Data is often gathered at the neighbourhood level, and many policies are also implemented at the neighbourhood level. A larger level of detail than neighbourhoods would make the model difficult to use in practice. Thus, the largest area size the model should use is neighbourhoods, with smaller being preferable.

***The model must be transparent such that the effects of different factors are clear. The model, therefore, cannot use machine learning.***

In the conversations, the importance of being able to explain the model results was emphasised. This ensures that the effect of different factors on the resulting parking occupancy can be seen, and the process can be repeated. Similarly, the municipality interviews showed that the transparency of the model is important in the communication to and acceptance by residents and council members. While there exist machine learning techniques that result in an explanatory model, scepticism about using these was expressed in the conversations and interviews.

### 3.3. Conceptual Model

Using the knowledge gained from the literature research of chapter 2, combined with the information from the informal conversations and the interviews, a conceptual model was created. This model is inspired by both the model from PARK (2024), described in subsection 2.2.3, and the classic 4-stage transport model as described in the book by Ortúzar and Willumsen (2011) and in subsection 2.4.1.

The resulting conceptual model is based on the interaction of supply and demand, combined with the idea of 'cost-minimisation', where costs are not necessarily monetary. To prevent confusion between monetary costs and general costs, this will be further referred to as 'resistance-minimisation'. The combination of these aspects leads to a conceptual model consisting of four steps:

1. Determine parking supply per area;
2. Determine parking demand per area;
3. Determine resistance factors between areas;
4. Assign parking demand to parking supply based on resistance-minimisation.

Depending on the way parking supply and demand are determined, it is possible to switch the first two steps. An example of how these two may influence each other was mentioned in section 2.1. Inci et al. (2015) and CROW (2017) showed that parking demand is influenced by parking supply via the parking pressure, or occupancy, in an area. Inci et al. (2015) showed that as soon as the parking occupancy reaches 85%, the additional demand is lower than it would have been with a higher supply. This means that for any area with a parking occupancy of at least 85%, there exists an unknown amount of latent demand that may need to be taken into account, depending on the goal of the forecast. As will be described in the following chapter, in this research, the parking supply and parking demand will be determined independently of each other. Therefore, the above-mentioned order will be used.

The first three steps are built up of several factors, which, when combined, form the supply, demand, or resistance. The final step, the assignment, is a seven-step algorithm, based on the assignment step of the 4-step transport model.

The theoretical parking supply, parking demand, and parking resistance are often not the same as the actual parking supply, parking demand, and parking resistance. As discussed in chapter 2, all of these can be influenced by the implementation of different policies. Additionally, they may also depend on the context of an area, such as the socio-economic factors describing the residents or visitors, the size of the city, the number of tourists in the city, or the time of year.

An overview of the resulting conceptual model is included in Figure 3.1.

### 3.4. Conclusion

The requirements for the model are set in consultation with the municipality of The Hague and Antea Group. The most important requirements are that the model needs to be transparent, include the effect of the current parking occupancy, and should use a level of detail of neighbourhoods or smaller. Based on these requirements and using the knowledge from the literature review, a conceptual model is created. The model uses the dynamics between parking supply and parking demand, combined with the concept of least resistance, to determine the parking assignment.

To be able to use the model, the conceptual model needs to be operationalised. This is done based on the available data and techniques. Operationalisation of the model requires several choices and assumptions to be made. The process of developing an operational model based on the conceptual model is described in chapter 4. This chapter will also further describe what each part of the model entails.

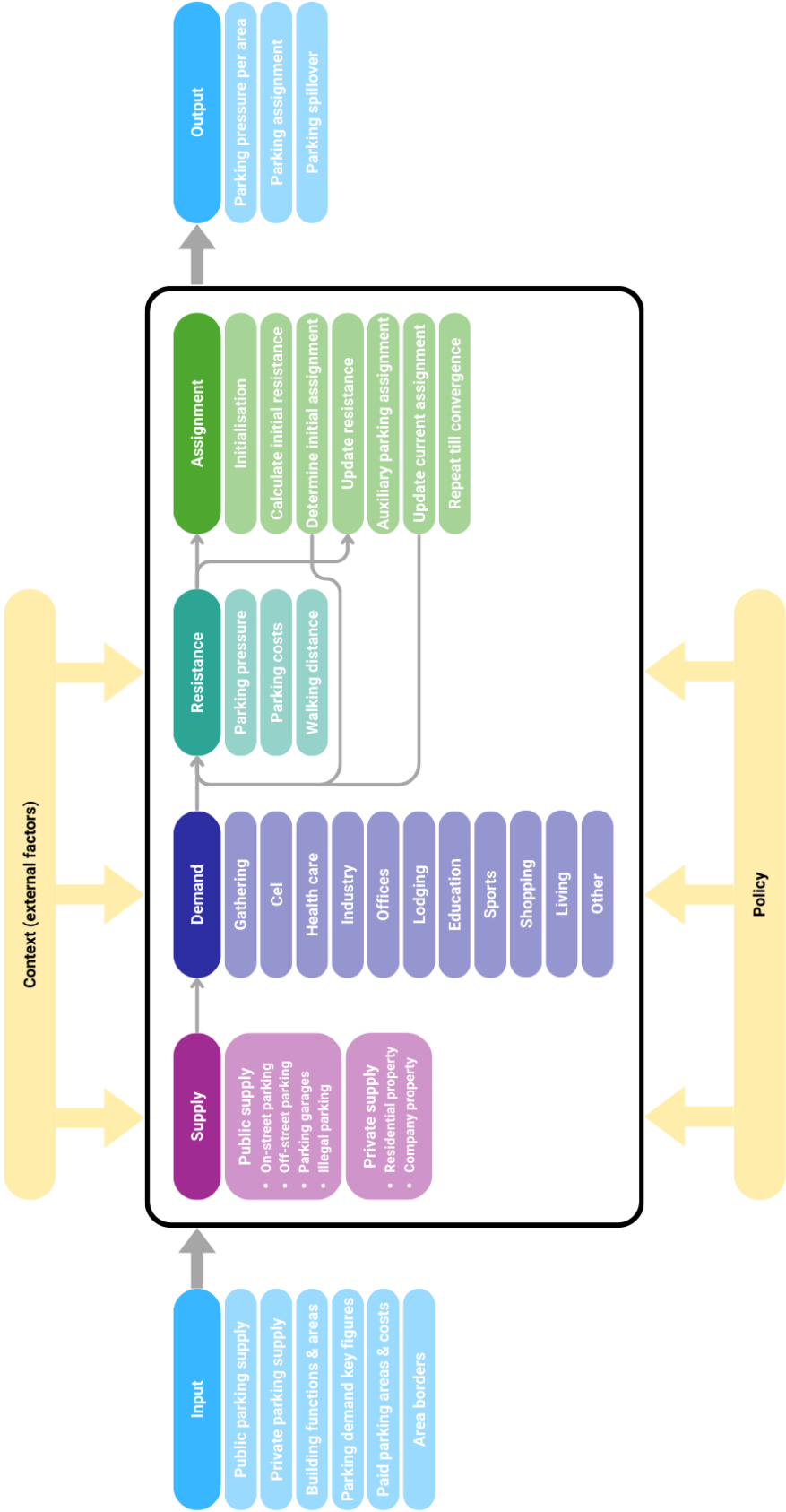


Figure 3.1: Conceptual model

# 4

## Operational Model Development

The conceptual model, as developed in chapter 3 and defined in Figure 3.1, is operationalised by determining for each step (supply, demand, resistance, assignment) what datasets and techniques are available to realise the step. Due to the limited existence of parking data and the limited knowledge of parking policy effects, some steps must be simplified by leaving out some categories or replacing them with a rough estimate. This chapter outlines how each step is constructed from the existing datasets and techniques, and how the resulting operational model works. It starts in section 4.1 with an overview of the general availability of parking-related data. This is followed in section 4.2 with a description of the construction of the parking supply based on several data sources. Section 4.3 then outlines how the parking demand for each area is determined. The calculation of the resistance factors for each area is explained in section 4.4. All stages of the operational model then come together in section 4.5, the assignment stage. Finally, section 4.6 gives the main conclusions of this chapter.

### 4.1. Data availability

To operationalise the conceptual model, several simplifications have to be made. This is due to the limited availability of parking-related data in the Netherlands. Especially the operationalisation of the supply and demand steps largely depends on the available data. Most municipalities in the Netherlands do not know how many parking spaces they have, nor exactly where they are located. The precise extent to what is and is not known about the parking supply, depends on the specific municipality. Generally, the knowledge will be more extensive for paid parking areas than for free public parking, which is more extensive than private parking.

Similarly, the actual parking demand for an area is unknown. Most municipalities will count the realised parking demand from time to time. However, the realised demand for an area often differs from the actual demand. The realised demand considers spillover parking from surrounding areas to be demand for the area itself. In the same way, spillover parking in surrounding areas will not be counted as part of the demand. Additionally, as shown in the literature review of chapter 2, areas with a parking occupancy higher than 85% result in latent demand. This latent demand is also not included in the counted realised demand. Therefore, the actual demand may be higher or lower than the realised demand, depending on the area (CROW, 2017, 2024; Kansen et al., 2018).

The parking supply and demand are estimated by combining multiple datasets and estimating their subcategories separately. For some of the supply or demand categories, several options are available. In those cases, the different options are weighed and the best option is chosen. What makes something the best choice depends on the specific case. Generally, the available datasets can be divided into large national datasets, containing information for all municipalities, and small regional datasets, containing information for one or a few municipalities. When national datasets are used, they are used in the same way for all municipalities. Meanwhile, the availability and usage of regional datasets will differ per municipality.

The large national datasets considered in this research are:

- **Basisregistratie Adressen en Gebouwen (BAG)** - The Dutch national database containing the exact location and address of all buildings in the Netherlands. For each building, its surface area is indicated. All buildings are assigned a function from the following list: *bijeenkomstfunctie* (gathering function), *celfunctie* (cell function), *gezondheidszorgfunctie* (healthcare function), *industriefunctie* (industrial function), *kantoorfunctie* (office function), *logiesfunctie* (lodging function), *onderwijsfunctie* (education function), *sportfunctie* (sports function), *winkelfunctie* (shopping function), *woonfunctie* (living function), and *overige gebruiksfunctie* (other usage function). It is possible for a building to be assigned multiple functions. In that case, the dataset does not indicate the building's primary function, or what percentage or surface area of the building is dedicated to each function (BAG, 2025; Kadaster, 2018).
- **Basisregistratie Grootchalige Topografie (BGT)** - An official topographical map of the Netherlands containing all buildings, roads, waterways, and greenery. The BGT links data to the different objects, allowing it to be used in various ways. Most data included in the BGT is provided by municipalities, provinces, and water authorities, meaning that the extensiveness and accuracy may not be consistent throughout the entire country. With regard to parking, it contains some of the parking supply in municipalities. It does not contain private parking, nor does it contain all public parking. For the parking included, it is only indicated that a location has official parking spaces and the total surface area for these parking spaces. It does not contain explicit parking capacities (BGT, 2025).
- **Centraal Bureau voor de Statistiek (CBS)** - The CBS is the Dutch bureau of statistics. They gather data on many aspects of society. A lot of this data is publicly available in published datasets. While there is no data on parking specifically, there is always the possibility of finding insightful data from the CBS (CBS, 2025c).
- **Nationaal Wegenbestand (NWB)** - A national database containing all public roads in the Netherlands. These are all roads with a street name or road number that are owned by the state, provinces, municipalities, or water authorities. It combines information from several databases, such as the BAG and the BGT. Municipalities, provinces, and road authorities also provide the database with information. The included information on parking comes from the BGT and is therefore similar to the information in the BGT. It contains indicated parking areas with their total surface area, no parking capacities (NWB, 2025).
- **Publication 744 from the CROW** - The CROW is the Dutch knowledge centre for infrastructure, public space, and traffic and transport. Among other things, they publish design guidelines for projects within these categories. One of these published guidelines is publication 744: *Parkeercijfers 2024*. This publication contains key figures indicating the expected parking demand range generated by a location based on its function and size. These key figures are further differentiated based on the urbanity of the area. The key figures can be differentiated by time of day by multiplying them by the attendance percentages per time of day (workday morning, workday afternoon, workday evening, workday night, *koopavond*, Friday afternoon, Friday evening, Saturday afternoon, Saturday evening, Sunday afternoon) included in the same publication. The goal of these attendance percentages is to determine if and to what extent double usage of parking spaces is possible (CROW, 2024; Rijksoverheid, n.d.).
- **Publications from the Dienst Wegverkeer (RDW)** - The RDW is the organisation responsible for the correct registration of all motor vehicles and driver's licences in the Netherlands. Due to this responsibility, they collect driving- and car-related data. Some of this is classified as open data and publicly available on their website. Among these open datasets is also some data on parking areas (RDW, 2025).

Besides these national databases, many municipalities have regional databases that can provide valuable insights. However, these differ strongly per municipality, and were searched for specific information in this research. Therefore, the availability and use of these databases will be discussed in the description of the operationalisation of the relevant part of the conceptual model. The following sections will describe how each part of the conceptual model is operationalised, based on the available datasets and techniques.

## 4.2. Parking supply

Based on the conceptual model in Figure 3.1, the first step is to determine the parking supply per area. This can be divided into two main categories: public supply and private supply, as shown in Figure 4.1. The public supply consists of on-street parking, off-street parking, parking garages, and illegal parking. The private parking supply consists of residential parking on private property and company parking on private property. As mentioned in section 1.2, this research assumes that all parking places are available to everyone. Therefore, private parking supply is assumed to be available to the public. This means that the total parking supply per area does not distinguish between public and private supply any more.

Municipalities in the Netherlands generally do not have an overview of the entire parking supply in their municipality. The availability of data or estimation techniques depend on the specific supply category considered. Therefore, the parking supply will be estimated by determining the best estimation technique for each category and combining the resulting estimates. The following subsections discuss the possible ways of estimating or determining the parking supply in each category.



Figure 4.1: Parking supply categories

### 4.2.1. On-street parking

The most generally visible and available type of parking is the on-street parking supply. As the name suggests, this includes all public parking spaces that are immediately accessible from the street. It consists of free parking and paid parking along the street. Parking sites, for which one first has to turn off the street onto the site to then find a parking spot, are not included in this category.

There are two options available to estimate the on-street parking supply in a municipality. The first option is to use a combination of some of the national datasets described above. The second option is to use a local dataset provided by the municipality.

From the national databases described above, the NWB can be used. This includes the parking areas from the BGT. These parking areas are planes with a location and total area. This means that for a street with parking along its entire length, this will be one plane with the total area available for parking. Therefore, to use this data, an estimation would have to be made of how many parking places each plane will contain. Since not every parking place has the same dimensions, these predictions are likely to deviate from the actual situation. Additionally, the information for these maps is based on information provided by municipalities. Not every municipality measures this the same way, meaning that the completeness and accuracy depend on the municipality in question.

The second option is to use a local dataset provided by the municipality. Many municipalities have some overview of the on-street parking supply. The accuracy and completeness of this overview will differ per municipality. Usually, the use of scanning cars for enforcement in paid parking areas requires a dataset saying whether a street contains on-street parking. However, the scanning cars do not need to know the exact location of each parking spot, nor the number of parking spots. This is therefore not always included in those datasets. Additionally, whether the dataset only includes on-street parking in paid parking areas, or also includes on-street parking in free parking areas will depend on the municipality.

Several of the municipalities of the larger cities in the Netherlands provide open source datasets. In multiple cases, these datasets include a set containing the parking places in the municipality. While this is likely to be the same data as they provided to the BGT, it is often more detailed. These datasets frequently contain the number of parking spaces for each parking plane instead of only the surface area. This eliminates the need for estimating the capacity of each plane based on its surface area (Gemeente Amsterdam, 2025; Gemeente Den Haag, 2025c; Gemeente Eindhoven, 2025; Gemeente Groningen, 2025).

The local datasets are generally at least as accurate and complete as the national dataset, and sometimes more detailed. Thus, the local datasets provided directly by the municipalities should be used whenever these are available.

**Choice.** *When available, use the local datasets provided directly by the municipality.*

#### 4.2.2. Off-street parking sites

The category of off-street parking sites refers to any publicly available parking area, for which cars have to turn off the street to access them. Examples are parking sites near shopping centres, supermarkets, and sports fields. Off-street parking sites can be paid parking as well as free parking. However, as will be seen in subsection 4.2.3, most datasets on parking garages also include paid parking off-street parking sites. Therefore, any off-street parking site with paid parking is treated as a parking garage.

**Assumption.** *Any off-street parking site with paid parking is treated as a parking garage.*

For the free off-street parking sites, several options were considered to determine their existence and capacity. One option seemed to be the open dataset of the RDW called ‘specifications parking area’ (RDW, 2025). This dataset should contain the capacities of the parking sites and garages in the Netherlands. However, as was seen during the case study in section 5.1, this dataset only includes paid parking sites and garages.

Another considered option is to estimate the off-street parking sites using the BGT. However, many sites are not included in the BGT. Additionally, it only gives the site’s surface area, which, depending on the site, can be the entire site, only the parking spots, or only the driving part. This makes it difficult to accurately estimate the capacity and existence of off-street parking sites. (BGT, 2025)

Since neither option accurately estimates the existence and capacity of off-street parking sites, they were not included in the model. This results in a slightly lower total parking supply than in reality. Depending on the estimation results for the other categories, a compensation factor may need to be applied.

**Choice.** *Free off-street parking sites are not included in the model.*

#### 4.2.3. Parking Garages

As mentioned above, off-street parking sites with paid parking are treated as parking garages. Therefore, parking garages are seen as any public off-street parking site with paid parking, both indoor and outdoor.

To determine the location and capacity of the parking garages, first, the national databases were considered. However, the BGT does not include indoor parking garages, and the BAG also does not include parking garages as a specific category (BAG, 2025; BGT, 2025).

The second option considered is to use local datasets. Many municipality websites have a list of most parking garages within the municipality. These often also include the outside paid parking sites, which drives the choice to consider these within the parking garages category. Depending on the municipality and the garage owner, these lists often also include the capacity of the parking garage and the payment regulations. Using the garage addresses, they can be linked to the area they are located in. These lists are not always entirely complete, and they may not always contain all capacities. However, no other databases containing parking garages were identified, making this the most accurate option.

**Choice.** *The existence, location, and capacity of garages must be provided by the municipality.*

#### 4.2.4. Illegal parking

Illegal parking can be defined as parking in a way that is not allowed. Dutch law distinguishes not paying the required fee from all other types of illegal parking. However, this research considers illegal parking as a part of the parking supply. Therefore, a different division is used. Illegal parking can then roughly be divided into two main types.

The first type is parking in an official parking spot without meeting the requirements to park there. This can, for example, be by not paying in a paid parking area, not having the right permit, or parking outside the allowed time frame. This option does not increase the parking supply, but may influence the interaction between parking supply and demand. However, this requires splitting parking supply and demand into separate target groups, which is outside the scope of this research.

The second type of illegal parking is cars parking outside official parking spots. While this is not allowed,

it does lower the remaining parking demand slightly and can therefore, in a way, be seen as additional parking supply. However, there is no general data available on when and where this happens. There are studies (Mingardo, 2016) that suggest this happens more in areas where the parking occupancy is high, but there are no clear numbers to use as additional parking supply. Therefore, illegal parking is not included in this model.

**Choice.** *Additional supply due to illegal parking is not included in the model.*

#### 4.2.5. Residential parking on private property

As was outlined in the previous sections, the available data for public parking is scarce. For private parking, however, it is close to non-existent. Residential parking on private property (in Dutch: POET, Parkeren Op Eigen Terrein) refers to any parking spot that can only be used by the residents of the building and, sometimes, their visitors. This includes driveways of houses, small house garages, and most parking sites or garages in apartment complexes. No data sources were found that provide insights into which houses have private parking or how much private parking there is in a city, district, or neighbourhood. Therefore, several estimation techniques were considered.

One option to estimate the amount of residential parking on private property is by the method described by Snelder et al. (2021). In this research, a method is described where the availability of residential parking on private property is estimated based on the available space around the house. This method determines the area of the property without buildings. If this area is large enough, it is assumed the property has a driveway. This gives a rough estimate, not taking into account whether or not it is possible to access the street from the property. The accuracy of the method has not yet been determined.

Another option is to use a general estimation of the amount of residential parking on private property. In their research, Ostermeijer et al. (2019) investigate the influence of residential parking costs on car ownership. As part of their research, they also used data from the Dutch Association of Real Estate Agents (NVM) and the Building Characteristics Netherlands (GKN). Based on this data, they conclude that in the Netherlands approximately 20% of residential properties owns a private off-street parking spot. They only considered single-family homes. Additionally, this percentage is not differentiated based on the characteristics of the area considered. In reality, it is likely that in the city centre, fewer properties will have a private driveway than in the suburbs. Furthermore, the percentage will not be the same for all places in the Netherlands, making this a very general percentage. However, for an initial general estimate, and due to the lack of more detailed data, it can be used.

**Assumption.** *Approximately 20% of residential properties in the Netherlands owns a private off-street parking spot.*

Based on the information above, neither method gives a very accurate estimate. The first method takes available space into account, but has not been validated. Therefore, it is unknown how the estimate differs from the actual situation and whether it is higher or lower. At the same time, it is a complex method to implement, requiring the combination of four sources of input data. The second method will give a supply that is likely slightly too high in the city centre, and slightly too low in the outer suburbs. The total supply generated by this method is likely close to the actual supply. Additionally, it is easy to implement. Since this thesis aims to develop and test a framework for a parking occupancy model, the rough estimate of 20% will be used. This percentage is combined with data from the BAG. While the estimate was made by only considering single-family homes, for the model, all buildings with the function 'living (wonen)' from the BAG were used. This is done as a way to take into account that apartment complexes also often have private parking sites. In this way, at least some of this parking is also taken into account.

**Choice.** *To account for residential parking on private property, for each area, 20% of buildings with the function 'living' in the BAG are assumed to have a private parking place.*

#### 4.2.6. Company parking on private property

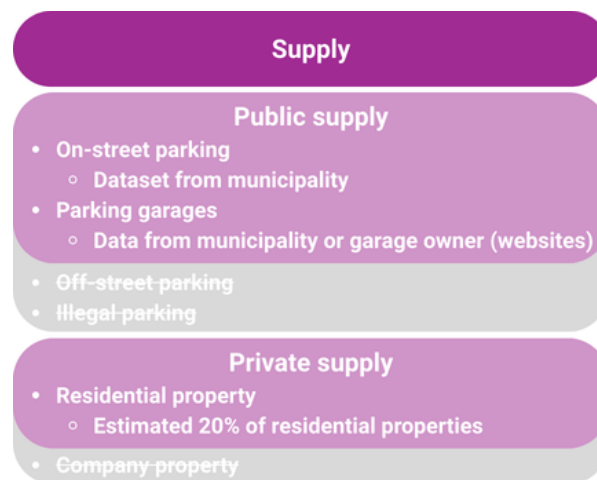
Many office buildings, warehouses, and factories have parking sites to ensure their employees can park near their place of work. Unfortunately, no data sources, methods, or estimates were found to determine the location and capacity of these parking sites. Therefore, company parking on private property is not included in the model. This results in a lower estimated total parking supply than in

reality. Therefore, as will be described below, the demand generated by offices will also be excluded from the model.

**Choice.** *Company parking on private property is not included in the model.*

#### 4.2.7. Total parking supply

The total parking supply per area is the sum of the categories described above. For completeness, Figure 4.2 shows the build-up of the parking supply with the categories that were not included greyed out. Since not all categories could be included, this total parking supply will likely be lower than the real parking supply. Especially the exclusion of the free off-street parking will result in lower supply for certain areas, while not influencing other areas. In some areas, this might be compensated for by the private residential supply. However, it is impossible to say for which specific areas the calculated supply is lower than the actual supply. Similarly, there might be areas where the calculated supply is higher than the real supply, but which areas those are cannot be said. Nevertheless, the main categories of parking supply are included, making it likely that the calculated supply is close to the actual supply in most areas.



**Figure 4.2:** Parking supply in operational model

### 4.3. Parking demand

Once the parking supply for each area is determined, the next step in the conceptual model of Figure 3.1 is the parking demand. The parking demand in an area depends on the built environment of the area. Kansen et al. (2018) discusses several factors influencing the parking demand in an area. According to them, the parking demand is mainly determined by the car ownership in an area and the generated mobility in the area. Which, in turn, depend on the built environment and amenities. To determine how much parking is needed in an area, municipalities often use the key figures as published in CROW (2024). This publication also confirms the dependency of parking demand on spatial factors and the availability of amenities. These key figures are subdivided into categories, where the size present of each category determines how much parking demand the category generates. However, the CROW categories are very specific, which can make them difficult to apply to existing areas, where the available information on the buildings is often less than in the case of construction areas. Therefore, to determine the parking demand for the model in this research, the categories from the BAG are used. Contrary to the CROW categories, the BAG categories and their size are available for existing areas. An overview of the categories determining parking demand as used in this model can be found in Figure 4.3.

As discussed in section 4.1, there is no direct data on parking demand per area. This is because only the realised demand can be measured. The realised demand is already influenced by the policy measures active in the area and on the parking occupancy in the area. It ignores the latent demand and counts spillover demand from surrounding areas as demand for the considered area (CROW, 2017, 2024; Kansen et al., 2018).

There are several options to determine the parking demand per area. The first option is to determine the current realised demand by actual counting. Municipalities already do this from time to time to determine the parking occupancy in areas where there may be parking problems. However, since parking demand is not constant over time, counting needs to happen at several different moments to paint the most accurate picture of the realised demand. As discussed, this determines the resulting demand or final assignment, rather than the original demand.

A second option to determine parking demand is to look at car ownership. As mentioned in Kansen et al. (2018), parking demand strongly depends on car ownership. Especially in residential areas, car ownership is a good indicator of the total parking demand for the area. At night and in the weekends, most cars are parked at the residence of the owner. However, during the day, or in areas with a large share of non-residential buildings, this cannot be directly used.

**Assumption.** *In residential areas, parking demand strongly depends on car ownership.*

A third option is using the key figures of CROW (2024) as an indicator of demand. The advantage of this is that it gives an indication of the parking demand for both residential and non-residential areas, and can be used for all times of the day. However, the CROW publication is not transparent about the way these figures are determined. Additionally, people in the field often consider these figures to be high, which is also confirmed by one of the interviews included in Appendix B and in the report of Kansen et al. (2018). This is mainly due to these figures being designed as minimum requirements to prevent parking problems in the area. They have to be higher than the expected demand to do so.

**Assumption.** *The key figures published by the CROW for minimum parking requirements are higher than the parking demand in the same area.*

Finally, a separate model could be created that is able to predict the parking demand per area, which may use any of the above techniques. This allows for a better calibration and more accurate prediction for future scenarios. Additionally, it allows for more possibilities for the inclusion of the direct effects of both policy and context factors on the parking demand. This is outside the scope of this current research, but may be considered as a possible future addition.

Thus, car ownership gives the most accurate estimation for the parking demand generated by residential buildings. While slightly too high, the CROW key figures give the most accurate prediction for the non-residential parking demand. Therefore, to operationalise this model, a combination of these options is used. The car ownership figures are used to determine the residential parking demand for each neighbourhood. The CROW figures are then used to determine the remaining demand per neighbourhood. The resulting estimates are the maximum demands generated by each category. As described in section 4.1, the CROW publication also contains attendance percentages. These attendance percentages indicate for each part of the day (workday morning, workday afternoon, workday evening, workday night, *koopavond*, Friday afternoon, Friday evening, Saturday afternoon, Saturday evening, Sunday afternoon) what percentage of this maximum demand is present. These percentages are applied to both the residential and the non-residential demand to determine the resulting demand per area for the time of day considered.

**Choice.** *Residential parking demand is estimated based on car ownership. The remaining parking demand is estimated using the CROW key figures combined with the BAG. The ratio between the demands from different functions is determined using the attendance percentages from the CROW.*

To be able to use the CROW key figures, the types of buildings in an area need to be known. These can be determined using the BAG. However, the BAG knows a much lower variety of functions than the CROW (Kadaster, 2018). Therefore, each function from the CROW is linked to the function of the BAG it best matches. An overview of which functions were linked can be found in Appendix C. There



Figure 4.3: Parking demand categories

are several CROW functions for which it is noted that the key figures are not very accurate. Therefore, these functions are not included. Additionally, there are some CROW functions for which the key figures are not based on surface area, but instead are based on the number of rooms or the number of people. These functions were also not included. Finally, the BAG function *overige gebruiksfunctie* is filtered out, since these include a lot of buildings that do not generate parking demand, such as transformer stations. This is also included in the overview in Appendix C.

Once each CROW function is matched to a BAG function, the parking demand for that BAG function is calculated as the average of the CROW key figures associated with it. The occurrence of each BAG function within an area is known; however, the distribution of the corresponding CROW functions within each BAG function is not available. As a result, a weighted average of the underlying CROW figures cannot be calculated. Instead, an unweighted average is used, which assumes that all CROW functions within a BAG function category occur equally often.

**Assumption.** *All CROW functions within a BAG function category occur equally often.*

**Assumption.** *The parking demand per BAG function category is the unweighted average of the CROW key figures linked to that category.*

In subsection 4.2.6, the choice was made not to include parking supply from parking on company property. This will mostly relate to parking at offices. Therefore, the parking demand generated by offices is also not taken into account. In the documentation of PARK (2024), a similar choice was made in relation to company parking.

**Choice.** *Demand generated by offices is not taken into account.*

As mentioned, the CROW publication also includes attendance percentages to determine what part of the maximum demand is present at the time of day considered. For these attendance percentages, the CROW differentiates fewer categories than for the key figures. However, there are still more and different categories than in the BAG. Similar to the key figures, each attendance category is linked to a BAG category. An overview of which categories are linked can again be found in Appendix C. Similar to the key figures, the resulting attendance percentage per BAG category is the unweighted average of the underlying CROW categories.

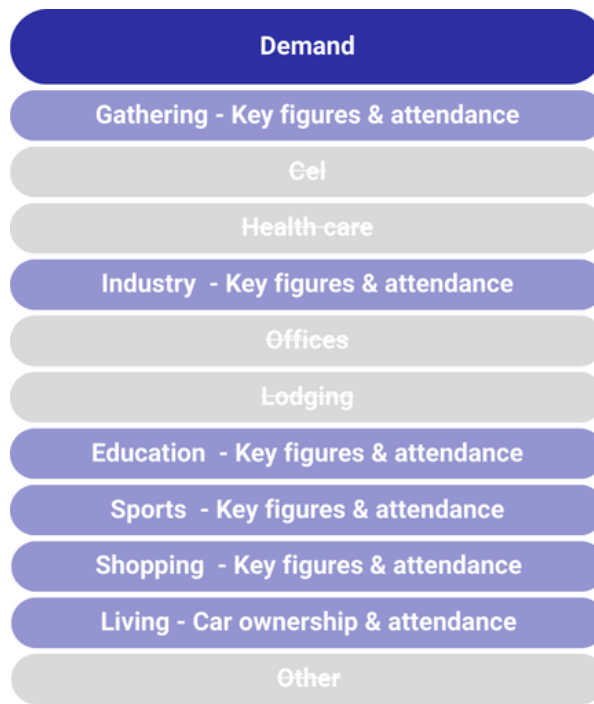
To determine the final total parking demand for an area at the considered time of day, the area of each non-residential building is multiplied by the just determined BAG key figure and the associated attendance percentage. These results are summed. The car ownership of the area is multiplied by the residential attendance percentage at that time of day. The total sum forms the demand in the area at that time of day. This can be displayed by the following formula:

$$D_{ti} = C_i \cdot AP_{t,res} + \sum_{j \in Bb_i} k_j \cdot A_j \cdot AP_{tj}, \quad (4.1)$$

where,

- $D_{ti}$  = Demand in area  $i$  at time of day  $t$ ;
- $C_i$  = Car ownership in area  $i$ ;
- $Bb_i$  = All BAG buildings in area  $i$  that do not have the function 'residential', 'office', or 'other';
- $k_j$  = The BAG key figure belonging to building  $j$ ;
- $A_j$  = The surface area of building  $j$ ;
- $AP_{t,res}$  = Residential attendance percentage at time of day  $t$ ;
- $AP_{tj}$  = Attendance percentage for building  $j$  at time of day  $t$ .

For completeness, an overview of the included and excluded categories and their data source is included in Figure 4.4.



**Figure 4.4:** Parking demand in operational model

## 4.4. Resistance factors

The next step in the conceptual model of Figure 3.1 is the parking resistance. The parking assignment in the model is according to least resistance. This is similar to the traffic assignment in the classic 4-stage transport model, described in subsection 2.4.1 and Ortúzar and Willumsen (2011), and the parking assignment in PARK (2024). To be able to assign parking according to least resistance, a resistance for each area needs to be determined. This resistance is updated in each iteration of the assignment algorithm. As discussed in section 2.3, the research of Pel and Chaniotakis (2017) determined that earlier studies showed parking location choice mainly depends on parking fees, walking distance, and access time. Where parking fees refers to the monetary costs of parking in a certain spot, walking distance refers to the distance between the parking spot and the final destination, and access time refers to the time it takes from arrival at or near the destination until a parking spot is found, this is also known as search time. Other studies also find different factors influencing parking location choice. However, these three factors are found in multiple studies, suggesting that these are the main factors influencing parking choice (chapter 2). Thus, they will be the factors used to determine the parking resistance in this research.

Initially, these factors do not have the same unit; parking fees is monetary, in this case in euros; walking distance is a distance, in this case measured in meters; and access time is a time variable, in this case measured in minutes. To determine the resistance value for an area, these factors need to be measured in the same unit. This can be done using walking speed, to convert walking distance to walking time, and the Value of Travel Time (VTT), which allows for conversion between values measured in time and values measured in euros. The research by Knoope (2023) contains the VTT per mode for travellers in the Netherlands.

In this thesis, the resistance will be measured in minutes of time lost. It is possible that the actual time lost due to a factor is not the same as the experienced time lost. An example of this phenomenon is that people usually prefer travelling 5 minutes longer than having to wait for 5 minutes (Fan et al., 2016). To take this into account, additional weights can be given to the different factors, transforming them from actual time lost to experienced time lost. However, these factors likely depend on additional factors, such as the city, trip purpose, or personal characteristics. To keep the operational model applicable to general situations, and because no direct data is available to determine the difference between actual time lost and experienced time lost, this research will assume that the actual time lost is equal to the

experienced time lost for all three factors.

**Assumption.** For all resistance factors, the actual time lost is equal to the experienced time lost.

The following subsections discuss per factor and for the full resistance function how they are determined and calculated.

#### 4.4.1. Parking fees

Many areas contain both paid parking and free parking. To determine one resistance value for the area at the time of day considered, the average monetary cost of parking in the area is calculated. This is done by calculating the total parking fees of all paid parking places together and dividing the result by the total parking supply in the area.

Usually, parking fees are based on the parking duration. The model developed in this research does not differentiate between trip purposes and does not include time outside the general time of day. Additionally, while the parking demand is determined by summing the demand generated by different categories, the parking assignment only considers the total demand and does not differentiate to these categories any more. Furthermore, no data was found on the difference in parking duration between these categories. Therefore, a general average parking duration will be used as the parking duration for everyone.

In Mingardo et al. (2022), research was done into the use of different pricing strategies on the parking duration of car travellers. In this research, data acquired from ParkMobile transactions in 2018 was used to determine average parking durations in the Netherlands. From this data, they found that the average parking duration for paid parking areas in the Netherlands is 112 minutes. Additionally, they found that for the four large municipalities Amsterdam, Rotterdam, The Hague, and Utrecht, the average parking duration in paid parking areas is 139, 101, 109, and 134 minutes, respectively.

Using this information, the total parking costs per area can be calculated. To do this, the cost of parking for the average duration at the time of day considered for each paid parking spot, both on-street and in garages, is determined. These costs are summed and divided by the total parking supply (free parking and paid parking) in the area. This gives the average parking fee per parking spot in the area.

The calculated average parking fee is a monetary value, and therefore, it has to be converted to a value for the time lost. This is done using the Value of Travel Time (VTT). According to Knoope (2023), the average VTT when travelling by car in the Netherlands is €10.42. Dividing the average parking fee by the VTT gives the average time lost by having to pay for parking in the area.

This can be summarised by the following formula:

$$PT_i = \frac{\sum_{j \in Qp_i} j \cdot c_j \cdot ad}{10.42 Q_i}, \quad (4.2)$$

where,

$PT_i$  = The time lost by having to pay for parking in area  $i$  in minutes;

$Qp_i$  = Paid parking supply in area  $i$ ;

$c_j$  = Parking cost of parking spot  $j$  per hour;

$ad$  = Average parking duration in hours;

$Q_i$  = Total parking supply in area  $i$ .

#### 4.4.2. Walking distance

Parking further away from one's destination leads to a longer walking time and distance from the parking place to the destination. Since the model does not currently factor in the exact destination nor the exact parking place of a traveller, the exact walking distance cannot be determined. Therefore, the walking distance is taken to be zero if the destination and parking space are in the same area  $i$ . If the traveller's destination is in area  $i$ , but they park in area  $j$ , the walking distance is taken as the distance between the centroids of areas  $i$  and  $j$ . The walking time is calculated using an average walking speed of 6 km/hr. This technique is similar to the technique used in PARK (2024).

### 4.4.3. Access time

The final factor influencing the resistance of an area is the access time. The access time, or search time, is defined as the time it takes from arrival at the destination until a parking space is found. The average access time in an area can be linked to the parking occupancy, or parking pressure, in the area. A higher parking occupancy means that there are fewer available parking spaces. This, in turn, means that the time spent searching for a parking place is longer.

The relationship between the parking occupancy and the access time has been determined by Lam et al. (2006) and was also used by Van der Tuin et al. (2021). In their research, Lam et al. (2006) relate parking occupancy to search time using a BPR-curve. The relationship found is:

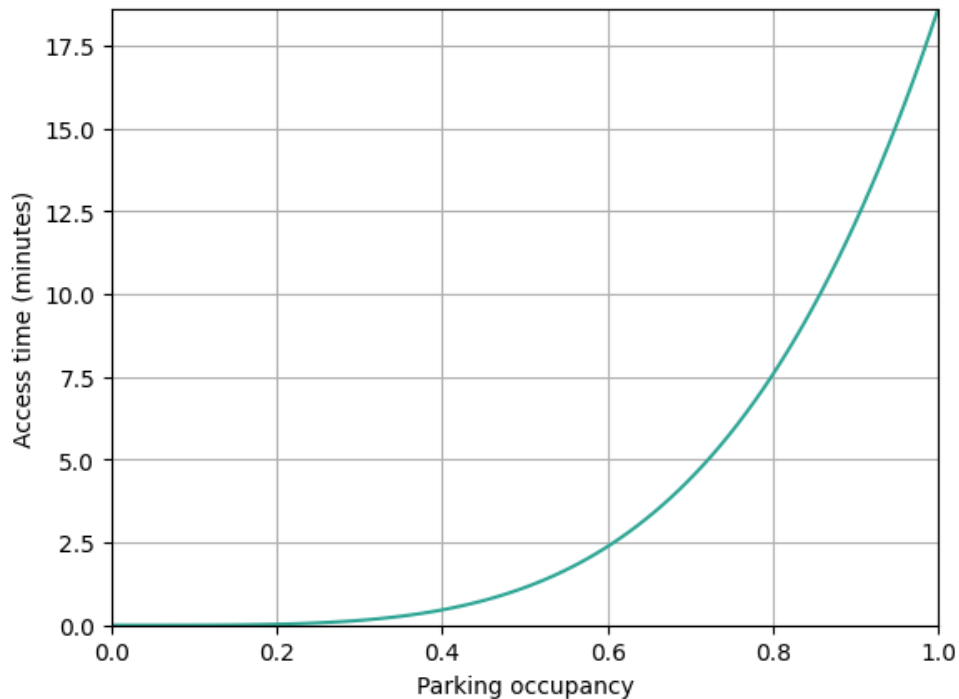
$$STh_i = 0.31 PP_i^{4.03}, \quad (4.3)$$

where  $STh_i$  is the time spent searching in area  $i$ , measured in hours, and  $PP_i$  is the parking occupancy in area  $i$ , calculated by dividing the number of parked cars by the number of available parking spaces. This can be rewritten to determine the search time in minutes, giving the following relationship:

$$ST_i = 18.6 PP_i^{4.03}, \quad (4.4)$$

with  $ST_i$  the search time in minutes for area  $i$ .

Figure 4.5 shows this relationship. As can be seen in this figure, the higher the parking occupancy, the faster the access time increases. As discussed in subsection 2.1.2, Chaniotakis and Pel (2015) showed that drivers find it important to find a parking spot within 8 minutes. From Figure 4.5, the parking occupancy corresponding to a search time of 8 minutes is just over 0.8. Inci et al. (2015) determined that parking occupancies over 85% lead to decreased demand. Therefore, all three of these studies (Chaniotakis & Pel, 2015; Inci et al., 2015; Lam et al., 2006) lead to similar results with regard to the relationship between access time and parking occupancy.



**Figure 4.5:** Relation between the search time in minutes and the parking occupancy in an area

#### 4.4.4. Resistance function

The final resistance factor for an area  $j$  for a traveller with a destination in area  $i$  is then given by the sum of these three factors:

$$TL_{ij} = PT_j + WT_{ij} + ST_j, \quad (4.5)$$

where,

$TL_{ij}$  = The total time lost by parking in minutes;

$PT_j$  = The time lost by having to pay for parking in minutes;

$WT_{ij}$  = The walking time between the areas in minutes;

$ST_j$  = The access time (search time) in minutes.

This resistance factor depends on the parking occupancy in the area. It is therefore not a constant factor, but rather a resistance function. The result of this is that the resistance factors of all areas change after assigning the parking demand to the parking supply according to least resistance. The updated resistance factors would often lead to a different parking assignment. This suggests that the assignment should take place iteratively.

## 4.5. Parking assignment

Once the parking supply, parking demand and resistance factors have been determined, the final step of the parking model is reached: the parking assignment. In this step, the parking demand is assigned to the parking supply based on the principle of least resistance. Since the parking occupancy in an area influences the resistance factors of that area, this cannot be done in one go. This is similar to assigning traffic to the fastest route, where the duration of a route depends on the congestion. Therefore, the design for this step is based on the assignment stage of the 4-stage transport model described in subsection 2.4.1.

In the 4-stage transport model, the goal of the assignment step is to assign the generated origin-destination matrix to the network by assigning everyone to their fastest route. Since the time a route takes depends on the congestion present on that route, and therefore on the amount of traffic already assigned to the route, this is usually done using an iterative process. One common approach is the method of successive averages described in subsection 2.4.1.

A similar approach is used in the assignment of this parking model, with some small adaptations. A dummy area is added with an infinite parking supply. A cut-off resistance is determined and set as a constant resistance for the dummy area. This ensures that demand can never be assigned to an area with higher resistance than this cut-off value. Assignment to the dummy area indicates that the demand is too high to be satisfied, and these people will no longer come to the area by car. This includes both people who will use an alternative form of transportation, as well as people who will not come at all.

There are multiple methods of determining the auxiliary parking assignment. The method that is best for the situation depends on three main factors. The model does not differentiate between different types of travellers, meaning that it entails a single user class. The value of the resistance function is independent of the specific traveller, so the model excludes stochastic effects. Finally, there is a limited supply of parking spaces, so it is a situation with capacity constraints. As described in subsection 2.4.1 and the book of Ortúzar and Willumsen (2011), this means that the auxiliary assignment should be done based on the process of a deterministic user equilibrium (DUE). This is implemented using a simple linear programming model:

$$\min \sum_{i \in I} \sum_{j \in I} x_{ij} \cdot TL_{ij} \quad (4.6)$$

$$s.t. \quad (4.7)$$

$$\sum_{j \in I} x_{ij} = D_i \quad \forall i \in I \quad (4.8)$$

$$\sum_{i \in I} x_{ij} \leq Q_j \quad \forall j \in I \quad (4.9)$$

$$x_{ij} \in \mathbb{N} \quad (4.10)$$

Where,

- $I$  = The set of all areas;
- $TL_{ij}$  = The total time lost by parking in area  $j \in I$  with a destination in area  $i \in I$ ;
- $D_i$  = The total parking demand for area  $i \in I$ ;
- $Q_i$  = The total parking supply in area  $i \in I$ ;
- $x_{ij}$  = Decision variable indicating what demand for location  $i \in I$  is assigned to location  $j \in I$ .

The variable  $TL_{ij}$  in Equation 4.6 corresponds to the same variable in Equation 4.5. Similarly, the variable  $Q_j$  in Equation 4.9 corresponds to the same variable in Equation 4.2. The variable  $D_i$  in Equation 4.8 also corresponds to  $D_{ti}$  in Equation 4.1. The linear program does not include the time variable that was part of the demand function. This is because the program uses a constant demand as input. Once the demand is determined in an earlier step of the model, the time aspect no longer changes and is therefore left out.

This linear programming model ensures that all parking demand is assigned in such a way that the total resistance experienced is minimised. Contrary to traffic modelling, where assignment higher than capacity leads to congestion, parking assignment has a hard capacity limit. This is enforced by Equation 4.9. If it is not possible to assign all demand to the area or an area for which the resistance is lower than the cut-off, the additional demand is assigned to the dummy. Since the dummy has a high resistance and the model minimises the total resistance, this will only happen if there is no other option.

#### 4.5.1. Iterative process

As mentioned before, the parking assignment is done using an iterative process where, after each iteration, the resistance values are updated based on the latest assignment. This process is continued until it converges to Wardrop's equilibrium described in subsection 2.4.1. Some of the terminology of Wardrop's equilibrium has to be interpreted in a different way than in the 4-stage transport model. In the 4-stage transport model, travellers are assigned to routes based on least travel time. Replacing routes by areas and travel time by parking resistance, Wardrop's equilibrium can be applied to the parking assignment.

**Definition (Wardrop's Equilibrium).** *All travellers choose their optimal route (area), such that no traveller can improve their travel time (parking resistance) by unilaterally changing routes (areas).*

To determine whether Wardrop's equilibrium has been reached, at the end of each iteration a stop criterium is checked. If Wardrop's equilibrium is reached, the total resistance should stay equal between assignments. This means that the total resistance in the current assignment should be equal to the total resistance in the auxiliary assignment. Since complete equality can take infinitely many iterations, the stop criterion checks if these two are *almost* equal. This gives the following stop criterion:

$$\frac{\sum_{i,j \in I} x_{ij}^{cur} \cdot TL_{ij} - \sum_{i,j \in I} x_{ij}^{aux} \cdot TL_{ij}}{\sum_{i,j \in I} x_{ij}^{aux} \cdot TL_{ij}} \leq 0.001. \quad (4.11)$$

In this equation,  $x^{cur}$  denotes the current assignment and  $x^{aux}$  denotes the auxiliary assignment, with the remaining variables the same as before.

According to Ortúzar and Willumsen (2011), Wardrop's equilibrium can be reached using the Method of Successive Averages (MSA). This method has the following iterative process:

1. Initialise process. All parking assignment is 0.
2. Calculate initial resistance matrix.
3. Determine initial parking assignment.
4. Update resistance matrix based on current assignment.
5. Determine new auxiliary parking assignment based on updated resistance.

6. Calculate current assignment using

$$\text{current assignment} = \text{previous assignment} + \frac{1}{n}(\text{auxiliary assignment} - \text{previous assignment}),$$

where  $n$  denotes the number of iterations.

7. Determine whether the stop criterion is reached. If the stop criterion is reached, the current assignment is the final assignment. Otherwise, repeat from step 4.

In this process, steps 3 and 5 use the linear programming model above to determine the parking assignment. Step 6 is the reason this process is called the Method of Successive Averages. It ensures that the current assignment is the average of all previous assignments. The  $\frac{1}{n}$  ensures that all assignments count equally. According to Ortúzar and Willumsen (2011), this ensures that the process converges to Wardrop's equilibrium. Finally, the process should stop once convergence is reached. This is checked using the stop criterion from Equation 4.11.

Once the stop criterion is met, meaning Wardrop's equilibrium is reached, the current assignment is the final assignment of the model. For all areas considered, the total number of cars assigned to that area is shown. This can then be used to determine the final parking occupancies for all areas in the considered situation by dividing the number of assigned cars by the parking supply of the area.

## 4.6. Conclusion

The conceptual model of chapter 3 is operationalised based on the available data and techniques for all parts of the model. For the parking supply and demand, several national databases were considered. Additionally, the possibilities for using regional datasets were investigated.

The parking supply consists of on-street parking, off-street parking, garages, illegal parking, residential parking on private property, and company parking on private property. For on-street parking, garages, and paid off-street parking, regional datasets are often available and should be used. No accurate databases were identified for residential parking on private property. However, a study was found showing that 20% of Dutch residential properties have private parking. Therefore, this average percentage can be used in combination with the BAG to estimate the private residential parking supply in each area. No data sources were found to identify the parking supply from free off-street parking, illegal parking, or company parking on private property.

The parking demand consists of residential parking demand and non-residential parking demand. The maximum residential parking demand of an area is determined by the car ownership of the area. The maximum non-residential demand of an area is determined by applying the CROW key figures to the building data from the BAG. These maximum demand numbers are transformed into expected demand for the time of day considered by multiplying them by the applicable attendance percentage from the CROW. Demand generated by offices is excluded to compensate for the excluded company parking supply.

The resistance of an area is influenced by three factors: parking fees, walking distance, and access time. The resistance of an area is measured in minutes of time lost. Therefore, the parking fees need to be converted to time using the Value of Travel Time (VTT) of 10.42 € per hour, and the average parking duration, 112 minutes, for paid parking areas in the Netherlands. The walking distance is converted to walking time using an average walking speed of 6 km/hr. The access time depends on the current parking occupancy in the area. Thus, assignment based on least-resistance is an iterative process, where the resistance values update each iteration.

The parking assignment takes place according to least-resistance using the Method of Successive Averages (MSA) until Wardrop's equilibrium is reached. A resistance cut-off is set. If parking demand cannot be assigned to supply within the cut-off, it is assigned to a dummy area until the next iteration. Using the final assignment, the expected parking occupancies for all areas can be determined.

The operationalised model will be tested in a case study. In this case study, the model is applied on the municipality of The Hague. The available regional datasets require some additional choices and assumptions. The case study will be performed in chapter 5.

# 5

## Case Study The Hague

The operational model from chapter 4 is tested using a case study on the municipality of The Hague. The goal of the case study is to both evaluate the accuracy of the resulting assignment, as well as to visualise how the model can be applied. For some aspects of the operational model, regional datasets are used. The availability and extensiveness of these datasets differ per municipality. The case study, therefore, aids in the determination of any changes required to apply the operational model. This chapter will go through the steps of the operational model and describe how it can be applied to the case of The Hague. Where applicable, the use of regional datasets is outlined, and the model results are visualised. The model is validated by comparing the results to parking occupancy counts provided by the municipality. Additionally, the determined parking supply is validated by comparing it to the counted parking supply included in the same dataset as the counted parking occupancies. Finally, the model is applied to demonstrate how it can be used to estimate the expected impact of a policy change.

Parking demand and resistance factors are (partly) dependent on the time of day. To account for this, the model is tested at two different times. This helps to better assess the model's accuracy. If the model were only tested at one time of day, there's a chance that the observed accuracy is just a coincidence. Testing at two different times reduces this risk. Additionally, different demand categories tend to dominate at different times of day, which leads to varying dynamics in the model.

Based on the interviews with The Hague discussed in subsection 3.1.2, most parking problems occur on workdays in the evening, when most residents are at home. Therefore, the first time of day used in the case study is a workday evening. The second time of day considered is a workday morning, when most people are away from home, introducing a different parking demand dynamic.

**Choice.** *The case study consists of two scenarios, both taking place in the municipality of The Hague. Scenario 1 takes place on a workday evening. Scenario 2 takes place on a workday morning.*

### 5.1. Parking supply

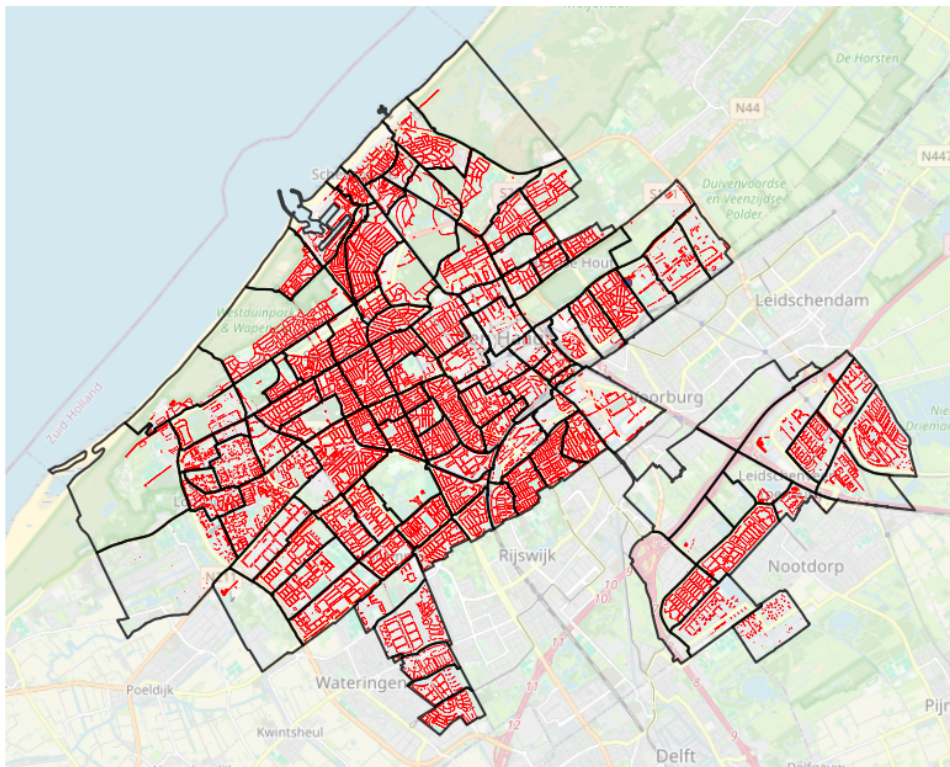
In the operational model, most of the public parking supply is determined using regional datasets where those are available. The Hague is one of the municipalities providing publicly available datasets online. This databank includes datasets on parking. Additionally, some datasets were received directly from the municipality, and some other websites were used.

#### 5.1.1. On-street parking

As discussed in subsection 4.2.1, in the operational model, the on-street parking supply is determined using local datasets whenever those are available. In the case of The Hague, an open dataset is available from their website (Gemeente Den Haag, 2025c). This dataset contains the on-street parking spaces in the municipality of The Hague, grouped per street or part of a street. For most of these groups, the dataset also states the parking capacity, providing the on-street parking supply. Additionally, the dataset contains some off-street parking sites and their capacity.

The accuracy of the dataset was checked using Google Street View. Several samples were taken from the dataset, and their stated capacity was checked by counting the existing parking spots on Google Street View. For the on-street parking areas that are within paid parking zones, the stated capacities are at most two parking spaces higher or lower based on the sampling. For the on-street parking areas outside paid parking zones, slightly larger deviations were found. However, these were usually not more than a couple of spots higher or lower than the stated capacity. The dataset can therefore be considered accurate for on-street parking based on the samples. Finally, the dataset also contained some off-street parking zones. While subsection 4.2.2 states that off-street parking zones would not be included in the model, their accuracy was still checked in the same way. For the sampled off-street parking zones, the stated capacity was either much lower (less than half) or much higher (more than double) the counted capacity. Therefore, the off-street parking zones were still excluded.

The dataset also contains information on the type of parking place, such as disabled parking spaces or spaces for loading and unloading. As stated in section 1.2, the model in this research does not differentiate based on the type of parking space. Therefore, every parking space in the dataset was treated as a publicly available parking space. In some cases, the special characteristics of the parking space were only for a specific time of day, so duplicates were filtered out to prevent double-counting those parking spaces. The resulting on-street parking supply locations are shown in red in Figure 5.1.



**Figure 5.1:** Location on-street parking The Hague

The dataset does not specify which neighbourhood a parking location is located in. Each parking location must therefore be matched to its corresponding neighbourhood based on the geographical data. Some parking locations are in multiple neighbourhoods. To prevent double-counting parking spaces and to determine the on-street supply as accurately as possible, the parking locations are split, with each part located in exactly one neighbourhood. The capacity of the original parking location is divided over the new parts based on the percentage of the original surface area each new part has. This results in decimal parking spaces for some neighbourhoods. Since other parts of the supply will also lead to decimal parking spaces, the results are not rounded to integers. Figure 5.3a shows the resulting on-street parking supply per neighbourhood.

While the accuracy of the dataset was checked using sampling in Google Streetview, Figure 5.1 shows

several neighbourhoods with very little on-street parking supply. Tables 5.1a and 5.1b show the ten neighbourhoods with the highest and lowest on-street parking supply, respectively. The difference in supply between the highest and lowest neighbourhoods shows that it is likely that supply data is missing for the neighbourhoods with the lowest supply. The validity of the on-street parking supply will therefore be further checked by comparing the values per neighbourhood to the counted values per neighbourhood. This will be further elaborated and performed in subsection 5.5.3.

**Table 5.1:** Highest and lowest on-street parking supply The Hague

(a) Ten neighbourhoods with the highest on-street supply		(b) Ten neighbourhoods with the lowest on-street supply	
Neighbourhood	On-street supply	Neighbourhood	On-street supply
Leyenburg	5378	Vlietzoom-West	0
Statenkwartier	5308.9	Tedingerbroek	0
Houtwijk	4424.9	Vliegeniersbuurt	1
Vogelwijk	3701.2	Vlietzoom-Oost	1
Valkenboskwartier	3685.9	Marlot	123
Dreven en Gaarden	3608	Bosweide	125
De Vissen	3299	De Uithof	170
Bezuidenhout-Oost	3237.3	Haagse Bos	210
Laakkwartier-Oost	3144.1	Bosjes van Pex	274
Belgisch Park	3032.1	Rivierenbuurt-Zuid	295

### 5.1.2. Parking garages

In the operational model, the existence, location, and capacity of parking garages are based on a list of garages provided by the municipality. Kapteijns (2024) is a letter to a committee of the municipal council of The Hague answering questions on parking. The answer to question 48 of this letter contains an overview of parking garages in The Hague, including their capacity and their owner. Additionally, the website The Hague & Partners (2025) contains an overview of most parking garages in The Hague, providing several additional garages compared to the letter. For some of the parking garages, this website also contains their capacity; for others, it can be retrieved from the website of the respective garage owner (APCOA, 2025; Gemeente Den Haag, 2025a; Interparking, 2025; P1 Parking, 2025; Parkeren Den Haag, 2025; QPark, 2025). Only the capacities not included in the letter were retrieved from somewhere else. Of those capacities, most were retrieved from the websites of the garage owners, since that is the most direct source and therefore likely the most accurate.

The garages are linked to the neighbourhood they are located in based on their address. Each garage is assumed to be located in exactly one neighbourhood, indicated by its address. For most garages, a capacity is listed in at least one of the available sources. The only garages where no capacity information was found are the garages from ParkBee. These garages were therefore not included.

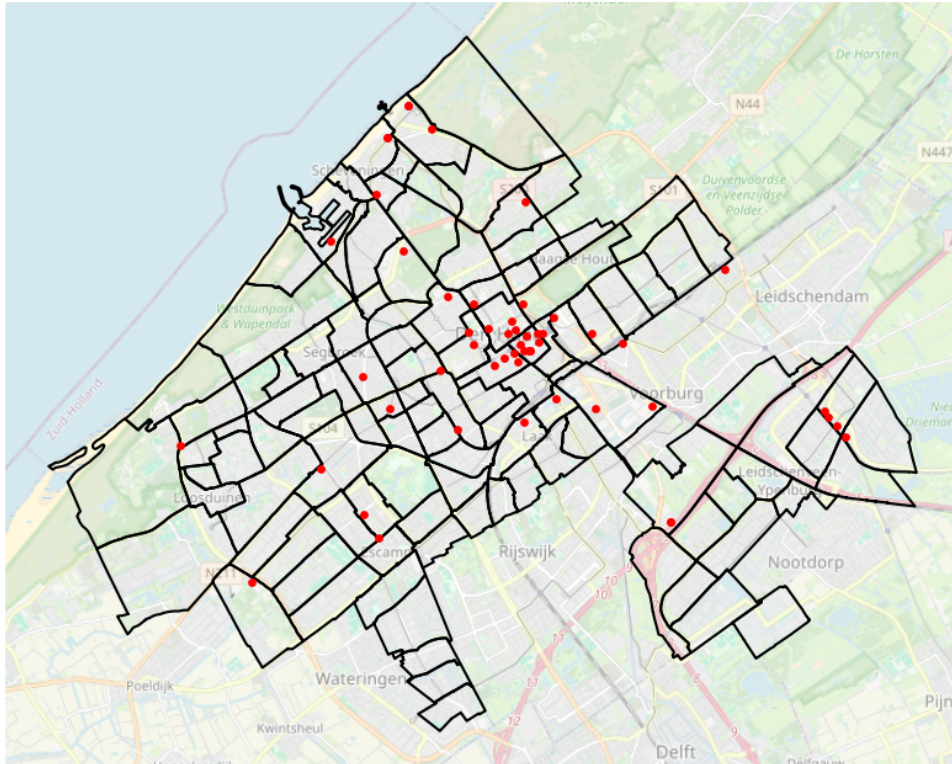
**Assumption.** *Each garage is located in exactly one neighbourhood, indicated by its address.*

**Choice.** *The ParkBee garages are excluded from the supply.*

Figure 5.2 indicates the locations of the included garages in red. Table 5.2 shows the ten neighbourhoods with the highest garage supply. Additionally, Figure 5.3b shows the resulting parking supply provided by garages per neighbourhood.

Figure 5.2 and Table 5.2 show that most parking garages are located near the city centre and near the beach. Both are places that attract visitors and have limited space. Visitors are more flexible in the exact parking location than residents, and parking garages allow for multiple levels of parking, requiring less public space. The higher concentration of parking garages near the city centre and the beach is therefore to be expected.

Comparing Table 5.2 with Tables 5.1a and 5.1b, it can be seen that two of the high garage supply neighbourhoods, *Belgisch Park* and *Leyenburg*, are also among the highest on-street supply neighbourhoods. Based on this, it is expected that these neighbourhoods will also generate a high parking demand. One explanation for the low on-street parking supply neighbourhoods in Table 5.1b could be



**Figure 5.2:** Location parking garages The Hague

that parking garages are used instead of on-street parking supply. However, none of these neighbourhoods are among the highest parking garage supply neighbourhoods. Therefore, this explanation is likely not true.

**Table 5.2:** Ten neighbourhoods with the highest garage supply The Hague

Neighbourhood	Garage supply
Belgisch Park	3151
Uilebomen	2478
Laakhaven-West	1796
Laakhaven-Oost	1338
Bezuidenhout-West	1248
Voorhout	1242
Zuidwal	1222
Morgenstond-Oost	1000
Bezuidenhout-Midden	925
Leyenburg	842

### 5.1.3. Residential parking on private property

The amount of parking supply provided by residential parking on private property is estimated to be 20% of the number of buildings with function *living* in the BAG according to subsection 4.2.5. For each neighbourhood, the number of buildings with function *living* is counted and the result is multiplied by 0.2. Since the on-street supply and the parking demand also produce decimal numbers, the results are not rounded to integers, but to one decimal. The resulting residential parking supply per neighbourhood for The Hague is included in Figure 5.3c. Table 5.3a shows the ten neighbourhoods with the highest residential parking supply. Table 5.3b shows the ten neighbourhoods with the lowest residential supply. Comparing these tables to Tables 5.1a, 5.1b, and 5.2, it can be seen that there is a large overlap in the

**Table 5.3:** Highest and lowest residential parking supply The Hague

(a) Ten neighbourhoods with the highest residential supply		(b) Ten neighbourhoods with the lowest residential supply	
Neighbourhood	Residential supply	Neighbourhood	Residential supply
Leyenburg	1648	Oostduinen	0.2
Zeeheldenkwartier	1327.6	Vliegeniersbuurt	0.2
Valkenboskwartier	1186	Tedingerbroek	0.2
Schildersbuurt-West	1156.4	De Rivieren	2.8
Houtwijk	1102	Vlietzoom-Oost	6
Bezuidenhout-Oost	1026.4	Vlietzoom-West	13.4
Laakkwartier-Oost	1019.4	Zuiderpark	20.2
Statenkwartier	1004	Kerketuinen en Zichtenburg	39.6
Kortenbos	933.4	Bosjes van Pex	41.2
Zuidwal	927.2	Marlot	69.4

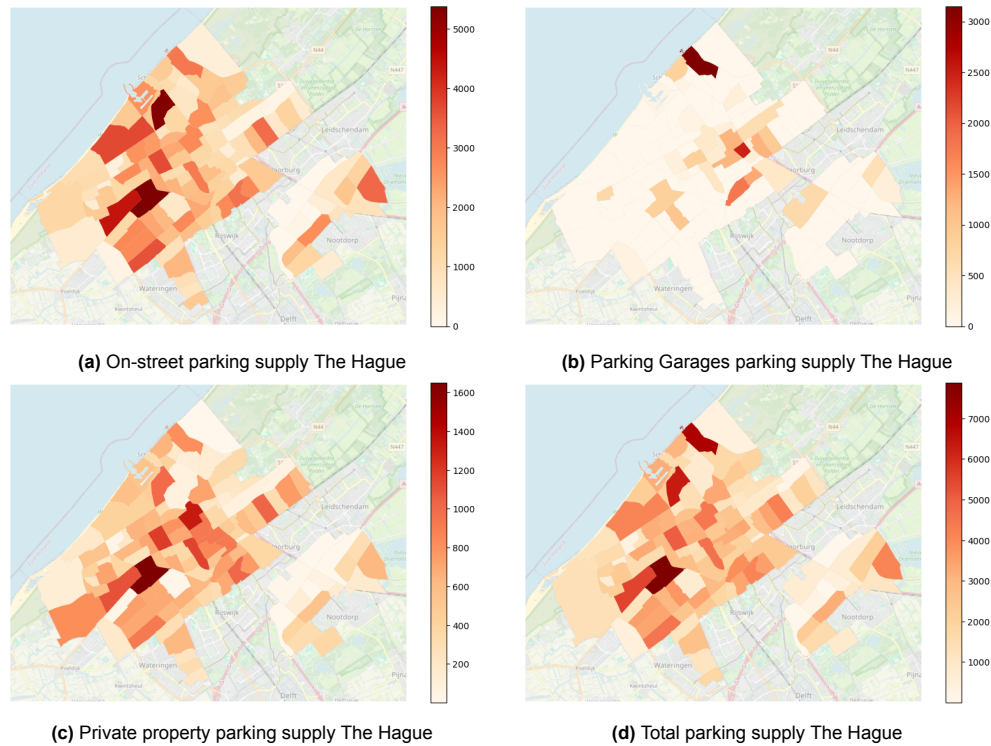
neighbourhoods. Six of the ten highest residential supply neighbourhoods are also among the ten highest on-street supply neighbourhoods. Additionally, *Zuidwal* is in both the highest residential and the highest garage supply neighbourhoods. Similarly, 6 of the lowest residential supply neighbourhoods are also in the 10 lowest on-street supply neighbourhoods. This suggests that possibly these neighbourhoods have a different function, possibly including a parking type not included in this model. For example, a neighbourhood mainly filled with offices would likely have very little on-street supply, nor would it have residential supply. Offices and their respective parking lots are not included in this model, so such a neighbourhood would show a low parking supply.

#### 5.1.4. Total parking supply

The total parking supply per neighbourhood is the sum of the parking supply provided by the three categories. The resulting total parking supply per neighbourhood is included in Figure 5.3d. Tables 5.4a and 5.4b show the ten neighbourhoods with the highest and lowest total parking supply, respectively. Eight of the ten highest total supply neighbourhoods are also in the top ten highest on-street supply neighbourhoods. There is also an overlap of eight neighbourhoods with the highest residential supply neighbourhoods, including the two not in the total supply top ten. Similarly, nine of the ten lowest total supply neighbourhoods are also named in either Table 5.1b or Table 5.3b or both. Surprising in this list is *De Reef*. This neighbourhood is not included in any of the other tables, but places ninth lowest total parking supply. Upon closer inspection, it has the thirteenth lowest on-street parking supply, the eleventh lowest residential parking supply, and no parking garages, causing it to not be included in any of the other lowest ten, but still have a low total parking supply.

**Table 5.4:** Highest and lowest total parking supply The Hague

(a) Ten neighbourhoods with the highest total supply		(b) Ten neighbourhoods with the lowest total supply	
Neighbourhood	Total supply	Neighbourhood	Total supply
Leyenburg	7868	Tedingerbroek	0.2
Belgisch Park	6999.1	Vliegeniersbuurt	1.2
Statenkwartier	6312.9	Vlietzoom-Oost	7
Houtwijk	5526.9	Marlot	192.4
Valkenboskwartier	5051.9	Bosweide	258.4
Schildersbuurt-West	4608.2	Bosjes van Pex	315.2
Dreven en Gaarden	4533	Oostduinen	371.5
Zeeheldenkwartier	4451.6	Rivierenbuurt-Zuid	395.8
Bezuidenhout-Oost	4263.7	De Reef	483.8
Laakkwartier-Oost	4163.5	De Uithof	489.4



**Figure 5.3:** Parking supply The Hague

## 5.2. Parking demand

In the operational model, the parking demand is determined by estimating the residential parking demand and the non-residential parking demand. The residential maximum parking demand is estimated based on car ownership. The non-residential maximum parking demand is based on the CROW key figures. To achieve the estimated parking demand, the CROW attendance percentages are multiplied by their respective maximum demands (section 4.3).

The CROW key figures are designed to be used to determine parking norms. The goal of parking norms is to prevent parking problems in the area. Therefore, they are always higher than the expected demand. This is confirmed by several of the conversations and interviews discussed in subsections 3.1.1 and 3.1.2. Since some supply categories had to be left out, this difference in demand estimated from the key figures compared to the actual demand is amplified. To decrease this difference and achieve a more realistic ratio between supply and demand, the estimated demand in the remainder of this case study is reduced by 10%. All stated quantities are the reduced quantities.

**Choice.** *The estimated demand is reduced by 10%.*

### 5.2.1. Residential parking demand

To estimate the residential parking demand per neighbourhood for The Hague, the data published by the Centraal Bureau voor de Statistiek (CBS) in CBS (2025d) is used. This dataset provides an overview of the number of households per neighbourhood, the number of cars owned per household for each neighbourhood, and the total number of cars owned per neighbourhood. For each neighbourhood, the car ownership is multiplied by the attendance percentages for residential workday evening and residential workday morning as determined in section 4.3. The resulting numbers form the residential parking demand and are included in Figures 5.5a and 5.5b. The ten neighbourhoods with the highest and lowest estimated residential parking demand for a workday evening in The Hague are included in Tables 5.5a and 5.5b, respectively. The results for a workday morning are similar and included in Appendix D.

**Table 5.5:** Highest and lowest residential parking demand workday evening The Hague

(a) Ten neighbourhoods with the highest residential demand workday evening		(b) Ten neighbourhoods with the lowest residential demand workday evening	
Neighbourhood	Res demand	Neighbourhood	Res demand
Leyenburg	5188.5	Tedingerbroek	0
Houtwijk	4261.5	Oostduinen	0
Kraayenstein en Vroondaal	3636	Zuiderpark	45
De Vissen	3361.5	Vlietzoom-Oost	58.5
Statenkwartier	3235.5	Rivierenbuurt-Zuid	148.5
Hoge Veld	3204	Vliegeniersbuurt	153
Schildersbuurt-West	3163.5	Bosjes van Pex	166.5
Dreven en Gaarden	2956.5	Haagse Bos	193.5
Laakkwartier-Oost	2929.5	De Reef	279
Zeeheldenkwartier	2839.5	Vlietzoom-West	310.5

There is overlap between the neighbourhoods generating the highest residential supply (Table 5.3a) and demand (Table 5.5a) and similarly between the neighbourhoods generating the lowest residential supply (Table 5.3b) and demand (Table 5.5b). However, none of the lists is exactly the same. This indicates that while there may be a correlation between the number of houses in a neighbourhood and the total car ownership in that neighbourhood, they are not directly proportional. Car ownership is influenced by more aspects, such as the socioeconomic background of the residents of the neighbourhood and the presence of amenities and public transport. This is also seen in the parking demand multiple regression model of Antea Group discussed in subsection 3.1.1.

While there is overlap in the rankings of the neighbourhoods in the residential supply and demand, the demand numbers are three to four times higher than the supply numbers. This may in part be due to the rough estimation technique used to estimate the residential supply. Nevertheless, it is also an indication of the need for parking supply other than on residential property. In the evening, most people are at home. Consequently, more parking spaces around the house are required for the residential demand than during the day. If all these parking spaces were on private property, they would be empty during the remainder of the day. By meeting part of the demand with public parking spaces, these spaces can be used to satisfy other demand categories during the day.

### 5.2.2. Non-residential parking demand

The remaining parking demand is calculated for a workday evening and workday morning using the CROW key figures as described in section 4.3. These key figures are set up as a range and are dependent on the urbanity of the area. Therefore, the information from the CROW publication is combined with the parking memo published by The Hague (Gemeente Den Haag, 2025b). This memo includes information on which urbanity category is used for each neighbourhood. An overview of the urbanity category used for each neighbourhood can be found in Figure 5.4.

Since The Hague is one of the largest cities in the Netherlands, for all these categories, the option *zeer sterk stedelijk* (very high urbanity) is used. The policy of The Hague is to use the minimum value of each range. Combining this with the knowledge that the key figures are usually overestimates for the parking demand, this case study will also use the minimum value of each range.

**Choice.** *From the CROW key figures, for each neighbourhood, the minimum value of the range for 'zeer sterk stedelijk' of its respective urbanity category is used.*

Section 4.3 describes the mapping between the CROW categories and the BAG categories. This mapping is included in Appendix C. In the mapping, some CROW categories were skipped, among others, the CROW categories for which the key figures were not based on surface area. For some of these skipped categories, the parking memo published by The Hague (Gemeente Den Haag, 2025b) contains parking norms based on surface area. For these categories, the norms from the parking memo were used. The specific categories and their mapping are included in Appendix C.

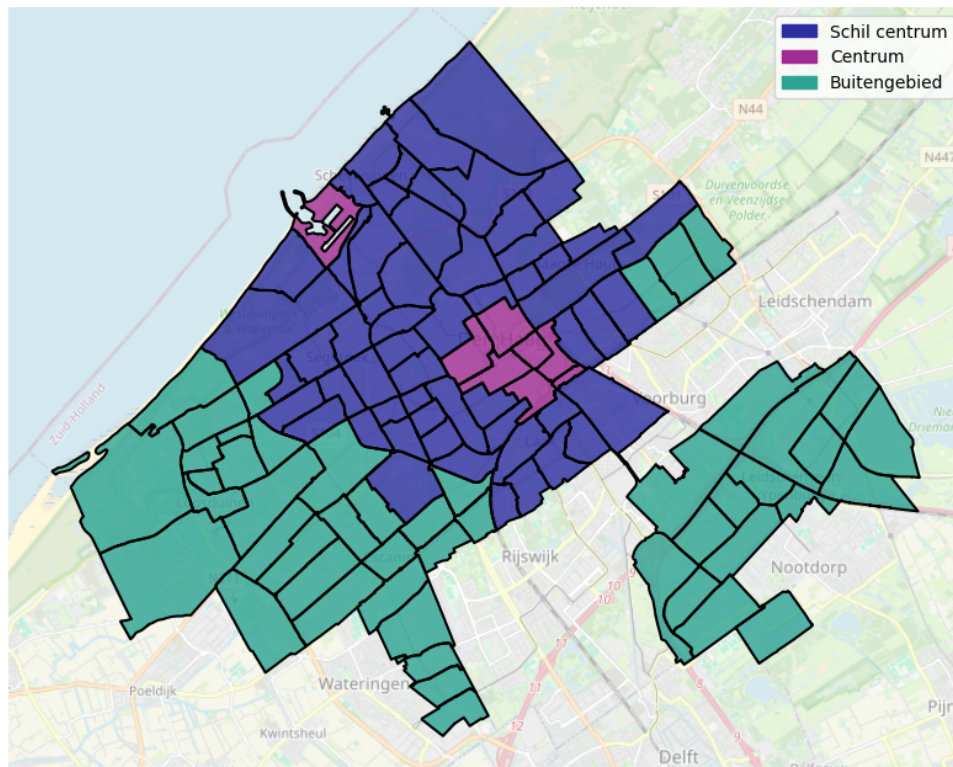


Figure 5.4: Urbanity categories The Hague

Some BAG objects have multiple functions. In that case, the first listed function is used unless the first listed function is 'other', then the second listed function is used. There is no way to tell from the BAG which function is the main function of a building. The resulting non-residential demand for a workday evening is shown in Figure 5.5c and for a workday morning in Figure 5.5d. The ten neighbourhoods with the highest and lowest non-residential parking demand for a workday evening are included in Tables 5.6a and 5.6b. The highest and lowest non-residential parking demand neighbourhoods for a workday morning are included in Tables D.2a and D.2b in Appendix D.

**Assumption.** *If a BAG object has multiple functions, the first listed non-'other' function is assumed to be the main function of the building.*

Table 5.6: Highest and lowest CROW parking demand workday evening The Hague

(a) Ten neighbourhoods with the highest CROW demand workday evening

Neighbourhood	CROW demand
Zuidwal	2024
Leyenburg	2004
Zorgvliet	1928
Binckhorst	1867
Belgisch Park	1724
Kortenbos	1711
Voorhout	1663
Kerketuinen en Zichtenburg	1559
Rosenburg	1446
Burgen en Horsten	1366

(b) Ten neighbourhoods with the lowest CROW demand workday evening

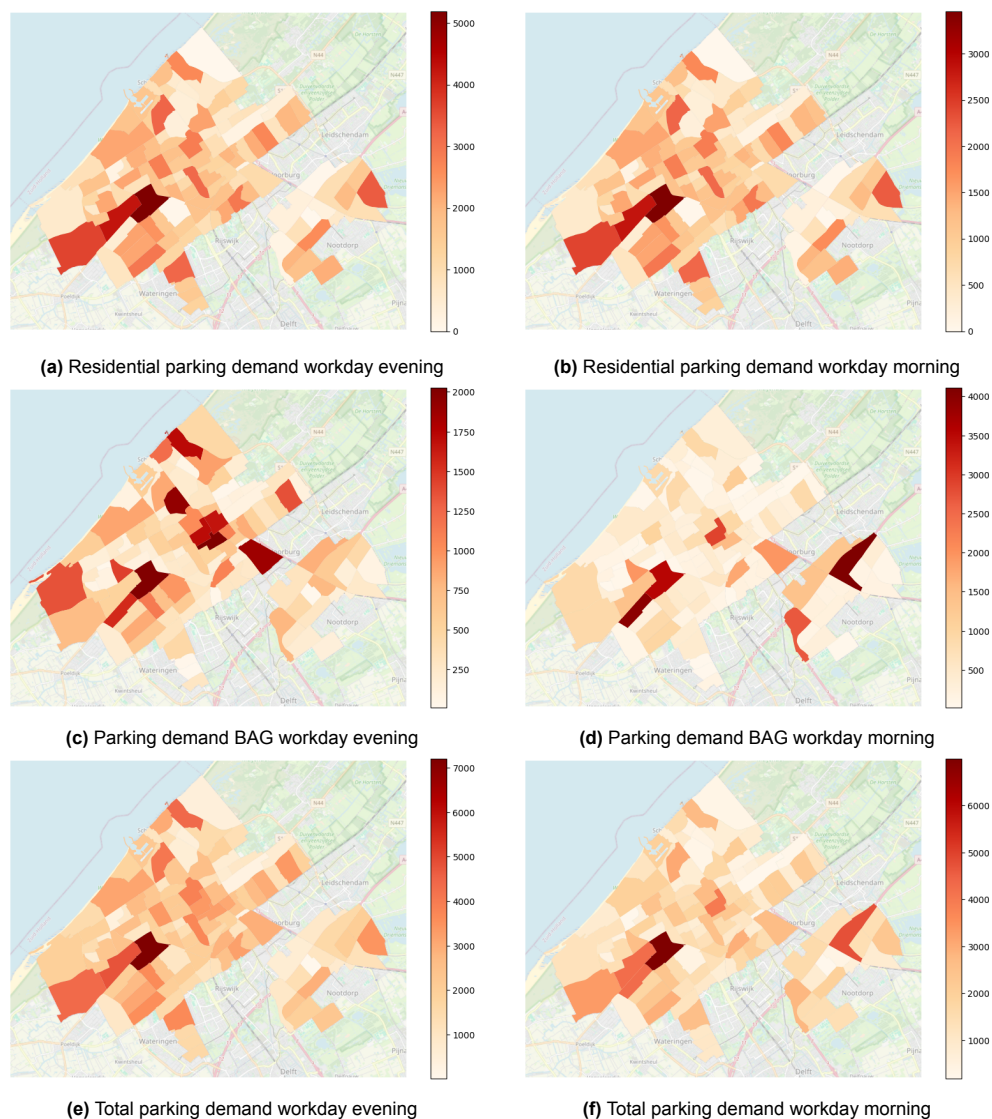
Neighbourhood	CROW demand
Tedingerbroek	9
Lage Veld	10
Componistenbuurt	20
Arendsdorp	32
Parkbuurt Oosteinde	32
Spoorwijk	39
Rivierenbuurt-Zuid	41
Westbroekpark	49
Waldeck-Zuid	61
De Vissen	87

Taking a closer look at the neighbourhoods in Tables 5.6a and 5.6b, it can be seen that the tables include several neighbourhoods that were not in any of the previous tables. Furthermore, there are large

differences between the evening and the morning tables. This is to be expected, since the activities people do in the evenings are mostly different from the activities people do in the mornings. Additionally, it has been said multiple times that in the evenings, most people are at home. This can also be seen from the demand tables. In the evening tables, the residential demand is much higher than the non-residential demand. However, in the morning tables, the non-residential demand is higher than the residential demand. This indicates that in the evenings, many people are at home, while in the mornings, many people undertake activities.

### 5.2.3. Total parking demand

The total parking demand per neighbourhood is the sum of the residential parking demand and the non-residential parking demand. The resulting total demand for a workday evening in The Hague is included in Figure 5.5e and for a workday morning in The Hague in Figure 5.5f. From these figures, it can already be noted that the parking demand for a workday morning is generally lower than the parking demand for a workday evening. There are some neighbourhoods for which the demand in the morning is higher than the demand in the evening. The distribution of the demand over the neighbourhoods in the morning is different from the distribution of the demand over the neighbourhoods in the evening.



**Figure 5.5:** Parking demand workday evening and workday morning The Hague

The ten neighbourhoods with the highest and lowest total parking demand for a workday evening are shown in Tables 5.7a and 5.7b and for a workday morning in Tables 5.8a and 5.8b.

**Table 5.7:** Highest and lowest total parking demand workday evening The Hague

(a) Ten neighbourhoods with the highest total demand workday evening

Neighbourhood	Total demand
Leyenburg	6473.25
Houtwijk	4308.75
Belgisch Park	3957.3
Kraayenstein en Vroonddaal	3940.2
Statenkwartier	3688.65
Zeeheldenkwartier	3472.65
Schildersbuurt-West	3364.65
Hoge Veld	3296.7
Morgenstond-West	3271.5
Dreven en Gaarden	3235.95

(b) Ten neighbourhoods with the lowest total demand workday evening

Neighbourhood	Total demand
Tedingebroek	8.1
Rivierenbuurt-Zuid	170.55
Haagse Bos	266.85
Bosjes van Pex	359.55
Oostduinen	420.3
Westbroekpark	453.15
Van Stolkpark en...	527.4
Vlietzoom-West	567.45
Arensdorp	583.65
Marlot	596.7

**Table 5.8:** Highest and lowest total parking demand workday morning The Hague

(a) Ten neighbourhoods with the highest total demand workday morning

Neighbourhood	Total demand
Leyenburg	6291
De Rivieren	4289.4
Kerketuinen en Zichtenburg	3849.3
Houtwijk	3832.2
Kortenbos	3589.2
Kraayenstein en Vroonddaal	2990.7
Statenkwartier	2753.1
Laakhaven-West	2659.5
Dreven en Gaarden	2655
Vliegeniersbuurt	2516.4

(b) Ten neighbourhoods with the lowest total demand workday morning

Neighbourhood	Total demand
Haagse Bos	160.2
Tedingebroek	165.6
Rivierenbuurt-Zuid	176.4
Bosjes van Pex	186.3
Marlot	246.6
Van Stolkpark en...	276.3
Oostduinen	281.7
De Reef	346.5
Westbroekpark	351.9
Arensdorp	387.9

From these tables, it is apparent that the distribution of the demand over the neighbourhoods is indeed different between the two times of day, especially for the high-demand neighbourhoods. Only five neighbourhoods are among the ten with the highest demand both in the morning and in the evening. However, for the lowest demand, nine of the ten neighbourhoods are the same at both times. Nevertheless, they generally have a lower demand in the morning than in the evening, with the exception of *Tedingebroek* and *Rivierenbuurt-Zuid*, which have a slightly higher demand in the morning. The difference in the distribution of demand shows again the difference in undertaken activities between the morning and the evening.

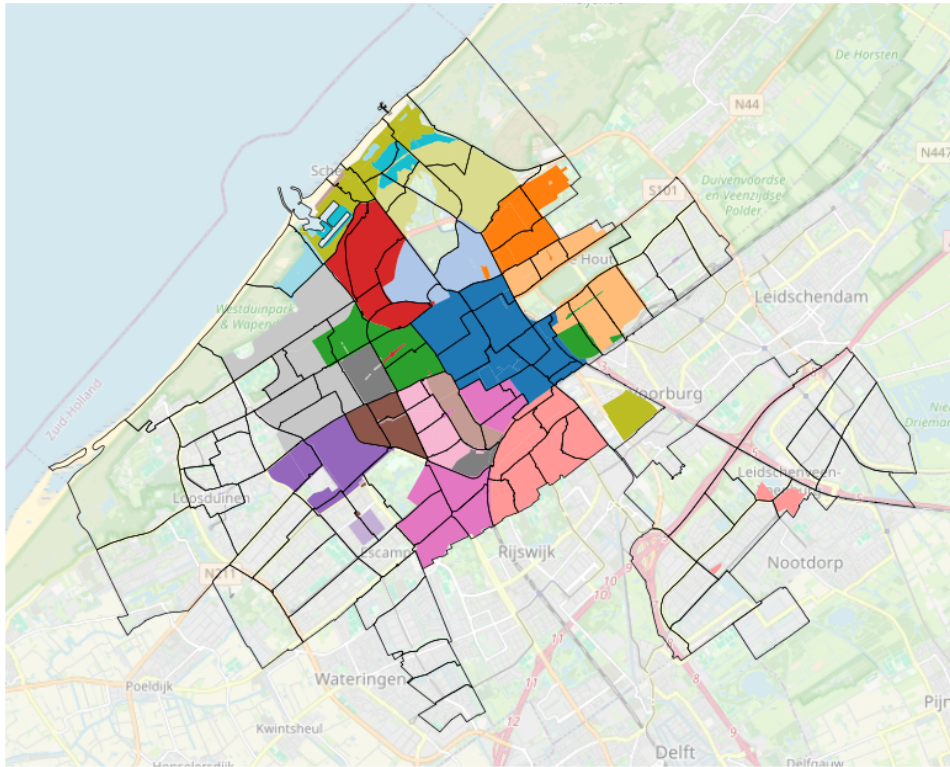
While the general estimated demand in the morning is lower than in the evening, this may not be the case in reality, or there may be a smaller difference. As discussed in chapter 4, demand and supply generated by offices are not taken into account. This will have a larger impact in the mornings than in the evenings.

### 5.3. Resistance factors

The resistance function consists of the factors parking fees, walking distance, and access time. The calculation of the last two is independent of the specific municipality or time of day and done exactly as described in subsections 4.4.2 and 4.4.3. For the resistance cut-off, a maximum walking distance of 1500 meters was set, similar to PARK (2024). The implementation of parking fees differs per municipality. For The Hague, the implementation is described below.

### 5.3.1. Parking fees

The Hague has various paid parking zones with varying rules on when and how much to pay. The parking zones for The Hague were retrieved from their public databank (Gemeente Den Haag, 2025d). This dataset contains both the geographical location of the parking zones in The Hague, as well as their payment rules. The different parking zones of The Hague are shown in Figure 5.6.



**Figure 5.6:** Paid parking zones The Hague, each colour is a different parking zone

As can be seen in this figure, the borders of the paid parking zones do not always overlap with the borders of the neighbourhoods. Most paid parking zones are in multiple neighbourhoods, and some neighbourhoods have multiple paid parking zones. Therefore, the paid parking zones are split up into smaller zones so that each small zone is included in exactly one neighbourhood. Next, for each smaller paid parking zone, the number of on-street parking spaces per zone is calculated in the same way as in section 5.1. This is multiplied by the parking fees for the parking zone for the average parking duration in The Hague of 109 minutes (subsection 4.4.1). Then, for each neighbourhood, these total parking costs per paid parking zone are summed for all paid parking zones in the neighbourhood, resulting in the total on-street parking fee for the neighbourhood.

Additionally, the parking garages have their own payment rules. The payment rules for the parking garages are retrieved from the same websites as their capacities (APCOA, 2025; Gemeente Den Haag, 2025a; Interparking, 2025; P1 Parking, 2025; Parkeren Den Haag, 2025; QPark, 2025; The Hague & Partners, 2025). The total parking fee per parking garage is calculated in the same way as the total on-street parking fee.

Finally, for each neighbourhood, the total on-street parking fee and the total parking fees for the garages in the neighbourhood are summed. The result is divided by the total parking supply in the neighbourhood, giving an average parking fee for the entire neighbourhood. This average parking fee for the neighbourhood is the parking fee used in the resistance function of Equation 4.5. This entire process is described by Equation 4.2.

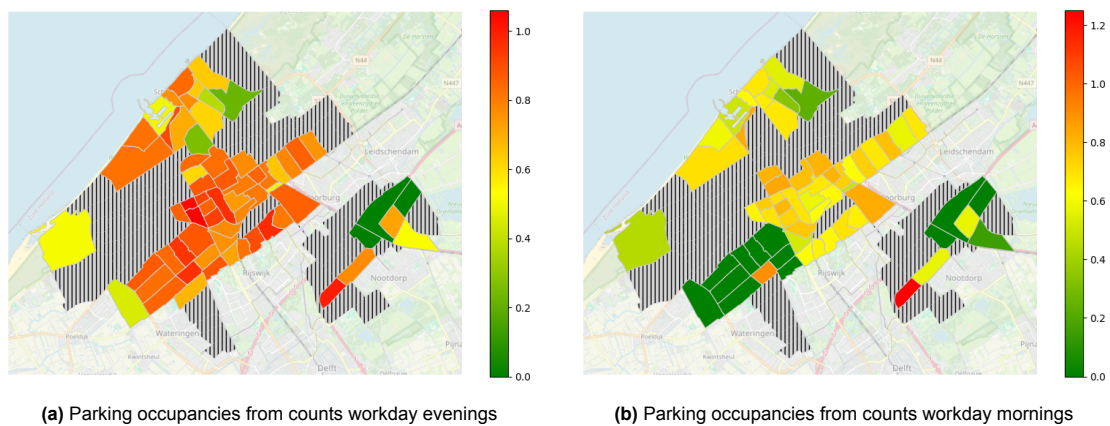
## 5.4. Parking assignment

Due to the estimation techniques used in both the parking supply and parking demand, the final supply and demand numbers are not always integers. Therefore, the requirement for the assignment to be integer as defined in Equation 4.10 was adjusted to allow for any non-negative real number. For interpretation purposes, the final assignment is rounded to the nearest integer.

## 5.5. Validation

The resulting model was run for two main scenarios. Scenario 1 considers the situation for a workday evening in The Hague. Scenario 2 considers the situation for a workday morning in The Hague. The model is validated by comparing the resulting parking occupancy to the actual parking occupancies retrieved from counts performed at the same time of day.

As a way to monitor parking problems or the effects of implemented policies, municipalities sometimes count the parking occupancies in neighbourhoods. This counting consists of counting the number of public (on-street) parking spaces that exist in the neighbourhood, and counting the number of cars parked at a given moment (divided into morning, afternoon, evening, night, and other), both inside and outside parking spaces. Figure 5.7a shows the parking occupancy per neighbourhood based on the counts conducted on workday evenings. Figure 5.7b shows the parking occupancy per neighbourhood based on the counts conducted on workday mornings. In these figures and all future figures showing parking occupancy per neighbourhood, green areas indicate a low parking occupancy and red areas indicate a high parking occupancy. The greyed-out areas indicate that for these neighbourhoods, no parking occupancy count on the respective time of day was available in the dataset. For many of them, parking occupancy counts for another day and time combination are available. For some neighbourhoods, multiple counts took place on workday evenings or mornings. In those cases, the average of all these counts was used.



**Figure 5.7:** Parking occupancy from counts

### 5.5.1. Scenario 1 - Workday evening

The first scenario considered is the situation in The Hague for a workday evening. Two versions of this scenario are considered. Initially, the model is run with all neighbourhoods included, resulting in scenario 1a. In section 5.2, it was shown that some neighbourhoods have very little on-street parking supply. As discussed, this may indicate a lack of data for these neighbourhoods in the on-street parking supply dataset. For some of them, this may have been compensated by the other parking supply categories, but not for all of them. This suggests that some of the neighbourhoods in the case study have a much lower parking supply than in reality. Therefore, a second variation of scenario 1 is considered, scenario 1b. For scenario 1b, neighbourhoods for which it is likely that on-street supply data is missing are excluded. Which neighbourhoods these are is determined by looking at the ratio between the parking demand and parking supply for each neighbourhood. For most neighbourhoods, the parking demand is at most 1.5 times as large as the parking supply. Allowing for some additional variation, a maximum ratio is set of 1.8 times the parking supply. This means that any neighbourhood

for which the parking demand is more than 1.8 times the parking supply is excluded in scenario 1b. The results of both scenarios are compared to the parking occupancy counts performed on a workday evening.

#### Scenario 1a - All neighbourhoods

The model was run with all neighbourhoods for a workday evening in The Hague. Solving the assignment took 37 iterations. The parking occupancies based on the final assignment are shown in Figure 5.8a. Additionally, Table 5.9 contains some general statistics about the parking assignment and parking occupancies from this scenario. The forecast occupancies are compared to the parking occupancies for a workday evening based on counts performed by the municipality of The Hague. Figure 5.8b shows the difference between the forecast occupancies and the counted occupancies. Blue areas indicate a negative difference, which means that the model underestimated the parking occupancy in the neighbourhood. The counted occupancy in these neighbourhoods is higher than the estimated occupancy. Orange areas indicate a positive difference and therefore an overestimation. In those areas, the estimated occupancy is higher than the counted occupancy. Table 5.10 shows some statistics about the model's predictive performance.

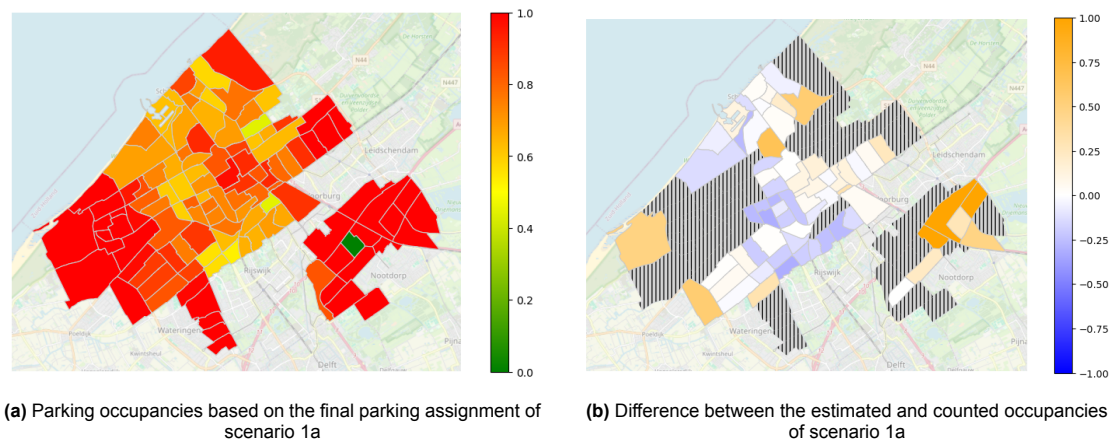


Figure 5.8: Results scenario 1a

In this scenario, almost half the areas end up with an occupancy of more than 85%. As mentioned in chapter 2, Inci et al. (2015) showed that as soon as the parking occupancy in an area becomes higher than 85%, the remaining demand decreases. Therefore, parking occupancies higher than 85% can be seen as problematic. From Figure 5.8a it can be seen that most of the neighbourhoods with such a high parking occupancy are near the borders of the municipality, in *Leidschenveen-Ypenburg* (the separate part located south-east of the main city), and in the city centre.

In the city centre, high parking occupancies are expected. The city centre of The Hague was designed for a time when cars were much less common. There is not a lot of space available to accommodate the increased use of cars, leading to high parking occupancies. Additionally, high parking occupancies near the beach of *Scheveningen* are also within expectations, since this is a popular recreation area, both for The Hague residents as well as residents of surrounding towns and cities. For the neighbourhoods in *Leidschenveen-Ypenburg* and the remaining border neighbourhoods, the high parking occupancies are not entirely expected. While these are mostly residential areas, meaning that the parking demand is highest in the evenings and nights, the parking occupancy is not expected to be this high in all neighbourhoods. One possible explanation lies in the data availability. From the plots of the parking supply, it is apparent that some of these neighbourhoods have very little on-street parking supply included in the dataset. This may not necessarily be accurate with the actual situation in these neighbourhoods. The result is scenario 1b, which excludes neighbourhoods for which supply data seems to be missing.

#### Scenario 1b - Maximum demand/supply ratio

As described, in scenario 1b, some neighbourhoods are excluded. These are the neighbourhoods with an estimated parking demand of more than 1.8 times the estimated parking supply. It is then likely that

some of the neighbourhood's supply data is missing from the used datasets. If those neighbourhoods are included, a large part of their demand has to be assigned to neighbouring areas. This means a much larger spillover than in reality. The neighbouring areas also have limited supply, leading to these areas also spilling over. In this way, missing supply for one neighbourhood can affect many more neighbourhoods. Therefore, excluding these neighbourhoods will likely lead to better overall estimations.

In scenario 1b, eleven neighbourhoods were excluded. The final assignment was reached after 52 iterations. The occupancies based on the final assignment of scenario 1b are shown in Figure 5.9a. In this figure, the excluded areas are coloured grey. Some statistics about the assignment and occupancies from this scenario can be found in Table 5.9. The forecast occupancies are compared to the same counted occupancies as in scenario 1a. The resulting differences can be seen in Figure 5.9b. Table 5.10 contains the statistics about the difference between the assignment of scenario 1b and the counted occupancies for easy comparison with scenario 1a.

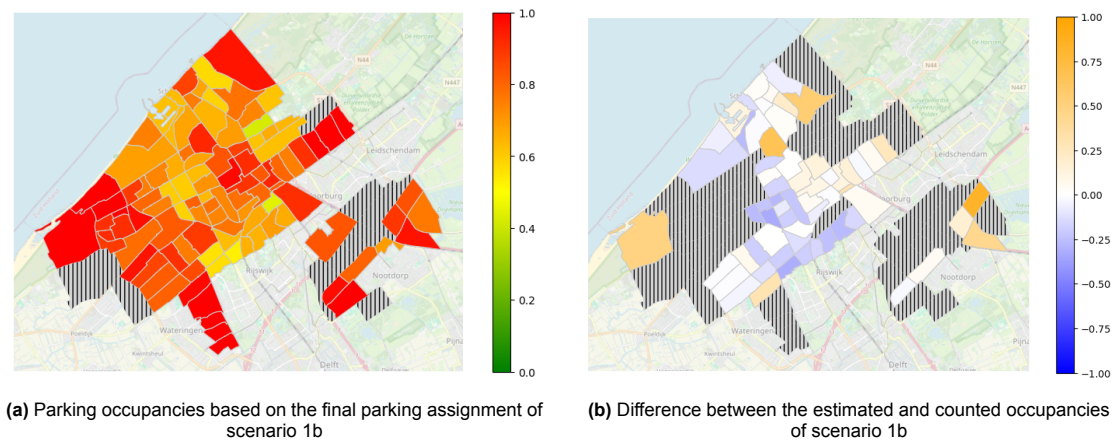


Figure 5.9: Results scenario 1b

Looking at the maps in Figures 5.8a and 5.9a, several of the red neighbourhoods of scenario 1a seem to be coloured lighter in scenario 1b. Some of the orange and yellow neighbourhoods also seem slightly lighter in scenario 1b. This is corroborated by the statistics in Table 5.9, which show that the mean parking occupancy and the standard deviation in scenario 1b are lower than in scenario 1a. Additionally, only a third of the considered areas end up with a parking occupancy of over 85%, compared to almost half the areas in scenario 1a. Another point of note is that in scenario 1b, no demand is assigned to the dummy area. This may not necessarily be realistic, because that would mean no one chooses another mode or another destination due to parking problems. However, it does indicate that the large problematic areas of scenario 1a have indeed been filtered out.

On average, both scenario 1a and 1b manage to accurately predict the parking occupancies in the neighbourhoods. Based on the statistics, the neighbourhoods not included in scenario 1b are among the neighbourhoods with the biggest deviation in scenario 1a. It corroborates the idea that data is missing for these neighbourhoods, leading to much higher parking occupancies in the model compared to the real data. This suggests that scenario 1b is indeed a more accurate representation of the situation, and a more accurate visualisation of the model. However, scenario 1b still has several neighbourhoods for which the predicted parking occupancy is more than 25% higher or lower than the actual parking occupancy. There are several possible explanations for these deviations. It is possible that the model does not yet work properly, either due to mistakes in the representation of people's choices, errors in the balance between supply and demand, or simplifications that were made. Additionally, it is likely to be influenced by mistakes in the data or missing data. As seen by the differences between scenario 1a and scenario 1b, the accuracy and completeness of the available data strongly depend on the neighbourhood considered. Since there are no available datasets known to contain all supply and/or demand for a neighbourhood, the determined supply and demand cannot be easily checked. For supply, it is possible to physically go out and count the parking places in a neighbourhood. This is done during the parking occupancy counts, but in those situations, only on-street parking places are counted.

### 5.5.2. Scenario 2 - Workday morning

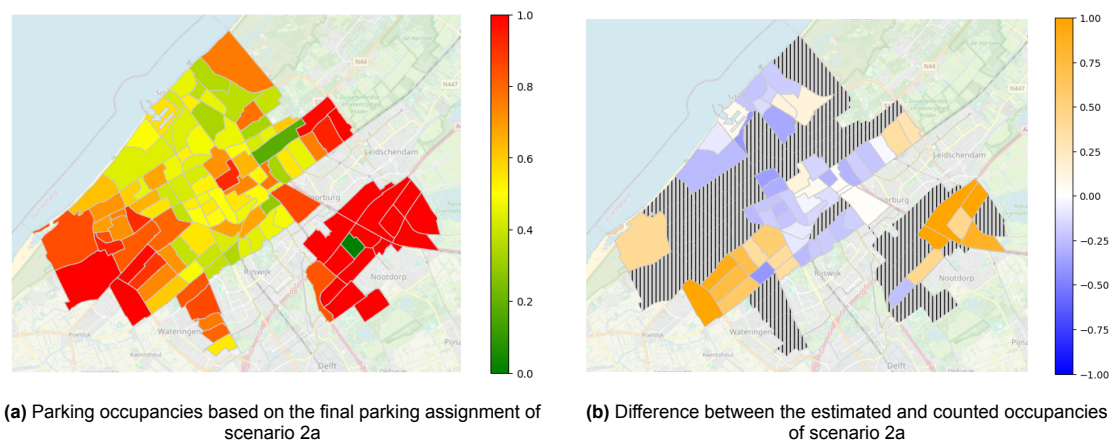
The model is further validated using a second time of day. If the model were only validated for one time of day, the results could be due to coincidence rather than model performance. By considering a second scenario, the probability of results being due to coincidence is limited.

The second scenario considered is a workday morning in The Hague. On workday evenings, most people are at home, resulting in residential parking supply and demand having the biggest influence on the result. On workday mornings, most people are not home. Therefore, non-residential parking supply and demand have a much bigger influence in this situation. Scenario 2 is therefore a contrasting scenario compared to scenario 1.

Similar to scenario 1, scenario 2 is divided into two sub-scenarios. Scenario 2a considers all neighbourhoods, similar to scenario 1a. Scenario 2b excludes neighbourhoods for which the ratio between the parking demand and parking supply is higher than 1.8, in the same way as in scenario 1b. Since the parking demand per neighbourhood in scenario 2b is not the same as in scenario 1b, it is possible for the excluded neighbourhoods to not be exactly the same neighbourhoods in both situations.

#### Scenario 2a - All neighbourhoods

The model was run for a workday morning using all neighbourhoods. It took 53 iterations until the final assignment was reached. The parking occupancies resulting from this final assignment are included in Figure 5.10a and the corresponding statistics can again be found in Table 5.9. Similar to scenario 1, the estimated occupancies are compared to the counted occupancies for a workday morning, shown in Figure 5.7b. For the neighbourhoods where multiple counts were available, the results were averaged. The resulting occupancy differences are included in Figure 5.10b. The statistics describing these results can be found in Table 5.10.



**Figure 5.10:** Results scenario 2a

As expected, for many neighbourhoods, the parking occupancies in this scenario are lower. On workday mornings, many people are away from home. In Figure 5.10a, high occupancies are visible in the city centre, in the outermost neighbourhoods, and in *Leidschenveen-Ypenburg*. For the city centre, this is to be expected. It is an area where the demand is always high, due to the area having all types of functions. There are people living there, as well as shops, offices, recreational activities, and hotels. The available space in the city centre is very limited. Therefore, meeting this high demand with sufficient parking supply is difficult and leads to high parking occupancies.

The high parking occupancies in the outermost neighbourhoods and *Leidschenveen-Ypenburg* are not expected. These areas are outside paid parking zones, making it more likely that the on-street parking supply data is not complete. Comparing the estimated occupancies for these neighbourhoods to the counted occupancies, it can be seen from Figure 5.10b that the model overestimates the occupancies in these areas, confirming that the estimated occupancies are too high.

From Figure 5.10b, it can also be seen that for the areas directly surrounding the city centre and the areas near the beach, the model in this scenario strongly underestimates the parking occupancy. A

possible explanation for this is the exclusion of office supply and demand in the model. The assumption was made that all office demand is satisfied by the office supply. However, this may not be entirely accurate and therefore lead to a lower estimated demand than in reality. The effect of this is higher in this scenario than it was in scenario 1, because on workday evenings, not many people have to be at offices, while on workday mornings they do. Excluding office demand and supply, therefore, has a larger impact on the occupancies in scenario 2 than in scenario 1.

Taking a closer look at Table 5.10, these observations are confirmed. Comparing scenarios 1a and 2a, it can be seen that the mean prediction difference for scenario 2a is higher than for scenario 1a. The standard deviation for scenario 2a is also higher than for scenario 1a, further indicating that the prediction of scenario 2a is less accurate than the prediction of scenario 1a. For almost half the validated neighbourhoods, the predicted occupancy is more than 0.25 higher or lower than the counted occupancies. This indicates that the model does not yet work well for a workday morning if all neighbourhoods are taken into account.

#### Scenario 2b - Maximum demand/supply ratio

Similar to scenario 1b, in this scenario, neighbourhoods for which the demand is more than 1.8 times the supply are excluded. Nine neighbourhoods were filtered out, which is two less than in scenario 1b. The neighbourhoods excluded in scenario 1b that are included in scenario 2b are: *Marlot* and *De Bras*. The model takes 82 iterations to reach the final assignment for this scenario. The results are shown in Figure 5.11a, where the excluded neighbourhoods are coloured grey. The estimated occupancies are compared to the counted occupancies. The comparison can be found in Figure 5.11b. Descriptive statistics of the assignment can be found in Table 5.9, and the statistics of the difference with the counts can be found in Table 5.10.

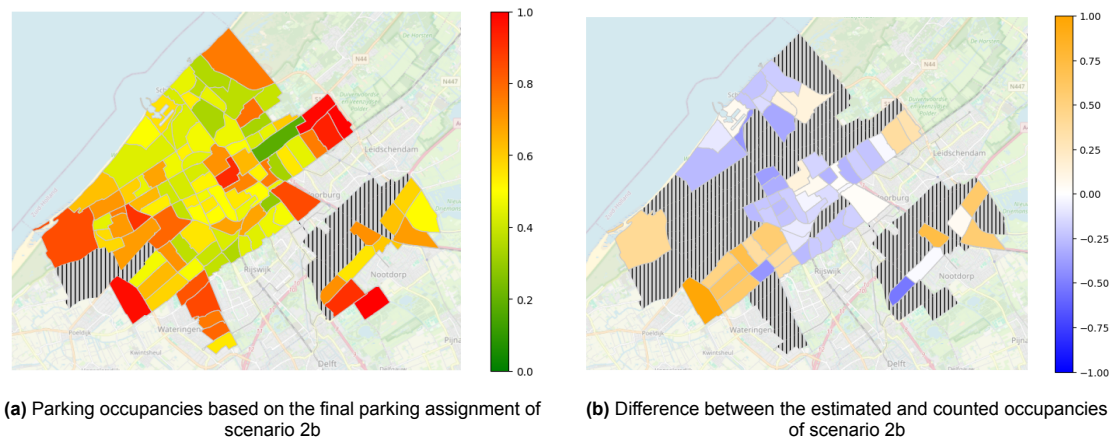


Figure 5.11: Results scenario 2b

Table 5.9: Model assignment statistics

	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
Number of areas	114	103	114	105
Mean	0.81	0.78	0.63	0.57
Standard deviation	0.19	0.16	0.24	0.18
Areas under 50%	4	3	46	47
Areas over 80%	62	47	32	13
Areas over 85%	53	37	26	10
Areas over 95%	38	19	19	4
Areas 100%	16	8	8	1
Assigned to dummy	2594	0	1905	0

Table 5.9 shows that the average estimated occupancy in scenario 2b is lower than in scenario 2a. This is an indication that the excluded areas were areas with a high predicted occupancy or areas

**Table 5.10:** Model predictive performance

	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b
Number of areas	65	62	62	61
Mean difference	0.058	0.008	0.068	0.009
Standard deviation	0.302	0.233	0.409	0.341
Minimum underestimation	-0.01	-0.01	-0.02	-0.02
Minimum overestimation	0.01	0.02	0.03	0.02
Maximum underestimation	-0.32	-0.33	-0.41	-0.53
Maximum overestimation	1.0	0.84	1.0	0.97
Areas within 10% difference	26	26	10	12
Areas within 25% difference	48	49	33	34

causing their neighbours to have a high predicted occupancy. This is confirmed by the decrease in the number of areas with an occupancy rate higher than 80% and the decrease in the number of areas with an occupancy of 100%. Additionally, no more cars are assigned to the dummy area in this scenario. Combining this information indicates that the excluded areas are indeed some of the main areas causing parking problems in the model's prediction. However, a lower predicted parking occupancy does not necessarily mean that the prediction is more accurate.

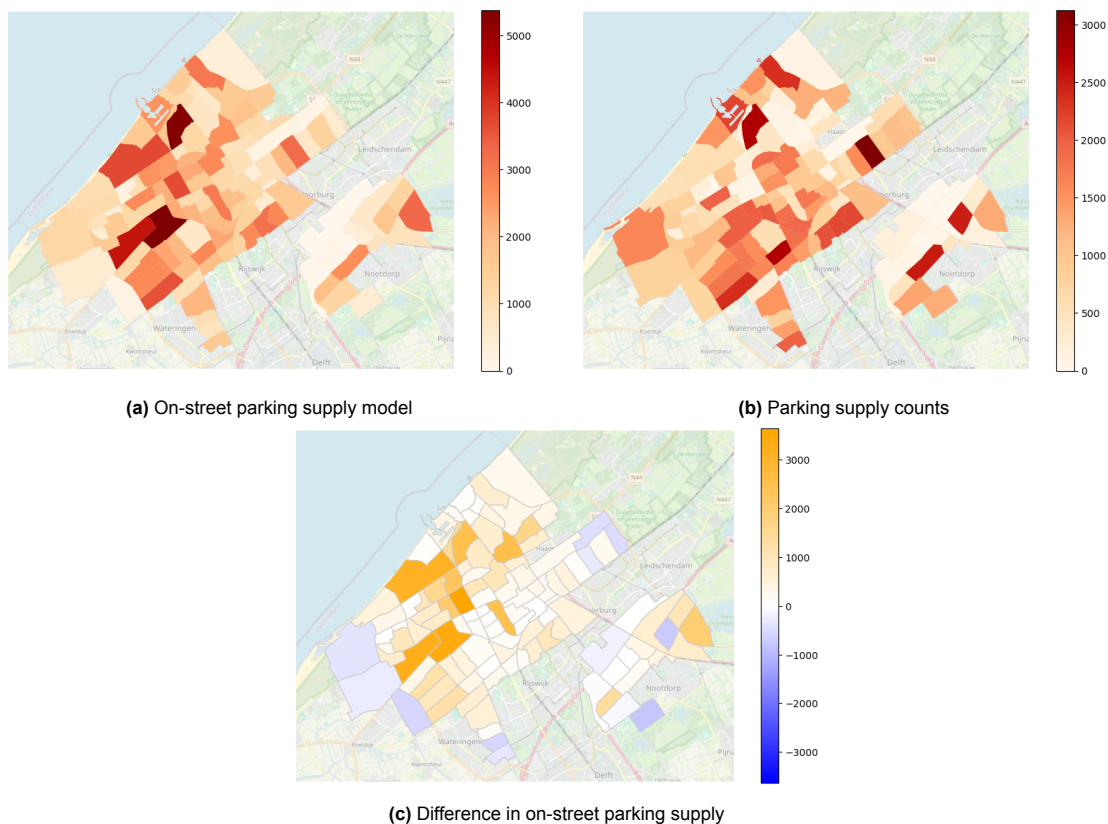
To determine the accuracy of this scenario compared to scenario 2a, the predicted occupancies are compared to the counted occupancies. The difference plot in Figure 5.11b is similar to the difference plot of scenario 2a shown in Figure 5.10b. Nevertheless, some of the dark orange areas of scenario 2a seem to be coloured lighter orange in this scenario. Several orange areas have turned almost white, and the one blue area in *Leidschenveen-Ypenburg* turned darker blue. Based on the two plots, scenario 2b seems to make a more accurate prediction of the parking occupancies. This is confirmed by the statistics in Table 5.10. This shows that the average prediction difference dropped from 0.068 to only 0.009, which is almost the same as in scenario 1b. The standard deviation also decreased, but is still higher than in both scenarios 1a and 1b. There is also a slightly larger part of the validated areas that is predicted within a 0.25 occupancy difference of the counted occupancies. However, this is still much less than in scenarios 1a and 1b.

In both scenarios 1 and 2, it is shown that excluding neighbourhoods for which the parking demand seems proportionally too high compared to the parking supply leads to more accurate predictions. Therefore, a closer look will be taken at the estimated parking supply used in the model.

### 5.5.3. Parking supply

On average, both scenarios 1 and 2 manage to somewhat accurately predict the parking occupancies in the neighbourhoods. Based on the statistics, the neighbourhoods not included in scenarios 1b and 2b are among the neighbourhoods with the biggest deviation in scenarios 1a and 2a. This corroborates the idea that data is missing for these neighbourhoods, leading to much higher parking occupancies in the model compared to the real data. This suggests that the b-scenarios are indeed a more accurate representation of the situation, as well as a more accurate visualisation of the model. However, scenarios 1b and 2b still have several neighbourhoods for which the predicted parking occupancy is more than 25% higher or lower than the actual parking occupancy. There are several possible explanations for these deviations. It is, of course, possible that the model does not yet work properly, either due to mistakes in the representation of people's choices, errors in the balance between supply and demand, or simplifications that were made. Additionally, it is likely to be influenced by mistakes in the data or missing data. As seen by the differences between all scenarios, the accuracy and completeness of the available data strongly depend on the neighbourhood considered. Since there are no available datasets that are known to contain all supply and/or demand for a neighbourhood, the determined supply and demand cannot be easily checked. For supply, however, it is possible to physically go out and count the parking places in a neighbourhood. This is done during the parking occupancy counts, but in those situations, only on-street parking places are counted.

The dataset containing the counts for the parking occupancies also contains the count of on-street parking spaces per neighbourhood. This gives the possibility of checking the accuracy of the parking supply used in the model. Since the counts only consider public on-street parking spaces, the parking supply from the counts, included in Figure 5.12b, is compared to the on-street parking supply used in the model, included in Figure 5.12a. The difference between the model supply and the counts supply is shown in Figure 5.12, where a difference greater than 0 indicates that the supply used in the model is greater than the supply according to the counts. While both datasets were provided by the municipality of The Hague, they do not give the same results. In general, there seem to be many neighbourhoods for which the model supply is slightly higher than the supply from the counts. Additionally, there are some neighbourhoods for which the counts are slightly higher. Notably, for all of these latter neighbourhoods, the final assignment from the model predicts a very high parking occupancy, whereas that is not the case based on the counts. This difference in supply might therefore explain the difference in the resulting occupancies. Similarly, for several of the neighbourhoods where the model uses a higher supply than the counts indicate, the model also results in a lower occupancy than the parking occupancies based on the counts.



**Figure 5.12:** Comparison of parking supply model and counts

The parking supply is mostly independent of time of day and can therefore be validated for all neighbourhoods. Since that is not the case for the parking occupancies, not all supply differences can directly be linked to occupancy differences. However, based on the available data, the largest differences in parking occupancy seem to correspond with the largest differences in parking supply. It is therefore likely that the model performs better if the same data for on-street parking supply is used to validate the results as was used to forecast. However, it is unclear which of the datasets most accurately represents the real situation, especially since the supply from the counts is also often different between counts.

## 5.6. Application

The goal of the model developed in this thesis is not only to model the current situation, but also to show the expected effects of policy measures on the parking occupancies. Therefore, an application scenario is used to determine whether and how the model can be used for this. One policy measure that was named several times in the interviews with the municipality of The Hague, discussed in subsection 3.1.2, is the removal of parking spaces in a neighbourhood. Therefore, for the application, the removal of on-street parking spaces in one neighbourhood was simulated.

In section 5.5, it was seen that scenario 1, a workday evening in The Hague, gave more accurate predictions than scenario 2, a workday morning in The Hague. Within scenario 1, scenario 1b gave the most accurate predictions. Additionally, the average predicted parking occupancy in scenario 1b is lower than in scenario 1a. Therefore, the effects of policy changes are more visible in scenario 1b, because there is more room available. Thus, in the application scenario, the policy change will be applied to the situation of scenario 1b, a workday morning in The Hague with some neighbourhoods removed. The original results of scenario 1b then serve as the reference. No additional neighbourhoods will be excluded. So if the removal of parking spaces in one neighbourhood leads to that neighbourhood not meeting the demand/supply ratio requirements any more, it will still be included.

To magnify the effect, a neighbourhood was chosen for which the parking occupancy in scenario 1b was under, but close to 80%, and for which the parking occupancies of most of its neighbours were also under 80%. This was done to ensure the neighbourhood had room for the removal of some parking places, but would also very likely result in a very high parking occupancy if many parking spaces were removed, moving some of the demand to the surrounding areas. One of the areas for which these conditions hold is the '*Groente- en Fruitmarkt*'. This will therefore be the target area considered in this scenario. In Figure 5.13, the location of the target area is indicated in dark blue. Additionally, all its neighbouring areas, meaning neighbourhoods within the maximum walking distance, are indicated in light blue.

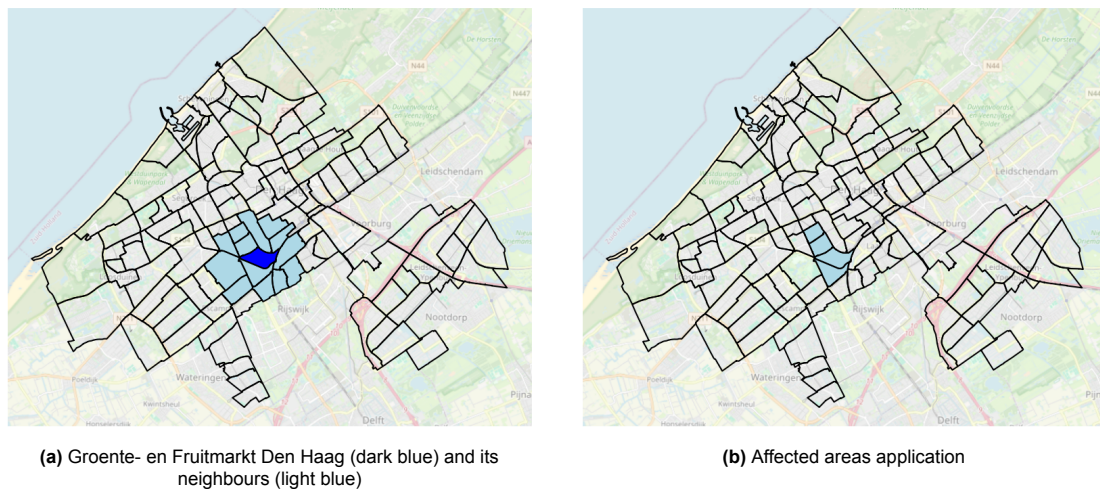


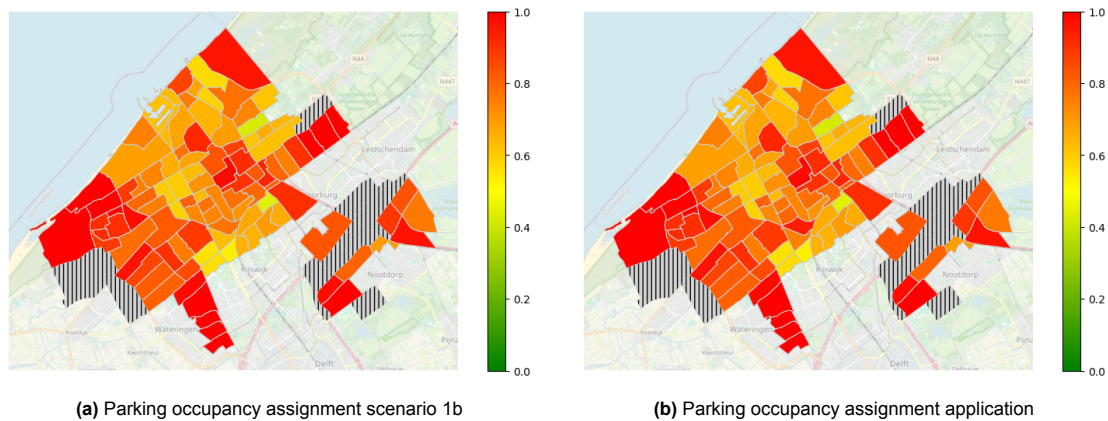
Figure 5.13: Involved areas application

To further magnify the effect, 50% of the on-street parking supply of the neighbourhood *Groente- en Fruitmarkt* was removed. The resulting parking occupancies for The Hague are shown in Figure 5.14. Additionally, the parking occupancies of the target area and its neighbours in scenario 1b and the application are included in Table 5.11.

From the figure, it can be seen that the target area has turned from orange to dark red, indicating a higher parking occupancy in the application compared to scenario 1b. Similarly, some of its neighbours seem to have turned a darker shade of orange compared to scenario 1b. This is confirmed by the parking occupancies in Table 5.11. There are only 4 areas directly affected by the change in parking supply. These areas are indicated in Figure 5.13b. The target area itself is of course affected, with a parking occupancy that increased from 77% to 95%, indicating that removing half the on-street parking

**Table 5.11:** Application - Parking occupancies Groente- en Fruitmarkt and its neighbours

	Scenario 1B	Application
On-street parking supply	2025.3	1012.65
Total parking supply	2357.7	1345.05
Groente- en Fruitmarkt	0.77	0.95
Schildersbuurt-West	0.74	0.74
Schildersbuurt-Noord	0.78	0.78
Schildersbuurt-Oost	0.71	0.71
Transvaalkwartier-Midden	0.77	0.78
Transvaalkwartier-Zuid	0.74	0.80
Oostbroek-Zuid	0.73	0.73
Zuiderpark	0.88	0.88
Moerwijk-Oost	0.53	0.53
Moerwijk-West	0.56	0.56
Moerwijk-Noord	0.63	0.75
Laakhaven-West	0.66	0.66
Spoorwijk	0.66	0.66
Laakkwartier-West	0.65	0.65

**Figure 5.14:** Application - 50% reduction of on-street parking supply at Groente- en Fruitmarkt

spaces will lead to parking problems in the neighbourhood. Additionally, three of its neighbouring areas also see their parking occupancy increased due to the spill-over effect. These are *Transvaalkwartier-Midden* increasing just 1% from 77% to 78%, *Transvaalkwartier-Zuid* with an increase from 74% to 80%, and *Moerwijk-Noord*, which sees the largest increase from just 63% to 75%.

While it is slightly surprising that only these neighbouring areas were affected, it is possible that the resistance factors are indeed lowest for these areas. This is likely influenced in part by the way the distance between areas is calculated. The distance between areas is equal to the distance between their centroids. However, that means that a large area that is touching the target area may still be further away than a small area that is not touching the target area. Additionally, The Hague has various paid parking regimes, making it likely that the monetary cost of parking differs per neighbouring area. Unfortunately, since this is a fictional scenario, there is no real-life data that can be used to validate the effects. However, based on the available information, the forecast seems realistic.

Based on the results of this application scenario, the model can indeed be used to determine the effect of certain policy changes, at least the effect of a change in supply, on the parking occupancy in the target neighbourhood and its neighbours.

## 5.7. Conclusion

The operational model was tested using a case study on the municipality of The Hague. To do so, the operational model was filled in step-by-step using local datasets where needed.

The supply in the operational model consists of 3 subcategories. For the on-street parking supply, a publicly available dataset was used. This dataset provides the location and capacity of the on-street parking supply in The Hague. However, for the areas outside the paid parking zones, the dataset is not entirely complete. Next, the location and capacities of the parking garages were added by combining information from a municipality letter and a list of parking garages from the internet. This way, for most parking garages, their location and capacity could be determined. The residential parking supply is based on a national dataset rather than a local one and is therefore exactly as described in the operational model: 20% of all BAG-buildings with function living.

The parking demand consists of the residential parking demand and the non-residential parking demand. The residential demand is determined using car ownership numbers published by the CBS. The non-residential demand is determined using the CROW key figures combined with the BAG. Information from the parking memo was used to determine the urbanity level of each neighbourhood. Additionally, this memo provided some extra categories to be included. For all CROW ranges, the minimum of the range for *zeer sterk stedelijk* was used. As described in the operational model, the resulting numbers are multiplied by the attendance percentages for the time of day considered. The total demand is reduced by 10% to compensate for both the overestimation caused by the CROW key figures and the exclusion of some supply categories.

Neither the parking supply nor the parking demand produces integer numbers. Therefore, the requirement for the assignment to be integer is removed.

The resulting model is validated using two main scenarios: a workday evening and a workday morning. This showed that the model is able to predict the parking occupancies for a workday evening well for most neighbourhoods, especially if neighbourhoods with missing supply data are excluded. The reduced accuracy of the predictions for a workday morning is likely due to the greater impact office supply and demand have at that time of day. Both are left out, but may not be the exact same size, leading to inaccuracies in the prediction.

Additionally, it was shown that the neighbourhoods with the largest prediction inaccuracies correspond with the neighbourhoods with the largest on-street supply inaccuracies. This suggests that the model can be largely improved by improving the quality of the available datasets for parking supply, both in accuracy and completeness.

A demonstration with the removal of on-street parking spaces in one neighbourhood showed that the current model can likely already be used to show the expected effect of a policy change on the parking occupancies in the target area and its surrounding areas. This is best done by comparing the situation without change to the situation with change, limiting the effect of inaccuracies.

# 6

## Conclusion and Recommendations

Many municipalities struggle with an increasing demand for the limited public space to be used for greenery and public amenities. This regularly takes space away from parking, while the parking demand is also increasing. One of the challenges municipalities face when trying to prevent parking problems is the difficulty of predicting the effect the removal of parking spaces or other possible policy implementations will have on the parking occupancies. Therefore, this thesis aimed to determine a way for municipalities to predict the impact of these possible policy changes on the parking occupancy levels within the municipality's borders. This answered the question: *How can the future parking occupancy in the different areas of a municipality be forecast, while showing the effect of policy measures and area characteristics on this occupancy?* In this chapter, the main conclusions of this research will be discussed, followed by recommendations for future steps and research.

### 6.1. Conclusion

Initially, a literature review was conducted to determine the current state-of-the-art with regard to the effects of policy measures on parking behaviour and the available parking models. This literature review revealed that for most parking policies, research on their effects is very limited and often non-existent. The most researched and implemented parking policies are parking capacity and paid parking. Nevertheless, even for these policies, the precise effect an implementation will have is unknown because it depends on the context in which it is implemented. The same is true for other policies, yet no research was found studying the exact ways context influences the effects of policy implementations. However, it was shown that implementing a policy to make parking less attractive in an area may result in spillover parking, where drivers choose to park in neighbouring areas that are cheaper or more convenient, simply shifting the problem.

Most existing parking models were developed in the past decade, with current developments focusing mainly on machine learning approaches and models that examine underlying parking behaviour and the resulting probabilities of occupancy. Nevertheless, many models still fail to account for the effects of parking capacity, and no commercially available models were identified in the literature. Therefore, in this thesis, a framework was developed for a model that is capable of including these aspects.

After identifying the current situation in the literature review, the requirements for a new model were established. This was done based on conversations with consultants of Antea Group and interviews with municipality workers of The Hague, the future users of such a model. This led to the following requirements:

- The model must include the effect of the current parking occupancy.
- The model should use a neighbourhood level of detail or smaller.
- The model must be transparent such that the effects of different factors are clear. The model, therefore, cannot use machine learning.

Based on the information from the literature review, the conversations, and the interviews, a conceptual model was defined. This model describes how the parking system works conceptually, providing the basis for the development of a model framework. The conceptual model is included in Figure 6.1. It shows that the parking system works as a balance between supply and demand. The assignment algorithm assigns the parking demand to the parking supply using the Method of Successive Averages (MSA) until Wardrop's equilibrium is reached. This uses the concept of least resistance, where the resistance depends on parking fees, walking distance, and access time.

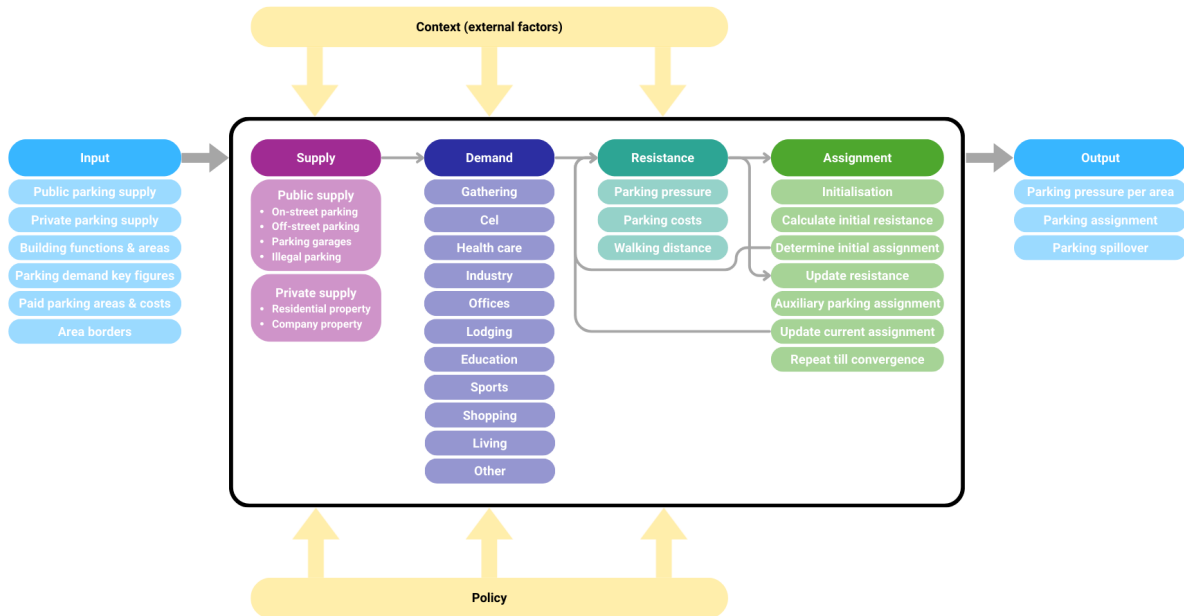


Figure 6.1: Conceptual model

Next, the conceptual model was operationalised based on what data and techniques are generally available. The workings of the operationalised model are described below.

The parking supply in an area consists of on-street parking, off-street parking, parking garages, illegal parking, residential parking on private property, and company parking on private property. No data on the amount and location of free off-street parking, illegal parking, and company parking on private property were found. These categories were therefore excluded from the model. On-street parking, parking garages, and paid off-street parking can best be estimated using regional datasets from the relevant municipality. For residential parking on private property, the supply is estimated to be 20% of the number of residential properties in the area. The exclusion of some of the supply categories means that the estimated parking supply is likely to be lower than the actual parking supply in many areas. These categories are not homogeneously distributed over a municipality, so the precise deviation will vary between areas. The underestimation is partially compensated for by also excluding the demand generated by offices, reducing the effect. Nevertheless, the exclusion of these categories is likely to lead to higher estimated parking occupancies, especially in areas where these categories provide a large supply. Similarly, the flat estimation of residential property supply is likely to skew the predicted occupancies slightly, resulting in higher occupancies in areas where the number of driveways is higher in reality and lower occupancies in areas where the number of driveways is lower in reality.

The parking demand per area is divided into two categories: residential demand and non-residential demand. The maximum residential demand is assumed to be equal to the total car ownership in the area. The maximum non-residential demand is estimated using the key figures published by the knowledge centre CROW, combined with the buildings' functions and surface areas according to the Basisregistratie Adressen en Gebouwen (BAG). Depending on the time of day considered (workday/weekend day, morning, afternoon, evening, or night), this maximum demand is reduced using the attendance percentages also published by the CROW. These attendance percentages indicate the part of the maximum demand per category that is expected to be present at that time of day. Additionally, since the

parking supply does not include parking at office buildings, parking demand generated by office buildings was also left out. The CROW key figures are designed to be used to determine minimum parking norms. Minimum parking norms are meant to prevent parking problems and are therefore higher than the expected demand. The key figures are thus an overestimation of the demand, leading to slightly higher predicted parking occupancies.

The next step involves the definition of the resistance function. The resistance of an area depends on the average parking fee per parking spot, the average walking distance from the parking area to the destination area, and the access time, which depends on the parking occupancy in the area. These were all defined in minutes of time lost, using the Value of Travel Time (VTT) to convert the parking fees, and an average walking speed to convert the walking distance. While there are more factors influencing parking choice behaviour, these factors were shown in earlier studies to have the largest influence. Therefore, they can be used well in an initial framework.

These all form the input for the MSA. In each iteration, the demand is assigned to the parking supply according to least resistance. The current assignment is then determined by averaging this auxiliary assignment with the previous assignments. The resistance values are updated, and a new iteration is started. This continues until Wardrop's equilibrium is reached.

The operationalised model was then tested using a case study on the municipality of The Hague. To validate the model, two scenarios were tested: the situation in The Hague on a workday evening and the situation in The Hague on a workday morning. The key figures used to determine the demand are known to overestimate the demand. Additionally, not all supply could be taken into account, amplifying this overestimation. Therefore, the estimated demand in the case study was lowered by 10%.

Comparing the resulting parking occupancy forecast by the model for a workday evening in The Hague to the real parking occupancy on a workday evening, the case study showed that the forecast occupancies were generally close to the real occupancies. For some of the neighbourhoods, it was shown that the available datasets were missing data, leading to higher occupancies than expected. This was especially apparent in the on-street parking supply dataset. Filtering out the neighbourhoods with missing supply data before assigning the parking demand led to a better overall prediction.

The predictions of scenario 2, a workday morning, were less accurate than the predictions of the first scenario. This is likely due to the impact of company supply and demand. Both were excluded from the model, but their values may not be exactly the same. On a workday morning, this has a much larger influence than on a workday evening, since in the morning, many people are at work, making this an important source of demand. Similar to the first scenario, the predictive accuracy in the second scenario increased when neighbourhoods with missing supply data were filtered out.

The on-street supply data used in the model was compared to the on-street supply data retrieved from parking occupancy counts. This comparison showed that the areas with the strongest deviation in on-street supply data corresponded with the areas with the least accurate predictions in the studied scenarios. This suggests that the model can be greatly improved by improving the quality of the parking supply data.

Additionally, it was demonstrated how the model can be used to predict the effect of a change in parking supply on the parking occupancies in the target area and its surrounding areas. While the forecast change was not completely as expected, it was realistic. The accuracy of this prediction cannot be verified. However, the model can be used to give an indication of the likely effects of a change in supply, especially when combined with expert opinion. Comparing the model results with the change to the model results without the change also reduces the effect of inaccuracies in the input data. Additionally, the model can likely be used to indicate the expected effects of aspects already included in the model dynamics. This includes the effects of:

- Changes in supply, both the removal of parking places, as well as the addition of extra parking places.
- Changes in demand, such as the construction of a new housing project, or measures to reduce car use, such as limiting the number of parking permits. This does require one to be able to estimate the effect of a change or measure on the demand. The model can then be used to see the effect on occupancy.

- Implementation of new paid parking areas, or changes in parking fees.

To conclude, the model designed in this thesis can be used to predict the impact of possible policy changes on the parking occupancy levels within the municipality's borders, especially when combined with expert judgment.

## 6.2. Recommendations

The model presented in this thesis is intended as a framework for a parking occupancy model. While it already provides a generally accurate forecast, there is significant room for further development and improvement. This section will discuss the effects of scoping on the resulting model and its usability. Additionally, several suggestions for improvements to the accuracy, explainability, and applicability of the model framework are discussed.

The scope used in this research can be divided into five main points. For each point, its expected effect on the model results and suggestions for improvement are described below.

The first point of the scope states that only passenger cars and vans will be considered. Buses and trucks are not part of the system of interest. They park in different places and have to abide by different rules. The policies of interest to the municipality in the situations described affect cars and vans, not trucks and buses. Therefore, this part of the scope does not influence the results, but ensures that the research focuses on the correct parts of the system.

The second assumption used is homogeneous supply and demand, meaning that every car is allowed to park everywhere. No differentiation was made between different types of parking places (private, disabled, electric charging, etc.). Similarly, no differentiation was made between different groups of people wanting to park, or their trip purpose. This affects the results and usability of the model in a couple of ways. First, it may lead to a slightly different parking assignment than in reality. This effect is not the same for all times of day or all areas. For example, on a workday evening, most private residential parking spaces will be used by their owners, leading to similar results as when they are not specified as private. On workday mornings, on the other hand, many of them will not be in use, effectively decreasing the general supply of the area. Another effect is in the usability of the model. Municipalities often want to know who will be affected by the implementation of a policy. The current model is not yet able to show which population groups or trip purposes are affected. Thus, determining a way to differentiate between different types of parking spaces or different types of drivers would likely lead to a more accurate and usable model.

Another benefit of using heterogeneous supply and demand is that it allows for the use of a heterogeneous resistance function as well. This would improve the accuracy of the model, since the estimated resistance for different people will be higher or lower in specific areas. In which areas the resistance is higher and in which it is lower depends on the specific person. This may lead to different parking assignments, which are likely more accurate. However, to be able to use heterogeneous supply, demand, and resistance, additional data on parking spaces and parking behaviour is needed. This data was not yet found, so it may take some additional work.

Next, the model assumes peak parking demand for a specified time of day. Municipalities want to prevent parking problems within their boundaries. Therefore, peak demands are of most interest, since they show whether parking problems occur at any point. However, it is possible that for some neighbourhoods this peak is very short and therefore does not actually cause many problems, while the model would suggest it does. It is therefore important to always combine the model results with common sense and to check estimated results with real results whenever possible.

The fourth assumption is that the average parking duration is considered to be the constant parking duration. In reality, people parking for a short period of time are affected by parking costs differently than people parking for a long period of time. Similarly, using an average parking cost means people who normally park for free in an area have a higher estimated resistance for the area than in reality. Additionally, two drivers parking for a short period of time may be able to use the same parking spot, effectively reducing the demand. However, since peak demand was assumed, this latter point is less relevant. Using averages assumes that the difference in effect for people who actually pay more and people who actually pay less is similar. This may not be the case, but additional data is needed to

confirm. This shows another way that the model could be extended to possibly improve its accuracy.

Finally, the model developed in this research is intended for use in municipalities in the Netherlands. It can be adapted for use in other countries as well, depending on the country considered. Depending on the way law-making is divided, it may be necessary to use different types and sizes of areas. Additionally, for optimal results, the weights of the resistance factors may need to be adjusted.

Besides the effects of the scoping on the model and its results, there are also some other ways the model can be improved.

The first clear area of improvement is the completeness and accuracy of the supply data. In the model framework, several supply categories had to be left out completely. The categories that were included were shown to also not always be accurate or complete, either because a rough estimate had to be made (residential parking on private property), or because available datasets are not always complete (on-street parking in The Hague). There are two main approaches to consider, depending on the goal of the improvement. If the goal is to further verify the model or to be able to use it for one specific municipality, the easiest approach is to physically count all parking spaces within that municipality. That way, all parking spaces can be included, and the model can be further verified and applied on that specific municipality. However, to be able to use the model in a more general way, an approach must be found that can estimate the number of parking spaces more accurately, independent of the specific municipality. One way to do that would be to develop a way to determine the location of parking spaces from satellite images. This could, for example, be done by training a machine learning model to do so. However, this would still require accurate supply data from several municipalities, but once the model is trained, it could be used for other municipalities as well, without having to physically count the parking supply again. There may also be possibilities to retrieve a more accurate prediction by combining available existing datasets. However, one has to be careful to check the accuracy and completeness of each dataset.

The second area in which the accuracy of the model can be improved is in the estimation of the parking demand. While the CROW key figures provide a useful starting point, they are generally known to overestimate the actual parking demand. Additionally, they are not able to take into account local area characteristics such as the proximity of a train station or the socio-economic background of the neighbourhood. This could be improved by developing a separate parking demand model that predicts the parking demand per area, taking these types of characteristics into account. Several models were identified that could be used as a basis for the development of such a demand model. The results from the demand model could then be used in the occupancy model to further improve its accuracy.

As mentioned above, the resistance function can be improved by making it heterogeneous. However, it can also be improved by recognising that the perceived time lost is often not equal to the actual time lost. The resistance function could be calibrated using a stated choice experiment. This may also show that not all factors have the same difference between perceived and actual time lost, further improving the resistance function and the explanatory nature of the model.

Finally, the model could be applied using smaller areas. From the interviews, it was learned that parking problems within a municipality are extremely local, often only within a couple of streets. By applying the model to smaller areas, these problems can be better identified. However, this again requires accurate input data for supply and demand. Otherwise, using smaller areas will not actually give more information, but may actually worsen the accuracy.

While there are many ways the model can still be improved and further developed, the framework developed in this thesis shows that the underlying concept is able to accurately describe the balance between parking supply and demand and, from that, predict the resulting parking occupancies. It combines several existing techniques and data sources with some new techniques, providing an initial step to a full parking occupancy model. Additionally, this thesis showed that the knowledge on parking policy effects is limited, and existing models often focus on one aspect of parking. Municipalities and consultants expressed a desire for a model that can be used to determine and communicate the expected effects of policy changes. Therefore, this framework fills both a scientific and a societal gap by providing a working concept in an area where this was not yet freely available.

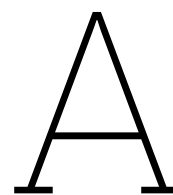
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Scientific Paper

# Forecasting Future Parking Occupancy: Developing a Parking Model Framework Using a Case Study on The Hague

A.J. Ohm<sup>a</sup>

<sup>a</sup>*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft, The Netherlands*

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## Abstract

One of the challenges municipalities face when trying to prevent parking problems is the difficulty of predicting the effect possible policy implementations will have on the parking occupancies. Therefore, a conceptual model was developed that uses the interactions between parking supply, demand, and choice behaviour to forecast the parking occupancy. In this research, this model is operationalised using existing data and techniques to form an operational model framework. The framework is tested and validated using a case study on the Dutch municipality of The Hague. While there are many ways the model can still be improved and further developed, the framework developed in this thesis shows that the underlying concept is able to accurately describe the balance between parking supply and demand and, from that, predict the resulting parking occupancies. It combines several existing techniques and data sources with some new techniques, providing an initial step to a full parking occupancy model.

*Keywords:* Parking, Parking occupancy, Parking demand, Method of Successive Averages, Parking supply, Parking policy

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## 1. Introduction

The number of cars worldwide is steadily increasing each year, all of which need a space to park. This presents a challenge for cities, which are already struggling with limited space. In the Netherlands, municipalities are responsible for most of the allocation of space within their boundaries, including the parking supply and, therefore, the parking policy. However, not only the demand for parking is increasing, also the demand for greenery, housing, bicycle parking, and other amenities increases, forcing municipalities to make difficult choices about how to allocate the scarce space.

Municipalities face several challenges within the parking domain alone. First, parking is a controversial topic. People expect to be able to park for free everywhere without wasting time searching, and local businesses often argue that increased parking fees or decreased supply will negatively affect their profits. However, research has shown that paid parking does not decrease local spending, while free parking may actually increase traffic congestion in the area (Rietveld and Koetse, 2008).

This presents the second challenge. Municipalities want to clearly communicate why they are implementing a policy and what the expected effect will be. However, the research on the effects of parking policy on parking behaviour is scarce, and the effects are very context-dependent. Therefore, often, the precise effect, or sometimes even the general effect, of a policy change is unknown.

These challenges are complicated further by the heterogeneity of parking. Some parking spaces specifically include or exclude certain cars or drivers, such as, among others, parking spaces for disabled car users, parking garages that do not allow electric vehicles, and private driveways.

The final challenge regards the cost of parking. The average car is parked 95% of the time (Mingardo, 2016), taking up space that could otherwise be used for housing, greenery, or other amenities. Additionally, building and maintaining parking spaces is expensive. Parking fees or permit fees do not generally cover these costs, because most people would not be willing to pay them. Therefore, the costs have to be paid by society. The additional effect is that car travel seems cheaper than it actually is, leading to increased car use.

This research specifically addresses the difficulty of determining the effects of planned policy changes. This paper aims to determine the accuracy of a conceptual model that uses the interactions between the different parts of the parking system to forecast the parking occupancy in different areas in a municipality. To do so, the conceptual model is operationalised to a model framework, forming a simplified version of a full parking occupancy model. This operational framework is then tested and validated using a case study on the Dutch municipality of The Hague.

### 1.1. Methodology

The conceptual model is operationalised based on available data and existing techniques. Therefore, literature is consulted to find possible approaches for the different aspects in the model. The data used is acquired in several ways. First, Dutch databanks such as <https://opendata.rdw.nl/> and <https://data.overheid.nl/> are searched. Additionally, many of the large municipalities in the Netherlands, such as Amsterdam, The Hague, and Eindhoven, publish datasets on their website. Additional data was found by following the advice of others. Any data needed for the operationalisation that was still missing after these initial searches was acquired by specific searching in Google.

The availability and data type in part depend on the specific municipality considered. Therefore, a case study is conducted on the municipality of The Hague to determine the validity and demonstrate the use of the designed model. The Hague is among the largest municipalities in the Netherlands and has an extensive open database, making this a good option for a case study.

To conduct the case study, the operationalised model was worked out with the data available for The Hague. Some additional data was received from the municipality, which was also incorporated. The model was tested for two times of day: a workday evening and a workday morning. The results of both scenarios were used to validate the model using real parking occupancy data received from The Hague.

### 1.2. Scope

The goal of this research is to develop a framework for a parking occupancy model to determine whether the underlying conceptual model works. Therefore, the scope of the research is narrowed down to ensure it can work with the scarcely available data while keeping enough complexity to represent the interactions between the different parking aspects. Therefore, the following assumptions are made describing the scope of this research:

- The model only considers passenger cars and vans. Trucks and buses are not part of the same parking system.
- Every car is allowed to park everywhere at any time. No difference is made between private and public parking. Similarly, designated parking spaces, such as those for disabled car users or electric charging, are available to everyone.
- The model studies peak parking occupancy at a specified part of the day (morning, afternoon, evening, or night), differentiating between a workday and a weekend day.
- The average parking duration is considered to be the constant parking duration for everyone.
- The model framework is intended to be used for municipalities in the Netherlands.
- Whenever necessary, the Dutch distinction between area sizes is used, translated to their closest English translation. These are, from largest to smallest: municipality (gemeente), borough (stadsdeel), district (wijken), neighbourhood (buurten). The term area is used in this research as a general term when the level of detail is either undetermined or irrelevant, meaning that it would work the same for the different levels of detail.

### 1.3. Reading guide

After this introduction, this paper starts with a short overview of the related literature in section 2, followed by a presentation of the conceptual model in section 3. Next, in section 4, this conceptual model is operationalised to form the operational model framework. The case study takes place in section 5. Finally, the conclusions and recommendations of this research can be found in section 6 and section 7, respectively.

## 2. Related literature

### 2.1. Parking policy

Parking policy encompasses all possible policy measures that can be taken in an attempt to influence parking behaviour or parking demand in an area directly. The existence of thorough scientific research depends on the specific measure in question. The body of scientific research is substantial for well-known measures, such as regulated or paid parking, while for other measures, there is no scientific research at all. Both CROW (2017) and Mingardo (2016) have created an overview of the existing knowledge on parking policy measures and their effect on parking behaviour and demand. In both reports, the possible policy measures are divided into several main categories. These categories are roughly the same for both, with the CROW considering one additional category, *social environment*, where the effect of social interactions on parking behaviour is discussed. The other categories defined are physical environment, digital environment, parking regimes, and marketing.

The physical environment category includes any policy that is executed by changes in the built environment. Within this category, *capacity measures* is most researched. When applying capacity measures, the supply of parking spaces in an area is either increased or decreased. The effectiveness of an increase or decrease in parking supply depends on the parking occupancy in the area. Inci et al. (2015) showed that the inflow rate, indicating demand, is relatively constant as long as the occupancy rate stays below 85%. Once the occupancy rate crosses this 85% line, the inflow sharply decreases with each additional car. This is confirmed by the research of Antonson et al. (2017) showing that a low parking capacity in a Swedish neighbourhood barely changed the parking demand of the neighbourhood. Many of the residents now simply parked in the neighbouring areas rather than their own neighbourhood. This behaviour is known as the *spillover effect*, a term describing the behaviour of motorists to park slightly further away if parking close by is either difficult or expensive (Mingardo, 2016).

The digital environment category includes any policies that require some form of digitalisation to work. Some of these policies make it easier to find a parking spot, others make it easier to pay and check payment. They result in less search traffic, reducing the traffic density in the area. As shown by Chaniotakis and Pel (2015), drivers find it important to find a parking spot within 8 minutes, especially if this is a cheap or free parking spot. The policies in the digital environment can help reduce the search times and therefore increase the number of people finding a spot within 8 minutes.

The category parking regimes includes any policy that sets rules or limits to parking in an area. Most of the research into parking policy effects involves the effect of parking fees on parking behaviour. Lehner and Peer (2019) compares the effect of parking fees on parking behaviour as found in 50 different studies. The study shows that the price elasticity of parking demand differs per situation and per research methodology. This is confirmed by looking at several studies such as Ostermeijer et al. (2019), Albert and Mahalel (2006) and CROW (2017).

So even for the most-researched aspect of parking policy effects, the precise effect is not entirely clear and likely to be very context-dependent. This is corroborated by the study of Rye and Koglin (2014), which shows that not only parking fees, but most parking policies are context-dependent.

Additionally, many places work with parking norms whenever a new construction project takes place. The effects of this can vary, depending on the area and whether minimum or maximum requirements are used. Setting minimum requirements helps to prevent parking congestion in the new and bordering areas, but also often leads to a higher parking supply than necessary. Maximum requirements have been shown to often lead to lower car usage, but may lead to a higher parking occupancy (Mingardo, 2016; CROW, 2017). For the categories marketing and social environment, little is known about the precise effects of their policies. Either because they are relatively new, or because they are often implemented in combination with other policies (CROW, 2017).

## 2.2. Existing models

Several attempts at creating parking models to forecast parking demand have been made. Especially in the past decade, the research into parking models has increased. The underlying conceptual model used in this research combines aspects from PARK (2024), Van der Tuin et al. (2021), and the classic 4-stage transport model described in the book of Ortúzar and Willumsen (2011).

The documentation PARK (2024) explains how parking choice behaviour is included in the Landelijk Model Systeem Verkeer en Vervoer (LMS), used in the Netherlands to predict transportation behaviour. It assumes parking demand and supply are known for each area, assigning demand to supply using the Method of Successive Averages (MSA) with all-or-nothing assignment. This method considers search time, walking time, and parking fees as costs. Demand can be allocated to any area within 15 minutes walking distance from the destination. Any remaining unassigned demand is allocated to a dummy area.

Van der Tuin et al. (2021) describes the Urban Tools Next II project, which aims to incorporate the effects of parking on the transport network. Special parking and walking links are added to the network, combined with a new travel time function to determine the best route, including parking and walking to the final destination. This model requires knowledge of the location and capacity of parking facilities, but there is no comprehensive database for all parking spaces in Dutch cities. The paper also outlines a method to estimate parking supply based on general datasets, highlighting the challenges of integrating parking data into broader transport models. It provides insights into possible techniques to estimate the parking supply and the relation between parking occupancy and search time.

Finally, the 4-stage transport model is used to predict traffic flows and can also be applied to routes with capacity limits. This indicates that techniques used to find the final assignment in this model, might also provide possibilities in the parking domain. Several of these techniques are discussed in the book of Ortúzar and Willumsen (2011), which also describes the situations in which each technique is best applied.

## 2.3. Parking behaviour

Additionally, some studies specifically study the factors influencing the underlying parking behaviour. One of these is the study of Pel and Chaniotakis (2017), a follow-up of the earlier-mentioned study Chaniotakis and Pel (2015). In this study, the researchers focus on the route taken when searching for parking, based on utility maximisation. They show that parking location choice mainly depends on access time, parking fees, and walking distance. These are some of the same factors mentioned by Khaliq et al. (2017), which studies parking behaviour to improve the PARKAGENT model developed by Benenson et al. (2008).

## 3. Conceptual Model

The underlying conceptual model for this research is based on the process used in PARK (2024) and the classic 4-stage transport model, often used in transport modelling and described in Ortúzar and Willumsen (2011). The conceptual model is based on the interaction of supply and demand, combined with the idea of 'resistance-minimisation'. The resulting assignment step is then similar to the assignment step of the 4-stage transport model.

An overview of the conceptual model is included in Figure 1.

## 4. Operational model development

The conceptual model is operationalised based on the available data and existing techniques.

### 4.1. Parking supply

The first step in the conceptual model is to determine the parking supply for each area in the municipality. The total parking supply can be divided into public supply and private supply. The public supply can be further divided into on-street parking, off-street parking sites, parking garages, and illegal parking. The private supply can be further divided into residential parking on private property and company parking on private property.

Municipalities in the Netherlands generally do not have an overview of the entire parking supply in their municipality. The availability of data or estimation techniques depends on the specific supply category considered. Therefore, the parking supply will be estimated by determining the best estimation technique for each category and combining the resulting estimates. The following subsections discuss the possible ways of estimating or determining the parking supply in each category.

For each category, the options of using national datasets are weighed against the options of using regional datasets. In general, national datasets allow for a single approach that can be applied to almost all municipalities, while regional datasets can be more detailed but may require a different approach for each municipality. Therefore, whether national or regional datasets are preferred depends on the specific datasets available for the category.

The national datasets or databases that are considered for the parking supply and parking demand are:

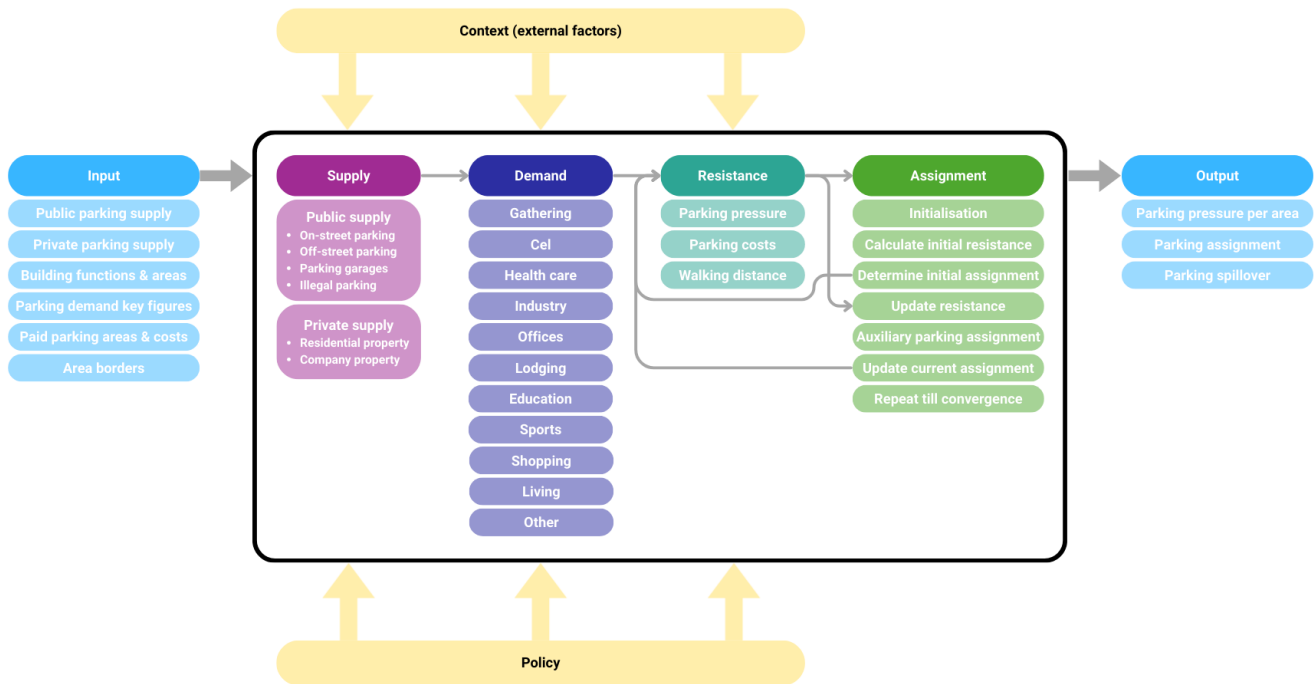


Figure 1: Conceptual model

- **Basisregistratie Adressen en Gebouwen (BAG):** Dutch national database containing the location and address of all buildings in the Netherlands. For each building, its surface area and function are indicated. Multiple functions may be assigned to the same building (BAG, 2025).
- **Basisregistratie Grootchalige Topografie (BGT):** An official topographical map of the Netherlands containing all buildings, roads, waterways, and greenery. Data included in the BGT is provided by municipalities, provinces, and water authorities, so the extensiveness and accuracy may not be consistent throughout the country (BGT, 2025).
- **Centraal Bureau voor de Statistiek (CBS):** The CBS is the Dutch bureau of statistics. They gather data on many aspects of society. A lot of this data is publicly available in published datasets. While there is no data on parking specifically, there is always the possibility of finding insightful data from the CBS (CBS, 2025b).
- **Nationaal Wegenbestand (NWB):** A national database containing all public roads in the Netherlands. These are all roads with a street name or road number that are owned by the state, provinces, municipalities, or water authorities. It combines information from several databases, such as the BAG and the BGT (NWB, 2025).
- **Publication 744 from the CROW:** The CROW is the Dutch knowledge centre for infrastructure, public space, and traffic and transport. This publication contains key figures indicating the expected parking demand range generated by a location based on its function and size. The key figures can be differentiated by time of day by multiplying them by the attendance percentages per time of day (CROW, 2017; Rijksoverheid).
- **Publications from the Dienst Wegverkeer (RDW):** The RDW is the organisation responsible for the correct registration of all motor vehicles and driver's licences in the Netherlands. Due to this responsibility, they collect driving- and car-related data. Some of this is classified as open data and publicly available on their website. Among these open datasets is also some data on parking areas (RDW, 2025).

#### 4.1.1. On-street parking

On-street parking describes all public parking spaces that are immediately accessible from the street. It consists of free parking and paid parking along the street. Parking sites, for which one first has to turn off the street onto the site to then find a parking spot, are not included in this category.

None of the national datasets directly contains the on-street data supply. However, the NWB and BGT contain data on the location and size of parking areas along the street. Based on the surface area of each parking area, an estimation of its parking capacity can be made. However, the size of parking spaces varies. Additionally, the data is provided by municipalities, so it may not be consistent throughout the country.

Many municipalities have some overview of their on-street parking supply. The accuracy and completeness of this overview will differ per municipality.

Usually, the use of scanning cars for enforcement in paid parking areas requires a dataset saying whether a street contains on-street parking. However, the scanning cars do not need to know the exact location of each parking spot, nor the number of parking spots. This is therefore not always included in those datasets. Additionally, whether the dataset only includes on-street parking in paid parking areas, or also includes on-street

parking in free parking areas, will depend on the municipality. While this is likely to be the same data as they provided to the BGT, it is often more detailed. These datasets frequently contain the number of parking spaces for each parking plane instead of only the surface area. This eliminates the need for estimating the capacity of each plane based on its surface area (Gemeente Amsterdam, 2025; Gemeente Den Haag, 2025c; Gemeente Eindhoven, 2025; Gemeente Groningen, 2025).

**Choice.** *When available, use the local datasets provided directly by the municipality.*

#### 4.1.2. Off-street parking sites

The category of off-street parking sites refers to any publicly available parking area, for which cars have to turn off the street to access them. Examples are parking sites near shopping centres, supermarkets, and sports fields. Off-street parking sites can be paid parking as well as free parking. Most datasets treat paid off-street parking sites as garages. Therefore, any off-street parking site with paid parking is treated as a parking garage.

**Assumption.** *Any off-street parking site with paid parking is treated as a parking garage.*

For the free off-street parking sites, several options were considered to determine their existence and capacity. One option seemed to be the open dataset of the RDW called ‘specifications parking area’ (RDW, 2025). However, this dataset only includes paid parking sites and garages.

Another option is to estimate the off-street parking sites and their capacity from the BGT. However, many sites are not included. For the included sites, it varies whether the stated surface area only describes the parking part, the driving part, or both (BGT, 2025).

Since neither option accurately estimates the existence and capacity of off-street parking sites, they were not included in the model. This results in a slightly lower total parking supply than in reality.

**Choice.** *Free off-street parking sites are not included in the model.*

#### 4.1.3. Parking Garages

Parking garages are seen as any public off-street parking site with paid parking, both indoor and outdoor. None of the listed national databases contains information on the existence, location, or capacity of parking garages.

Many municipality websites have a list of most parking garages within the municipality, often including the outside paid parking sites. Depending on the municipality and the garage owner, these lists often also include the capacity of the parking garage and the payment regulations. These lists are not always complete, but no other options were identified, making this the most accurate approach.

**Choice.** *The existence, location, and capacity of garages must be provided by the municipality.*

#### 4.1.4. Illegal parking

Illegal parking can be defined as parking in a way that is not allowed. One way of illegal parking is parking outside official

parking spots. This decreases the remaining demand slightly and can thus be seen as additional parking supply. The study of Mingardo (2016) suggests this happens more in areas where the parking occupancy is high, but there are no clear numbers to use as additional parking supply. Therefore, illegal parking is not included in this model.

**Choice.** *Additional supply due to illegal parking is not included in the model.*

#### 4.1.5. Residential parking on private property

Residential parking on private property refers to any parking spot that can only be used by the residents of the building and, sometimes, their visitors. This includes driveways of houses, small house garages, and most parking sites or garages in apartment complexes. No data sources were found that provide insights into which houses have private parking or how much private parking there is in a city, district, or neighbourhood. Therefore, several estimation techniques were considered.

One option to estimate the amount of residential parking on private property is by the method described by Snelder et al. (2021). This is a complex method combining multiple datasets. The accuracy of the method has not yet been determined.

Another option is to use a general estimation of the amount of residential parking on private property. In their research, Ostermeijer et al. (2019) investigate the influence of residential parking costs on car ownership. As part of their research, they show that approximately 20% of residential properties in the Netherlands own a private off-street parking spot. This percentage will not be the same for all places in the Netherlands, nor for all neighbourhoods within a municipality. However, it can be used as an initial estimate.

Neither method gives a very accurate estimate. The first method takes available space into account, but is difficult to implement and has not been validated. Therefore, it is unknown how the estimate differs from the actual situation and whether it is higher or lower. The second method will give a supply that is likely slightly too high in the city centre, and slightly too low in the outer suburbs. The total supply generated by this method is likely close to the actual supply. Additionally, it is easy to implement. Since this research aims to develop and test a framework for a parking occupancy model, the rough estimate of 20% will be used. This percentage is combined with data from the BAG to determine the residential parking supply per area.

**Choice.** *To account for residential parking on private property, for each area, 20% of buildings with the function ‘living’ in the BAG are assumed to have a private parking place.*

#### 4.1.6. Company parking on private property

Many office buildings, warehouses, and factories have parking sites to ensure their employees can park near their place of work. However, no data sources, methods, or estimates were found to determine the location and capacity of these parking sites. Therefore, company parking on private property is not

included in the model. This results in a lower estimated total parking supply than in reality.

**Choice.** *Company parking on private property is not included in the model.*

#### 4.1.7. Total parking supply

The total parking supply per area is the sum of the categories described above. Figure 2 shows the build-up of the parking supply with the excluded categories greyed out. Since not all categories could be included, this total parking supply will likely be lower than the real parking supply. Especially the exclusion of the free off-street parking and company parking will result in lower supply for certain areas, while not influencing other areas. In some areas, this might be compensated for by the private residential supply. However, it is impossible to say for which specific areas the calculated supply is lower than the actual supply. Similarly, there might be areas where the calculated supply is higher than the real supply, but which areas those are cannot be said. Nevertheless, the main categories of parking supply are included, making it likely that the calculated supply is close to the actual supply in most areas.

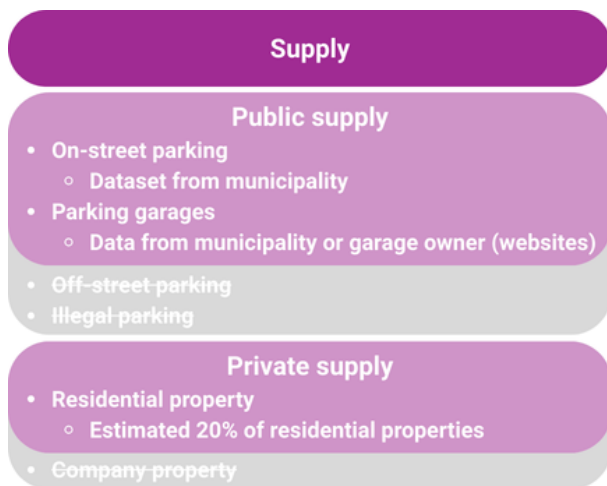


Figure 2: Operational parking supply

#### 4.2. Parking demand

Once the parking supply for each area is determined, the parking demand per area needs to be estimated. According to Kansen et al. (2018), the parking demand is mainly determined by the car ownership in an area and the generated mobility in the area. To determine how much parking is needed in an area, municipalities often use the key figures as published in CROW (2024). This publication also confirms the dependency of parking demand on spatial factors and the availability of amenities.

No direct data on the parking demand per area is available. This is because only the realised demand can be measured. Using the realised demand as actual demand ignores the effects of parking resistance in the area and its surrounding areas on the demand. Spillover parking is counted as demand for the area parked in, instead of the destination area. Additionally, latent

demand caused by other resistance factors is ignored. The realised demand is therefore not a good measure to determine the parking demand per area (Kansen et al., 2018; CROW, 2017, 2024).

As mentioned in Kansen et al. (2018), parking demand strongly depends on car ownership. One option to determine parking demand is, therefore, to look at car ownership. Especially in residential areas, car ownership is a good indicator of the total parking demand for the area. At night and in the weekends, most cars are parked at the residence of the owner. However, during the day, or in areas with a large share of non-residential buildings, this cannot be used directly.

**Assumption.** *In residential areas, parking demand strongly depends on car ownership.*

Another option is to use the key figures published in CROW (2024) as an indicator for demand. The advantage of this is that it gives an indication of the parking demand for both residential and non-residential areas, and can be used for all times of the day. However, the CROW publication is not transparent about the way these figures are determined. Additionally, these figures are meant to be used to determine minimum parking norms, resulting in them giving an overestimation of the parking demand. This is also confirmed by Kansen et al. (2018).

**Assumption.** *The key figures published by the CROW for minimum parking requirements are higher than the parking demand in the same area.*

To operationalise this model, a combination of these two options is used. The car ownership figures are used to determine the residential parking demand for each neighbourhood. The CROW figures are then used to determine the remaining demand per neighbourhood. They are combined with information from the BAG to determine the surface area of each category present in the area. The resulting estimates are the maximum demands generated by each category.

The CROW publication uses more detailed building categories than are available in the BAG. Therefore, each category of the CROW is matched to the relevant BAG category. For any category in the BAG, the unweighted average of the CROW key figures matched to that category forms the new key figure. Most key figures in the CROW publication are based on the surface area. However, some are based on the number of rooms or the number of students. The categories not based on surface area are excluded, since the required information to use them is not generally available. Additionally, there are some categories for which the CROW placed a footnote saying the key figures are inaccurate. These categories are also excluded. Furthermore, the BAG function *overige gebruiksfunctie* (other) is filtered out. This function describes buildings whose main function does not attract people, such as transformer stations (Kadaster, 2018). Finally, to compensate for the missing supply from companies, the demand generated by offices is also excluded.

**Assumption.** *The parking demand per BAG function category is the unweighted average of the CROW key figures linked to that category.*

**Choice.** *Demand generated by offices is not taken into account.*

The resulting included CROW categories per BAG category are as follows:

- **Bijeenkomstfunctie (Gathering):** Bibliotheek, bisocoop, filmtheater/filmhuis, theater/schouwburg, musicaltheater, casino, dansstudio, wellnesscentrum, sauna/hammam, in-doorspeeltuin/kinderspeelhal, discotheek
- **Industriefunctie (Industry):** Bedrijf arbeidsintensief/ bezoekersextensief, bedrijf arbeidsextensief/ bezoekersextensief
- **Onderwijsfunctie (Education):** Kinderdagverblijf
- **Sportfunctie (Sports):** Fitnessstudio/sportschool, fitnesscentrum, sporthal en sportzaal, tennishal, squashhal, zwembad (overdekt), zwembad (open lucht), kunstijsbaan
- **Winkelfunctie (Shopping):** Supermarkt, groothandel algemeen, stadsdeel-, wijk-, buurt- en dorps (winkel)centrum, kringloopwinkel, bruin- en witgoedzaken, woonwarenhuis/woonwinkel (overig), woonwarenhuis (zeer groot), meubelboulevard/woonboulevard, winkelboulevard, outletcentrum, bouwmarkt, tuincentrum, groencentrum

For the BAG functions not listed, no CROW categories meeting the discussed requirements were identified.

The publication from the CROW also contains attendance percentages. These indicate, for a given time of day, per category, what percentage of the maximum demand is present. Therefore, the maximum demand figures have to be multiplied by the relevant attendance percentage to determine the parking demand for a given time of day.

**Choice.** Residential parking demand is estimated based on car ownership. The remaining parking demand is estimated using the CROW key figures combined with the BAG. The ratio between the demands from different functions is determined using the attendance percentages from the CROW.

To determine the final total parking demand for an area at the considered time of day, the area of each non-residential building is multiplied by the just determined BAG key figure and the associated attendance percentage. These results are summed. The car ownership of the area is multiplied by the residential attendance percentage at that time of day. The total sum forms the demand in the area at that time of day. This can be displayed by the following formula:

$$D_{it} = C_i \cdot AP_{t,res} + \sum_{j \in Bb_i} k_j \cdot A_j \cdot AP_{t,j}, \quad (1)$$

where,

$D_{it}$  = Demand in area  $i$  at time of day  $t$ ;

$C_i$  = Car ownership in area  $i$ ;

$Bb_i$  = All BAG buildings in area  $i$  that do not have the function ‘residential’, ‘office’, or ‘other’;

$k_j$  = The BAG key figure belonging to building  $j$ ;

$A_j$  = The surface area of building  $j$ ;

$AP_{t,res}$  = Residential attendance percentage at time of day  $t$ ;

$AP_{t,j}$  = Attendance percentage for building  $j$  at time of day  $t$ .

For completeness, an overview of the included and excluded categories and their data source is included in Figure 3.

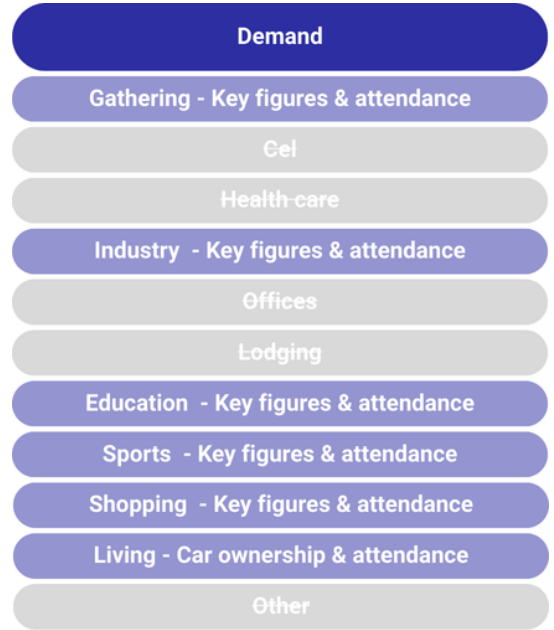


Figure 3: Operational parking demand

#### 4.3. Resistance factors

The parking assignment in the model is according to least resistance. This is similar to the traffic assignment in the classic 4-stage transport model, described in Ortúzar and Willumsen (2011), and the parking assignment in PARK (2024). To be able to assign parking according to least resistance, a resistance for each area needs to be determined. This resistance is updated in each iteration of the assignment algorithm. The research of Pel and Chaniotakis (2017) determined that earlier studies showed parking location choice mainly depends on parking fees, walking distance, and access time. Where parking fees refers to the monetary costs of parking in a certain spot, walking distance refers to the distance between the parking spot and the final destination, and access time refers to the time it takes from arrival at or near the destination until a parking spot is found, this is also known as search time. These three factors are found in multiple studies, suggesting that these are the main factors influencing parking choice. Thus, they will be the factors used to determine the parking resistance in this research.

To determine the resistance value for an area, these factors need to be measured in the same unit. The walking distance is converted to walking time using an average walking speed of 6 km/hr. The parking fees are converted to time lost using the Value of Travel Time (Knoope, 2023). This way, the resistance for an area can be measured in minutes of time lost, where the assumption is made that the actual time lost from a factor is equal to the experienced time lost from the factor.

**Assumption.** For all resistance factors, the actual time lost is equal to the experienced time lost.

#### 4.3.1. Parking fees

Many areas contain both paid parking and free parking. To determine one resistance value for the area at the time of day considered, the average monetary cost of parking in the area is calculated. This is done by calculating the total parking fees of all paid parking places together and dividing the result by the total parking supply in the area.

Usually, parking fees are based on the parking duration. In this research, a general average parking duration will be used as the parking duration for everyone. Mingardo et al. (2022) found that the average parking duration for paid parking areas in the Netherlands is 112 minutes. Additionally, they found that for the four large municipalities Amsterdam, Rotterdam, The Hague, and Utrecht, the average parking duration in paid parking areas is 139, 101, 109, and 134 minutes, respectively.

The average parking fee per parking spot in the area is then calculated by summing the costs of parking for the average duration for all paid parking spots, both on-street and in garages, and dividing this by the total parking supply in the area.

The average parking fee per parking spot is converted to minutes of time lost by using the VTT. According to Knoope (2023), the average VTT when travelling by car in the Netherlands is €10.42.

This can be summarised by the following formula:

$$PT_i = \frac{\sum_{j \in Q_{p_i}} j \cdot c_j \cdot ad}{10.42 Q_i}. \quad (2)$$

In this formula  $i$  indicates the area considered,  $PT_i$  indicates the time lost by having to pay for parking in minutes,  $Q_{p_i}$  is the set of all paid parking supply in the area,  $c_j$  denotes the cost of parking spot  $j$ ,  $ad$  is the average parking duration, and  $Q_i$  indicates the total parking supply in the area.

#### 4.3.2. Walking distance

Parking further away from one's destination leads to a longer walking time and distance from the parking place to the destination. Since the model does not currently factor in the exact destination nor the exact parking place of a traveller, the exact walking distance cannot be determined. Therefore, the walking distance is taken to be zero if the destination and parking space are in the same area  $i$ . If the traveller's destination is in area  $i$ , but they park in area  $j$ , the walking distance is taken as the distance between the centroids of areas  $i$  and  $j$ . The walking time is calculated using an average walking speed of 6 km/hr. This technique is similar to the technique used in PARK (2024).

#### 4.3.3. Access time

The access time, or search time, is defined as the time it takes from arrival at the destination until a parking space is found. The average access time in an area can be linked to the parking occupancy in the area. A higher parking occupancy means that there are fewer available parking spaces and that the time spent searching for a parking place is longer.

The relationship between the parking occupancy and the access time has been determined by Lam et al. (2006) and was also used by Van der Tuin et al. (2021). In their research, Lam

et al. (2006) relate parking occupancy to search time using a BPR-curve. The relationship found converted to minutes is:

$$ST_i = 18.6 PP_i^{4.03}, \quad (3)$$

where  $ST_i$  is the time spent searching in area  $i$ , measured in minutes, and  $PP_i$  is the parking occupancy in area  $i$ , calculated by dividing the number of parked cars by the number of available parking spaces.

From this relationship, it follows that the higher the parking occupancy, the faster the access time increases. Chaniotakis and Pel (2015) showed that drivers find it important to find a parking spot within 8 minutes. From the relationship, the parking occupancy corresponding to a search time of 8 minutes is just over 0.8. Inci et al. (2015) determined that parking occupancies over 85% lead to decreased demand. Therefore, all three of these studies (Chaniotakis and Pel, 2015; Inci et al., 2015; Lam et al., 2006) lead to similar results with regard to the relationship between access time and parking occupancy.

#### 4.3.4. Resistance function

The final resistance factor for an area  $j$  for a traveller with a destination in area  $i$  is then given by the sum of these three factors:

$$TL_{ij} = PT_j + WT_{ij} + ST_j, \quad (4)$$

where  $TL_{ij}$  is the total time lost by parking in minutes,  $PT_j$  the time lost by having to pay for parking in minutes,  $WT_{ij}$  the walking time between the areas in minutes, and  $ST_j$  the access time in minutes.

This resistance factor depends on the parking occupancy in the area. It is therefore not a constant factor, but rather a resistance function. The result of this is that the resistance factors of all areas change after assigning the parking demand to the parking supply according to least resistance. The updated resistance factors would often lead to a different parking assignment. This suggests that the assignment should take place iteratively.

#### 4.4. Assignment

In this step, the parking demand is assigned to the parking supply based on the principle of least resistance. Since the parking occupancy in an area influences the resistance factors of that area, this cannot be done in one go. This is similar to assigning traffic to the fastest route, where the duration of a route depends on the congestion. Therefore, the design for this step is based on the assignment stage of the 4-stage transport model described in Ortúzar and Willumsen (2011).

Some adaptations are made to the regular approach. A dummy area is added with an infinite parking supply. A cut-off resistance is determined and set as a constant resistance for the dummy area. This ensures that demand can never be assigned to an area with higher resistance than this cut-off value. Assignment to the dummy area indicates that the demand is too high to be satisfied, and these people will no longer come to the area by car. This includes both people who will use an alternative form of transportation, as well as people who will not come at all.

The designed model entails a single user class, without stochastic effects and with capacity constraints. Therefore, a deterministic user equilibrium (DUE) is used in combination with the method of successive averages (MSA) (Ortúzar and Willumsen, 2011). This is implemented using a simple linear programming model:

$$\min \sum_{i \in I} \sum_{j \in I} x_{ij} \cdot TL_{ij} \quad (5)$$

$$s.t. \quad (6)$$

$$\sum_{j \in I} x_{ij} = D_i \quad \forall i \in I \quad (7)$$

$$\sum_{i \in I} x_{ij} \leq Q_j \quad \forall j \in I \quad (8)$$

$$x_{ij} \in \mathbb{N} \quad (9)$$

Where,

$I$  = The set of all areas;

$TL_{ij}$  = The total time lost by parking in area  $j \in I$  with a destination in area  $i \in I$ ;

$D_i$  = The total parking demand for area  $i \in I$ ;

$Q_i$  = The total parking supply in area  $i \in I$ ;

$x_{ij}$  = Decision variable indicating what demand for location  $i \in I$  is assigned to location  $j \in I$ .

The variable  $D_i$  in Equation 7 corresponds to  $D_{ii}$  in Equation 1. The linear program does not include the time variable that was part of the demand function. This is because the program uses a constant demand as input. Once the demand is determined in an earlier step of the model, the time aspect no longer changes and is therefore left out.

#### 4.4.1. Iterative process

The parking assignment is done using an iterative process where, after each iteration, the resistance values are updated based on the latest assignment. This process is continued until it converges to Wardrop's equilibrium (Ortúzar and Willumsen, 2011). Some of the terminology of Wardrop's equilibrium has to be interpreted in a different way than in the 4-stage transport model. Replacing routes by areas and travel time by parking resistance, Wardrop's equilibrium can be applied to the parking assignment.

**Definition (Wardrop's Equilibrium).** *All travellers choose their optimal route (area), such that no traveller can improve their travel time (parking resistance) by unilaterally changing routes (areas).*

To determine whether Wardrop's equilibrium has been reached, at the end of each iteration, the following stop criterion is checked:

$$\frac{\sum_{i,j \in I} x_{ij}^{cur} \cdot TL_{ij} - \sum_{i,j \in I} x_{ij}^{aux} \cdot TL_{ij}}{\sum_{i,j \in I} x_{ij}^{aux} \cdot TL_{ij}} \leq 0.001. \quad (10)$$

In this equation,  $x^{cur}$  denotes the current assignment and  $x^{aux}$  denotes the auxiliary assignment, with the remaining variables the same as before.

All this leads to the following iterative process describing the MSA:

1. Initialise process. All parking assignment is 0.
2. Calculate initial resistance matrix.
3. Determine initial parking assignment.
4. Update resistance matrix based on current assignment.
5. Determine new auxiliary parking assignment based on updated resistance.
6. Calculate current assignment using

$$cur. assignment = prev. assignment + \frac{1}{n}(aux. assignment - prev. assignment),$$

where  $n$  denotes the number of iterations.

7. Determine whether the stop criterion is reached. If the stop criterion is reached, the current assignment is the final assignment. Otherwise, repeat from step 4.

According to Ortúzar and Willumsen (2011), the  $\frac{1}{n}$  in step 6 ensures that the process converges to Wardrop's equilibrium.

Once the stop criterion is met, meaning Wardrop's equilibrium is reached, the current assignment is the final assignment of the model. For all areas considered, the total number of cars assigned to that area is shown. This can then be used to determine the final parking occupancies for all areas in the considered situation by dividing the number of assigned cars by the parking supply of the area.

## 5. Case Study The Hague

### 5.1. Supply The Hague

The parking supply in the model consists of on-street parking supply, supply from parking garages, and residential parking on private property.

The on-street parking supply is determined using local datasets whenever those are available. In the case of The Hague, an open dataset is available from their website (Gemeente Den Haag, 2025c). This dataset contains the on-street parking spaces in the municipality of The Hague, grouped per street or part of a street. For most of these groups, the dataset also states the parking capacity, providing the on-street parking supply. Additionally, the dataset contains some off-street parking sites and their capacity.

The accuracy of the dataset was checked using sampling in Google Street View. For the on-street parking supply in paid parking zones, the dataset is accurate based on the sampling. For the on-street parking supply outside paid parking zones, the capacities stated in the dataset are sometimes off by a few parking spaces. Generally, the dataset is also accurate for the on-street parking outside paid parking zones based on the sampling. However, not all locations seem to be included. For the off-street parking sites, the sampling showed capacities more

than twice as large as or less than half of the stated capacities. Therefore, the off-street parking sites are filtered out.

The dataset also contains information on the type of parking places (disabled parking, electric charging, loading and unloading, etc.). For this research, this information is filtered out and resulting double parking spaces are removed, ensuring that every parking space is counted exactly once.

The parking locations from the dataset are matched to the neighbourhood they are located in based on their geographical data. Some locations from the datasets are located in multiple neighbourhoods. Those locations are split, with each part in exactly one neighbourhood. The capacity is divided over the new parts based on the percentage of the original surface area each new part has.

The resulting on-street parking supply per neighbourhood is shown in Figure 4.

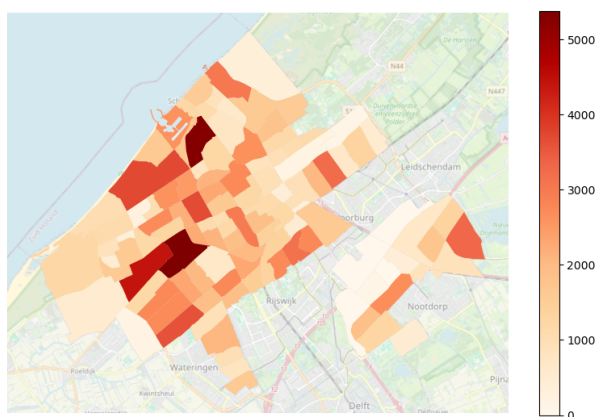


Figure 4: On-street parking supply The Hague

The existence, location, and capacity of parking garages are based on information either provided directly by the municipality or included in a list of parking garages on a municipality-related website. In the case of The Hague, a letter was provided answering several questions regarding parking within the municipality (Kapteijns, 2024). The answer to question 48 of this letter contains an overview of parking garages in The Hague, including their capacity and their owner. Additionally, the website The Hague & Partners (2025) contains an overview of most parking garages in The Hague, providing several additional garages compared to the letter. For some of the parking garages, this website also contains their capacity; for others, it can be retrieved from the website of the respective garage owner (APCOA, 2025; Interparking, 2025; P1 Parking, 2025; Parkeren Den Haag, 2025; QPark, 2025; Gemeente Den Haag, 2025b). Only the capacities not included in the letter were retrieved from somewhere else. Of those capacities, most were retrieved from the websites of the garage owners, since that is the most direct source and therefore likely the most accurate.

The garages are linked to the neighbourhood they are located in based on their address. Each garage is assumed to be located in exactly one neighbourhood, indicated by its address. If a parking garage is not included in one of the above-mentioned lists, or its capacity is not included, the garage is excluded from

the supply. The resulting supply provided by parking garages per neighbourhood in The Hague is shown in Figure 5.

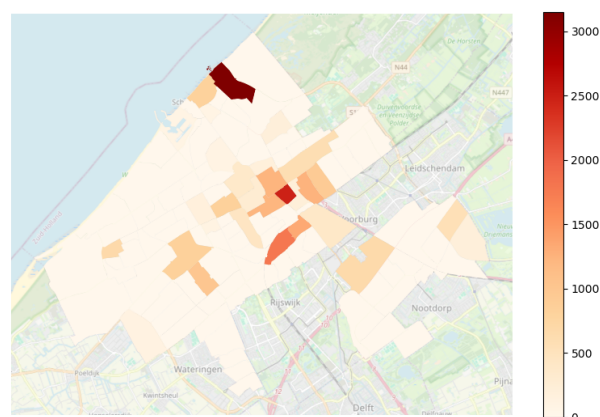


Figure 5: Garage parking supply The Hague

The amount of parking supply provided by residential parking on private property is estimated to be 20% of the number of buildings with function *living* in the BAG. For each neighbourhood, the number of buildings with function *living* is counted and the result is multiplied by 0.2. The results are rounded to one decimal. The resulting residential parking supply per neighbourhood for The Hague is included in Figure 6.

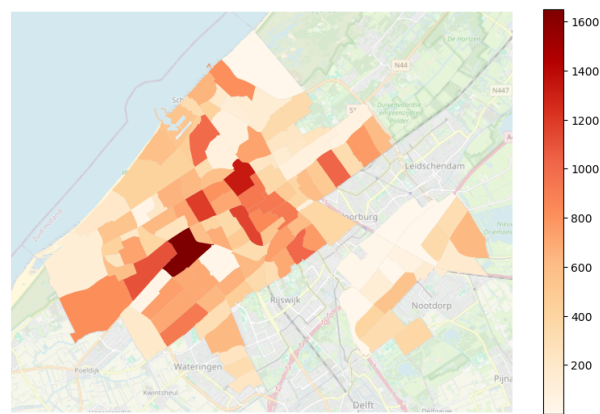


Figure 6: Residential private parking supply The Hague

The total parking supply per neighbourhood is the sum of the parking supply provided by the three categories. The resulting total parking supply per neighbourhood is included in Figure 7.

Based on these figures, there seem to be some neighbourhoods for which the estimated parking supply is much lower than expected. This may be due to data for these neighbourhoods missing in the used datasets. However, it is also possible that these neighbourhoods mainly have offices and the related private company supply, or large off-street parking sites. The supply for these neighbourhoods will therefore have to be compared to the demand to determine whether their estimated supplies are within model expectations.

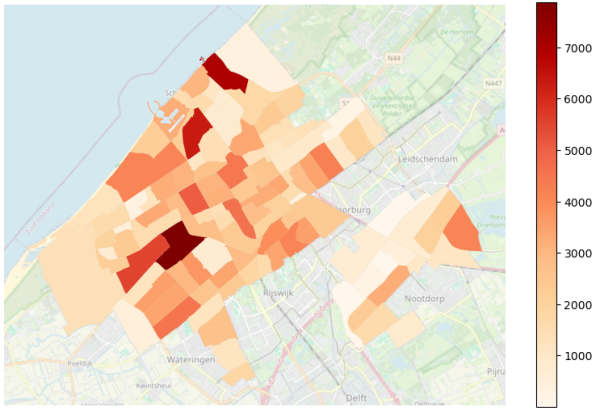


Figure 7: Total parking supply The Hague

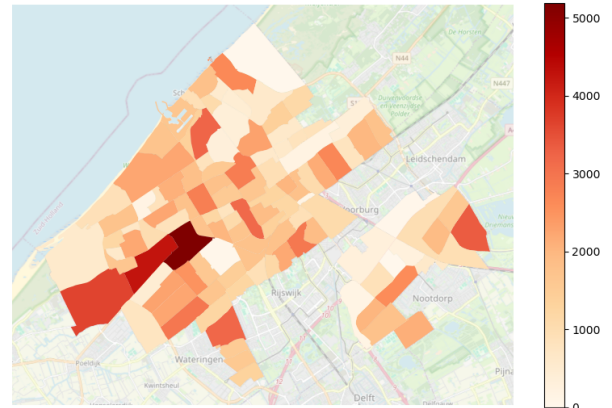


Figure 8: Residential parking demand workday evening

## 5.2. Demand The Hague

The expected parking demand for the specified time of day is determined by combining the residential parking demand, based on car-ownership, and the non-residential parking demand, based on the CROW key figures, with the attendance percentages for the relevant time of day. In this case study, two times of day are considered: a workday evening (scenario 1) and a workday morning (scenario 2). These are contrasting scenarios, since on workday evenings, most people are at home, while on workday mornings, most people are away from home. This is likely to be reflected in the estimated demand for both scenarios.

The CROW key figures overestimate the parking demand. Additionally, not all parking supply could be included, amplifying this difference. To ensure a realistic ratio between the supply and demand, all demand is lowered by 10%. All stated demand quantities are these reduced quantities.

The residential parking demand per neighbourhood is based on the car ownership. The average number of cars owned per household for each neighbourhood and the total number of cars owned per neighbourhood are published by the Centraal Bureau voor de Statistiek (CBS) (CBS, 2025a). The car ownership per neighbourhood is multiplied by the relevant attendance percentage and reduced by 10%. The resulting residential parking demand for a workday evening is shown in Figure 8.

The non-residential parking demand is estimated using the CROW key figures. These key figures are set up as a range and are dependent on the urbanity of the area. Therefore, the information from the CROW publication is combined with the parking memo published by The Hague (Gemeente Den Haag, 2025a). This memo includes information on which urbanity category is used for each neighbourhood. The neighbourhoods assigned *centrum* or *CID & Binckhorst* in appendix 2 of the memo are assigned urbanity category *centrum*. The neighbourhoods assigned *voorrologse wijken* in the memo are assigned *schil centrum*, and the neighbourhoods assigned *naoerlogs* are assigned *buitengebied*.

Since The Hague is one of the largest cities in the Netherlands, for all these categories, the option *zeer sterk stedelijk* (very high urbanity) is used. The policy of The Hague is to

use the minimum value of each range. Combining this with the knowledge that the key figures are usually overestimates for the parking demand, this case study will also use the minimum value of each range.

In subsection 4.2, an overview was given of which CROW categories are linked to each BAG category. In this mapping, several CROW categories had to be skipped because their key figures were not based on surface area. For some of these skipped categories, the parking memo of The Hague contains parking norms based on surface area. Since the parking norms in the memo are based on the key figures of the CROW, these norms are used to add some of the skipped categories. The categories included from the memo per BAG category are listed below. For the non-listed BAG categories, no additional categories are included.

- **Gezondheidszorgfunctie (Health care):** Ziekenhuis/ medisch centrum, verpleeghuis, arts/maatschap
- **Logiesfunctie (Lodging):** Hotel/hostel werknemers
- **Onderwijsfunctie (Education):** Primair onderwijs, middelbaar onderwijs, ROC, HBO/WO

Some BAG objects have multiple functions. In that case, the first listed function is used unless the first listed function is 'other', then the second listed function is used. There is no way to tell from the BAG which function is the main function of a building. The resulting non-residential demand for a workday evening is shown in Figure 9.

The residential parking demand and non-residential parking demand are summed for each neighbourhood, forming the total estimated parking demand. Figure 10 shows the resulting total parking demand for a workday evening in The Hague. Figure 11 shows the total parking demand for a workday morning in The Hague. As expected, the distribution of the demand is different for a workday evening than for a workday morning. Additionally, the height of the estimated demand is lower in the morning. This can likely be explained by the exclusion of demand generated by offices, which has a much bigger impact during workday mornings than during workday evenings.

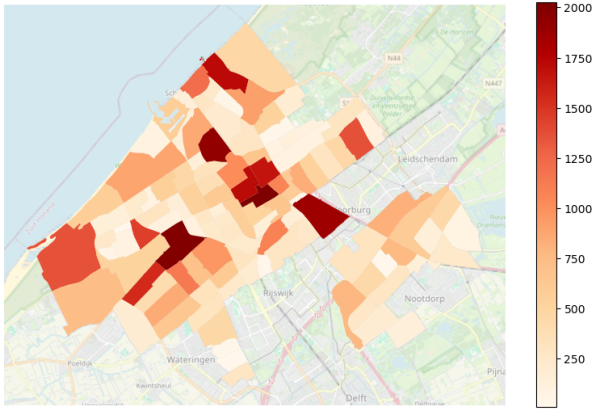


Figure 9: BAG parking demand workday evening

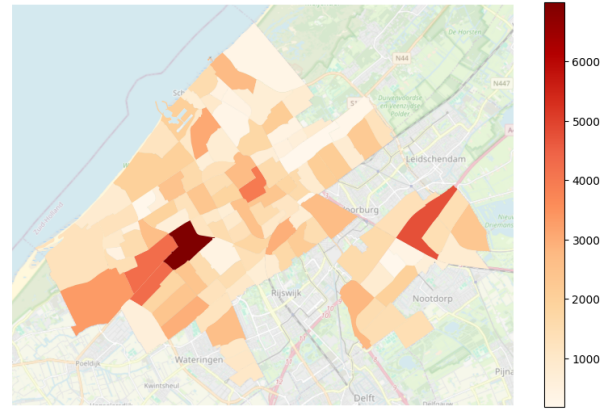


Figure 11: Total parking demand workday morning

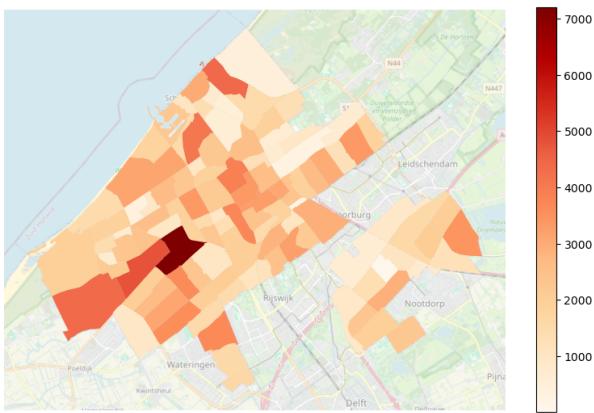


Figure 10: Total parking demand workday evening

### 5.3. Resistance The Hague

The resistance function consists of the factors parking fees, walking distance, and access time. The calculation of the last two is independent of the specific municipality or time of day and is done exactly as described before. For the resistance cut-off, a maximum walking distance of 1500 meters was set, similar to PARK (2024). The implementation of parking fees differs per municipality.

The Hague has various paid parking zones with varying rules on when and how much to pay. The parking zones for The Hague were retrieved from their public databank (Gemeente Den Haag, 2025d). This dataset contains both the geographical location of the parking zones in The Hague, as well as their payment rules.

The paid parking zones are split up into smaller zones so that each small zone is included in exactly one neighbourhood. Next, for each smaller paid parking zone, the number of on-street parking spaces per zone is calculated in the same way as in the estimation of the on-street supply. This is multiplied by the parking fees for the parking zone for the average parking duration in The Hague of 109 minutes (Mingardo et al., 2022). Then, for each neighbourhood, these total parking costs per paid parking zone are summed for all paid parking zones in the neighbourhood, resulting in the total on-street parking fee

for the neighbourhood.

Additionally, the parking garages have their own payment rules. The payment rules for the parking garages are retrieved from the same websites as their capacities. The total parking fee per parking garage is calculated in the same way as the total on-street parking fee.

Finally, for each neighbourhood, the total on-street parking fee and the total parking fees for the garages in the neighbourhood are summed. The result is divided by the total parking supply in the neighbourhood, giving an average parking fee for the entire neighbourhood. This average parking fee for the neighbourhood is the parking fee used in the resistance function of Equation 4. This entire process is described by Equation 2.

### 5.4. Assignment The Hague

Due to the estimation techniques used in both the parking supply and parking demand, the final supply and demand numbers are not always integers. Therefore, the requirement for the assignment to be integer was adjusted to allow for any non-negative real number. For interpretation purposes, the final assignment is rounded to the nearest integer.

### 5.5. Simulation

The resulting model was run for two scenarios. Scenario 1 considers the situation for a workday evening in The Hague. Scenario 2 considers the situation for a workday morning in The Hague. The model is validated by comparing the resulting parking occupancy to the actual parking occupancies retrieved from parking occupancy counts performed by the municipality at the same time of day. This counting consists of counting the number of public (on-street) parking spaces that exist in the neighbourhood, and counting the number of cars parked at a given moment (divided into morning, afternoon, evening, night, and other), both inside and outside parking spaces.

During the estimation of the parking supply, it was seen that for some neighbourhoods, the estimated parking supply was much lower than expected, suggesting that data might be missing for those neighbourhoods. To determine which neighbourhoods those are, the ratio between the demand and the supply for each neighbourhood is calculated. For most neighbourhoods, this ratio is less than 1.5, meaning that the demand is at

most 1.5 times the supply. If neighbourhoods with a high ratio are included, a large part of their demand has to be assigned to neighbouring areas. This means a much larger spillover than in reality. The neighbouring areas also have limited supply, leading to these areas also spilling over. In this way, missing supply for one neighbourhood can affect many more neighbourhoods. Allowing for some additional variation, while ensuring that the neighbourhoods with much higher ratios do not negatively influence the model results, all neighbourhoods with a ratio higher than 1.8 are filtered out in both scenarios.

### 5.6. Scenario 1 - Workday evening

The first scenario considered is the situation in The Hague for a workday evening. Figure 12 shows the parking occupancies based on the counts performed by the municipality. Not for all neighbourhoods counts were available from a workday evening. Those neighbourhoods are coloured grey. For some of the other neighbourhoods, multiple counts were available. In those cases, the average of the counted occupancies is used.

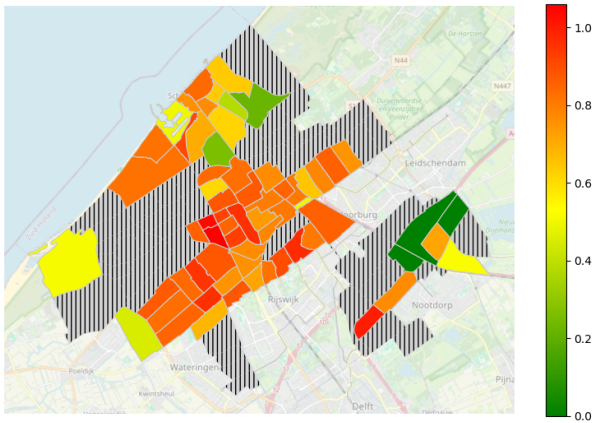


Figure 12: Parking occupancy counts workday evening

In scenario 1, eleven neighbourhoods were excluded. The final assignment was reached after 52 iterations. The occupancies based on the final assignment of scenario 1 are shown in Figure 13. In this figure, the excluded areas are coloured grey, red areas indicate a high parking occupancy, and green areas indicate a low parking occupancy. Some statistics about the assignment and occupancies from this scenario can be found in Table 1.

In this scenario, a third of the considered areas end up with a parking occupancy of over 85%. Inci et al. (2015) showed that as soon as the parking occupancy in an area becomes higher than 85%, the remaining demand decreases. Therefore, parking occupancies higher than 85% can be seen as problematic. From Figure 13 it can be seen that most of the neighbourhoods with such a high parking occupancy are near the borders of the municipality, in *Leidschenveen-Ypenburg* (the separate part located south-east of the main city), and in the city centre.

The parking occupancies estimated by the model for a workday evening are compared to the parking occupancies determined by counting for a workday evening. The difference plot

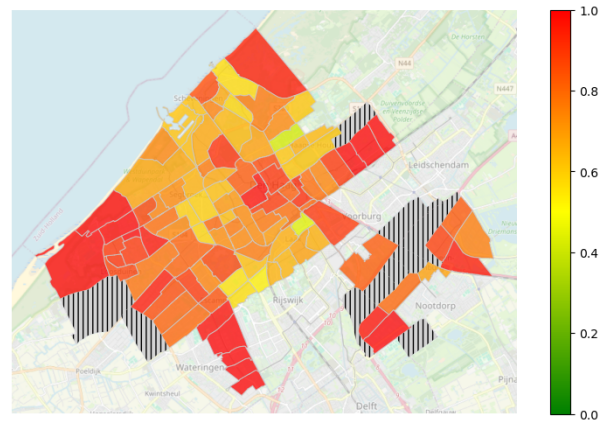


Figure 13: Parking occupancies scenario 1 - workday evening

is shown in Figure 14. In this figure, areas with a difference greater than 0 are coloured orange, indicating that the model overestimated the parking occupancy, and areas with a difference smaller than 0 are coloured blue, indicating that the model underestimated the parking occupancy. Additionally, Table 2 shows some descriptive statistics of these differences.

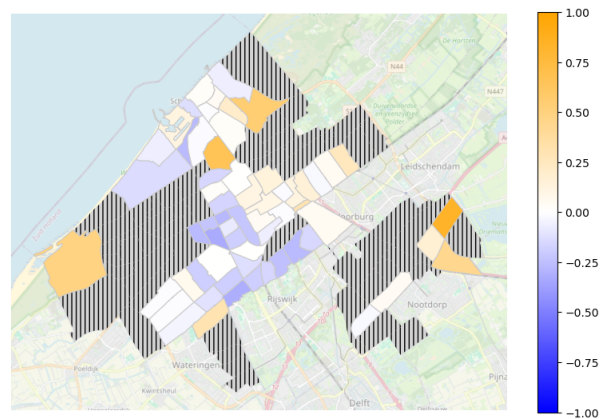


Figure 14: Difference in parking occupancies model and counts scenario 1 - workday evening

In general, the model manages to accurately estimate the parking occupancies. However, there are several areas for which the predicted parking occupancy is more than 0.25 higher or lower than the counted occupancy. There are several possible explanations for these deviations. It is possible that the model does not yet work properly, either due to mistakes in the representation of people's choices, errors in the balance between supply and demand, or simplifications that were made. Additionally, it is likely to be influenced by mistakes in the data or missing data. The accuracy and completeness of the available data strongly depend on the neighbourhood considered. Since there are no available datasets that are known to contain all supply and/or demand for a neighbourhood, the determined supply and demand cannot be easily checked. For supply, it is possible to physically go out and count the parking places in a neighbourhood. This is done during the parking occupancy

counts, but in those situations, only on-street parking places are counted.

### 5.7. Scenario 2 - Workday morning

The model is further validated using a second time of day. If the model were only validated for one time of day, the results could be due to coincidence rather than model performance. By considering a second scenario, the probability of results being due to coincidence is limited.

The second scenario considered is a workday morning in The Hague. On workday evenings, most people are at home, resulting in residential parking supply and demand having the biggest influence on the result. On workday mornings, most people are not home. Therefore, non-residential parking supply and demand have a much bigger influence in this situation. Scenario 2 is therefore a contrasting scenario compared to scenario 1.

The results of the model will again be compared to the values of the parking occupancy counts for a workday morning shown in Figure 15.

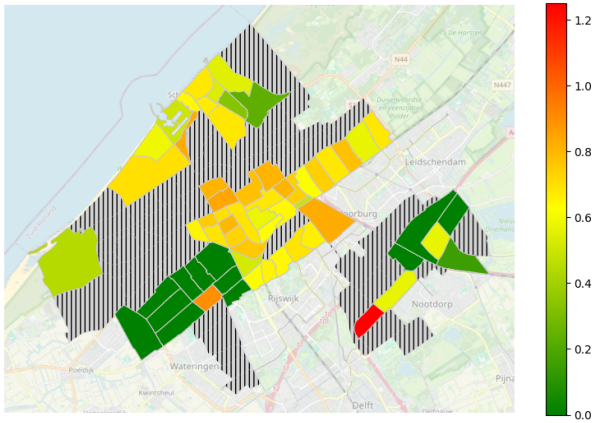


Figure 15: Parking occupancy counts workday morning

Similar to scenario 1, scenario 2 excludes neighbourhoods for which the ratio between the parking demand and parking supply is higher than 1.8, in the same way as in scenario 1. Since the parking demand per neighbourhood in scenario 2 is not the same as in scenario 1, it is possible for the excluded neighbourhoods to not be exactly the same neighbourhoods in both situations. The model takes 82 iterations to reach the final assignment for this scenario. The results are shown in Figure 16, where the excluded neighbourhoods are coloured grey. Table 1 shows some statistics of this assignment for easy comparison with scenario 1.

As expected, for many neighbourhoods, the parking occupancies in this scenario are lower. On workday mornings, many people are away from home. In Figure 16, high occupancies are visible in the city centre, in the outermost neighbourhoods, and in *Leidschenveen-Ypenburg*. For the city centre, this is to be expected. It is an area where the demand is always high, due to the area having all types of functions. There are people living there, as well as shops, offices, recreational activities, and hotels. The available space in the city centre is very limited. Therefore,

Table 1: Model assignment statistics

	Scenario 1	Scenario 2
Number of areas	103	105
Mean	0.78	0.57
Standard deviation	0.16	0.18
Areas under 50%	3	47
Areas over 80%	47	13
Areas over 85%	37	10
Areas over 95%	19	4
Areas 100%	8	1

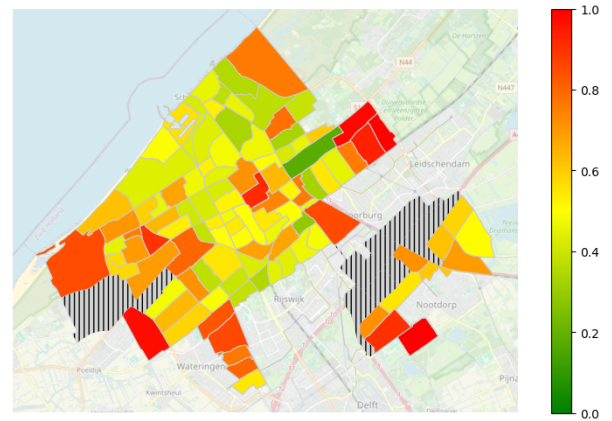


Figure 16: Parking occupancies scenario 2 - workday morning

meeting this high demand with sufficient parking supply is difficult and leads to high parking occupancies.

The high parking occupancies in the outermost neighbourhoods and *Leidschenveen-Ypenburg* are not expected. These areas are outside paid parking zones, making it more likely that the on-street parking supply data is not complete.

Comparing the results of this scenario to the counts of a workday morning in the same way as in scenario 1, gives the difference plot shown in Figure 17. The corresponding descriptive statistics are included in Table 2.

Table 2: Model predictive performance

	Scenario 1	Scenario 2
Number of areas	62	61
Mean difference	0.008	0.009
Standard deviation	0.233	0.341
Minimum underestimation	-0.01	-0.02
Minimum overestimation	0.02	0.02
Maximum underestimation	-0.33	-0.53
Maximum overestimation	0.84	0.97
Areas within 10% difference	26	12
Areas within 25% difference	49	34

The comparison confirms that the high parking occupancies in the outer neighbourhoods and *Leidschenveen-Ypenburg* are overestimations of the actual parking occupancies. This is

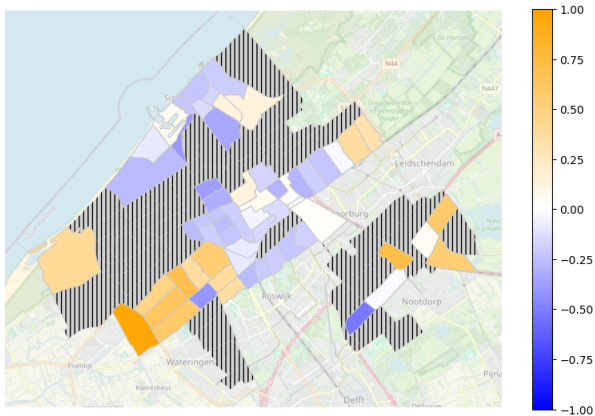


Figure 17: Difference in parking occupancies model and counts scenario 2 - workday morning

likely for the same reasons as in scenario 1.

From Figure 17, it can also be seen that for the areas directly surrounding the city centre and the areas near the beach, the model in this scenario strongly underestimates the parking occupancy. A possible explanation for this is the exclusion of office supply and demand in the model. The assumption was made that all office demand is satisfied by the office supply. However, this may not be entirely accurate and therefore lead to a lower estimated demand than in reality. The effect of this is higher in this scenario than it was in scenario 1, because on workday evenings, not many people have to be at offices, while on workday mornings they do. Excluding office demand and supply, therefore, has a larger impact on the occupancies in scenario 2 than in scenario 1.

Taking a closer look at Table 2, these observations are confirmed. Comparing scenarios 1 and 2, it can be seen that the mean prediction difference for scenario 2 is similar to scenario 1. However, the standard deviation for scenario 2 is higher than for scenario 1, indicating that the prediction of scenario 2 is less accurate than the prediction of scenario 1. For almost half the validated neighbourhoods, the predicted occupancy is more than 0.25 higher or lower than the counted occupancies. This indicates that the model does not yet work as well for a workday morning as it does for a workday evening.

## 6. Conclusion

Many municipalities struggle with an increasing demand for the limited public space to be used for greenery and public amenities. This regularly takes space away from parking, while the parking demand is also increasing. One of the challenges municipalities face when trying to prevent parking problems is the difficulty of predicting the effect possible policy implementations will have on the parking occupancies. Therefore, in this research, an earlier developed conceptual model was transformed into an operational framework and tested using a case study to determine the accuracy of the underlying conceptual process.

During the operationalisation, it was seen that the available data on parking supply is very limited. No data on the amount and location of free off-street parking, illegal parking, and company parking on private property were found, leading to the exclusion of these categories from the model. For the remaining categories, the inclusion is either dependent on the data availability of the considered municipality, or it uses a rough estimate. The exclusion of some of the supply categories means that the estimated parking supply is likely to be lower than the actual parking supply in many areas. These categories are not homogeneously distributed over a municipality, so the precise deviation will vary between areas. The underestimation is partially compensated for by also excluding the demand generated by offices, reducing the effect. Nevertheless, the exclusion of these categories is likely to lead to higher estimated parking occupancies, especially in areas where these categories provide a large supply. Similarly, the flat estimation of residential property supply is likely to skew the predicted occupancies slightly, resulting in higher occupancies in areas where the number of driveways is higher in reality and lower occupancies in areas where the number of driveways is lower in reality.

For the parking demand, the data availability is better. There is no direct data on the actual parking demand per area. However, a combination of car ownership and key figures leads to an estimation of the parking demand that includes all categories. Since the key figures are designed to determine minimum parking requirements, the estimated parking demand is likely to be higher than the actual parking demand, leading to slightly higher predicted parking occupancies.

The information on resistance factors is better. The main factors influencing resistance have been studied before and can thus be directly used.

The operational model framework is tested using a case study on the municipality of The Hague. To validate the model, two scenarios were tested: the situation in The Hague on a workday evening and the situation in The Hague on a workday morning. Since both the estimated supply and estimated demand are expected to lead to higher parking occupancies, the estimated demand in the case study was lowered by 10%.

For some of the neighbourhoods, the available datasets were missing supply data, which would lead to higher occupancies. Therefore, neighbourhoods with missing supply data were filtered out before assigning the parking demand.

Comparing the resulting parking occupancy forecast by the model for both scenarios to the real parking occupancy, the case study showed that the forecast occupancies were generally close to the real occupancies. The predictions of scenario 2, a workday morning, were less accurate than the predictions of the first scenario. This is likely due to the impact of company supply and demand, which were both excluded from the model, but may not have the same values.

To conclude, the conceptual model likely describes the parking system well. However, further testing with more complete data is required to further confirm. This model can likely already be used to predict the impact of simple policy changes on the parking occupancy levels within the municipality's borders, especially when combined with expert judgment.

## 7. Recommendations

The model presented in this thesis is intended as a framework for a parking occupancy model. While it already provides a generally accurate forecast, there is significant room for further development and improvement. First, it is important to further validate the model with complete and accurate supply data, such that no categories or neighbourhoods need to be excluded. The easiest and fastest approach would be to physically count all parking spaces in a municipality. However, then the model can only be validated and used for that municipality. To study the parking system more thoroughly or apply the model to other municipalities, it is better to develop an approach that works for all municipalities. One way to do that would be to develop a way to determine the location of parking spaces from satellite images.

Another way in which the accuracy of the model can be improved is by developing a separate parking demand model that predicts the parking demand per area, taking into account local area characteristics such as the proximity of a train station or the socio-economic background of the neighbourhood. Several models exist that could be used as a basis for the development of such a demand model. The results from the demand model could then be used in the occupancy model to further improve its accuracy.

Improving the supply and demand estimation techniques can also lead to the possibility of using heterogeneous supply and demand, and with that, work towards a heterogeneous resistance function. This allows for better prediction of policy effects. Besides estimating the general effect of a policy, it gives the possibility of determining who is affected, allowing municipalities to specifically target certain groups, such as long-parking vehicles.

While there are many ways the model can still be improved and further developed, the framework developed in this thesis shows that the underlying concept is able to accurately describe the balance between parking supply and demand and, from that, predict the resulting parking occupancies. It combines several existing techniques and data sources with some new techniques, providing an initial step to a full parking occupancy model.

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# B

## Interviews

### B.1. Interview 1

**Job Title:** Traffic Modeller

**Experience:** 1 year at the municipality of The Hague, before that elsewhere

**Short job description:** Working with and developing a new version of the traffic model V-MRDH. Answering (internal) questions about traffic flows using forecasts.

Parking is one of the biggest questions and a source of complaints for residents.

*Explanation of the conceptual model*

#### **What input data is used in the V-MRDH model?**

Many columns of direct input data (SEGs: Socioeconomic Data) are used to estimate traffic movements. Now, 46 columns, which will become approximately 72. These include: car ownership per household (0, 1, 2, 3 or more), simple breakdown by population (under 11, under 34, total), education (Now: basic, other; new classification: basic, secondary, MBO, HBO & WO, special), types of jobs in the labour force (now: industry, services, retail, other, new classification: more). Income is not yet included, but will be included in the future.

This data is available at the neighbourhood level. The model zones are smaller, so they contain an estimate based on the measured neighbourhood level data. We never fill in things that are not known, because we only want to make statements based on things we do know. The model works with a base year (2020) for which all these data are available and then makes a forecast for the forecast years, also from these data (linked to population development).

#### **How is the input determined for the forecast years?**

There is an estimate for population development in general. This development may also be a decrease in certain neighbourhoods. This is supplemented by knowledge about planned construction projects, although it is not always known how many houses a project will contain.

Similar for network development. This is estimated based on current expectations, but it may have to be adjusted again in the future.

#### **How reliable are the results?**

It is good to take into account that sometimes you get results that are not correct. It is especially important that you are able to explain what is happening in the model. Preferably not a black box (or as little as possible). This sometimes gives opportunities to make incorrect results a little more realistic; the question is how much that still says about the situation.

The model is calibrated based on actual traffic counts. It still matters in which order the calibration takes place. Whether a road is viewed first or last has a significant influence. This gives opportunities to try different options in the calibration process.

**In what kind of situations is this model used?**

The most important thing is to predict the effect of a change. In particular, the difference in the forecast year between doing nothing and making an adjustment. Think of introducing 30 as the speed limit for (almost) all roads, making something a one-way street, or closing a street.

In addition, there are questions about cocoon calculations for traffic control systems, where people want to know how much traffic is driving in and out.

Sometimes, also the simple question: how much traffic is driving here?

You can also use it for big questions such as building a metro line or closing the A12. These big questions are almost always outsourced to consultancy firms. If there is time, this will be recalculated. People are often looking for a certain answer. As a result, a question often comes back several times with small adjustments until the answer is acceptable.

**Can you use this model for all changes?**

The model is not very flexible for questions that were not thought of in advance. For example, the vehicle categories do not go beyond light, medium, and heavy. At the same time, you would actually like to know how many of them are electric or within a particular emission category. This is now solved by applying a reduction factor to circumvent the shortcomings.

The model is built for larger roads and waterways. As a result, it is not always correct for small streets. This is solved with the help of another tool that can predict that last bit better. Mainly used for noise calculations.

**Do people easily accept the results of such a model?**

This is accepted quite easily for car traffic, presumably also because it is easier to predict (fewer route options and more data). For cyclists, the route choice is difficult to predict (many more options) and, therefore, more difficult to substantiate. People often do not agree with the cycling predictions.

**At what level of detail would a parking model have to work to be interesting?**

Districts are too big. Neighbourhoods are possible, that is the scale level at which information is often given. However, questions sometimes come in at street level. Streets vary a lot in length, so if you choose streets, you have to attach a fixed length to them. Postal code areas in The Hague are uniquely shaped and often very elongated. For other cities, that would be an option, but in The Hague, this is not practical.

Preferably a little more intricate than neighbourhoods. Above all, try to keep different functions separate.

We do notice that parking problems are really very local.

**How is it determined how many parking spaces will be created somewhere?**

The parking standards that are maintained in The Hague are very complicated due to all kinds of regulations. A large series of if-then statements must be evaluated to determine which standard applies.

**What is the most important thing that a parking model should be able to do?** To give an estimate of the parking pressure and whether parking close to or far away has been successful. And above all, keep it explainable. People accept surprisingly much from models as long as you can explain when things are not going well and what can be tried. As long as you can explain it, even though the result is wrong, people are still willing to use it.

## B.2. Interview 2

**Job title:** Mobility Advisor

**Experience:** 1-2 years

**Short job description:** Advising on safety and the parking standard in construction projects, and making use of data (in this regard). In addition, with regard to reports, complaints, and citizen letters within the parking domain, responsible for the areas where paid parking does not apply (paid parking areas is the responsibility of the enforcement organisation).

### **How do you come into contact with the parking domain in your daily work?**

Legal side: parking policy. Such as issuing building permits tested against the parking policy and writing permit texts.

Subjective/political side: perceived parking pressure. Speaking to residents. This can be due to a pre-announcement of a construction project or existing concerns about parking. The measured parking pressure is not experienced the same by everyone. Sometimes, there is also an imbalance between well-thought-out policy and experienced policy.

### **What are problems within the theme of parking that come up regularly and are difficult to solve?**

Parking is always a point of discussion within developments. It is a cost item for developers, and the standards used by The Hague are perceived as high by developers, which can stand in the way of developments.

At the same time, we notice that residents experience a shortage of parking spaces. This is sometimes a real feeling, that people are afraid that a development in their neighbourhood will cause problems.

Residents are also quick to blame new developments for increasing crowds and problems, while even without these developments, the city is becoming increasingly busy.

### **How is it dealt with when people indicate feeling it will become too busy?**

There are two storylines in this.

The autonomous growth: prosperity increases, the number of inhabitants increases, and so the number of cars increases. This is managed and steered as well as possible by introducing policy measures such as parking regulations. However, the spillover effect must be kept in mind. Sometimes also by indicating powerlessness.

The project-related growth often lies with project teams. It is usually talking to existing residents, explaining that new residents have to park on their own property. Conversation with new residents is sometimes forgotten.

### **How is the choice made between different possible measures in an area?**

This is essentially a political choice. The department does play an advisory role in this. In addition, there is the possibility for residents to apply for parking regulations in their neighbourhood.

### **Does it also happen that residents contact you to express their concerns about parking around their homes? How is this handled? (Resident from existing city, area without parking regulation)**

Yes, that happens. Parking regulation will eventually be introduced in all existing city, pre-Vinex areas (Escamp, Loosduinen, Mariahoeve), so a clear story is available.

That plan is not there in the Vinex and post-Vinex areas, which makes it more difficult to explain. There, you notice that there is a lot of point-by-point parking pressure and a higher perceived parking pressure than the measured parking pressure.

### **How do people react to the suggestion of introducing paid parking?**

Area-dependent. In Escamp, you notice that the problem is so pressing that people are happy with the introduction of parking regulations. In Leidschendam-Ypenburg: "never mind".

### **Do you see any difference in that response depending on the socioeconomic characteristics of a neighbourhood?**

Correlation is visible, but it does not mean the difference is because of it. In Escamp, you see more vulnerable groups and more people who are car-dependent (irregular/night shifts). There, paid parking is experienced as more peaceful out of necessity. In Leidschendam-Ypenburg, you see more cars per household, and the resistance is also higher there.

*Explanation of the conceptual model***Do you see opportunities in the use of such a model in the problems just discussed?**

Yes. It is important that several criteria can be filled in. Mentions, among other things, lowering/increasing the number of parking spaces, parking regulation, and the separation of different types of residents.

**What is the most important thing the model should already be able to do in the short term?**

I remove x parking spaces, that means y for the parking pressure. Possibly being able to adjust the number of inhabitants in the area.

**Are there any situations that have not been mentioned in which you see added value in having a model that can also predict the future?**

It can help create support, both externally (towards residents/developers) and internally (other departments). You notice that many people are unaware of the effects of parking on the city, and then pictures can help paint a picture and substantiate problems.

**B.2.1. Ranking questions***Policy measures (most to least important):*

Being able to determine the effect of...

1. Parking pressure
2. Introducing/increasing parking fees
3. Change in the number of parking spaces
4. Introduction of permit parking
5. Introduction of permit ceiling
6. Places of shared cars
7. Change in payment zone boundaries
8. Adjustment of regime times

*Context factors (most to least important):*

Being able to determine the effect of...

1. New development of housing
2. Type of buildings and building density
3. Socioeconomic environmental factors
4. New development recreational (incl. shopping)
5. New industrial development (offices, schools, ...)

On a scale of:

Policy measures (0) to Environmental factors (100): 70

**Explanation:** *Policy measures are also politically determined, which makes such a tool more interesting for environmental factors*

District Level (0), Neighbourhood Level (33), Postcode4 Level (66) to Postal Code Level (100): 70

More factors (0) to More Detail Level (100): 51

**Explanation:** *Depending on what there is enough reliable data for*

**Suggestions**

- Consider using hexagons as areas instead of the district/neighbourhood boundaries.
- Consider talking to other colleagues; they may have a different idea.

## B.3. Interview 3

**Job title:** Parking Policy Officer

**Experience:** 15+ years

**Short job description:** Work on parking policy within the municipality. When and how to implement or adjust policy. Work on long-term parking strategy.

**How do you come into contact with the parking domain in your daily work?**

The parking domain is my core business. That is mainly thinking about: What is the parking strategy? How can we use parking policy to keep the city liveable and accessible in the future?

This must then be translated into an implementation policy. This is partly the responsibility of another department, but the strategic policy side and parking norms memo (*nota parkeernormen*) is with us. The parking norms memo outlines how many parking spaces you must create in new developments.

**The parking norms memo is based on the parking norms of the CROW. How is it determined where in the bandwidth of the CROW the norms for The Hague are located?**

When updating the memo in 2021, we looked at the car ownership of residents in The Hague. We have linked this to the different housing types. Based on this, it was decided to sit at the lower end of the bandwidth.

In addition, it is also a bit of ambition. We know that if you set the standard too high, you build more parking spaces, which means more cars in the city, and the roads are more congested. Lower standards also help in the mobility transition from people from the car to the bicycle and into public transport.

**What other methods are being used to stimulate the mobility transition?**

There is a discount on the parking norms when focusing on shared mobility. There has been a lot of discussion about that, but a shared car would replace 4-5 passenger cars, so you have to build fewer parking spaces. This is also interesting for developers because it is often financially attractive to offer some shared cars and thus have to build fewer parking spaces. However, we don't know yet to what extent this actually works and in what situations it does or does not.

**What are problems within the theme of parking that come up regularly?**

Of course, what affects the residents most is when the parking pressure is too high. This may, for example, be because norms that are too low have been applied. We try to limit this by setting a permit ceiling. When this was decided, however, it turned out that the system could not yet handle it. As a result, many more permits have been issued than there are parking spaces in the districts in question. There was already a limit per address, but not per district. This causes complaints from residents who want more parking spaces, while the municipality actually wants fewer parking spaces.

At the end of this year, the new system that can handle this ceiling should come into force, but this does not solve the problem yet. People who already have a permit do not lose it. So that will be a process of many years.

**According to the parking norms memo, efforts are being made to have parking on private property as much as possible. This makes dual use difficult. How has that been included in the policy?**

Most development takes place in existing districts. There are already public parking spaces on the street here. They will not disappear. To prevent the pressure in these neighbourhoods from becoming much higher, parking on private property will be realised for the new developments. To ensure that people use these spaces, they are often not entitled to a parking permit, which means parking on the street is impossible.

**Are there any other things you can do if parking pressure is too high?**

People often ask for extra parking spaces. According to our policy, we are not going to do that. However, possibilities are being looked at to make better use of existing parking spaces. This concerns, for example, using the capacity of companies at night for residents. Companies would then get paid for this, which also makes it attractive to them.

**When introducing paid parking, are the wishes of residents taken into account?**

The policy plan first stated that paid parking would be introduced in many districts on the condition that there was support for it. This has since been adjusted so that support is no longer necessary but still includes resident participation.

**The window times for paid parking in The Hague are very varied. How are these determined?**

This was mainly based on the type of parker that should be banned by the introduction of paid parking. As a result, there are now many different regimes. This will be reduced to about three regimes.

**Experiments have been carried out in Scheveningen with a fixed daily rate. How was the effect of this determined?**

A combination of parking pressure counts, parking duration measurements, and conversations with residents and entrepreneurs.

*Explanation of the conceptual model***Do you see opportunities in the use of such a model in the problems just discussed?**

For example, in the study into the use of parking spaces at companies. It is easier to achieve if you can show the effect in advance. So mainly to substantiate policy interventions in the communication to the council.

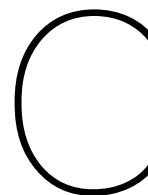
The same applies to the introduction of a permit ceiling, to map out the effect of this.

**Are there any situations that have not been mentioned in which you see added value in having a model that can also predict the future?**

It can also be useful in communicating with residents.

**Do you have any further suggestions?**

It is important to include permit limits. Someone with a permit for one area is not likely to park in another.



## Linking BAG and CROW functions

Table C.1 shows for each BAG category, which categories of the attendance percentages are linked to it. The resulting attendance percentage for the BAG category at the considered time of day, is the average of the attendance percentages of the categories linked to it.

**Tabel C.1:** Mapping between BAG functions and attendance percentage functions

<b>BAG category</b>	<b>Attendance categories</b>
bijeenkomstfunctie celfunctie gezondheidszorgfunctie	Bioscoop/theater/podium/enzovoort  Sociaal medisch: arts/therapeut/consultatiebureau, verpleeghuis/ verzorgingstehuis, ziekenhuis: patiënten inclusief bezoekers, zieken- huis medewerkers
industriefunctie kantoorfunctie logiesfunctie onderwijsfunctie sportfunctie winkelfunctie woonfunctie overige gebruiksfunctie	Kantoor/bedrijven, commerciële dienstverlening Kantoor/bedrijven, commerciële dienstverlening Restaurant Dagonderwijs, avondonderwijs Sportfuncties binnen, sportfuncties buiten Detailhandel, grootschalige detailhandel, supermarkt Woningen bewoners, woningen bezoekers

Additionally, Table C.2 shows for all BAG functions which CROW functions have been linked to it, as described in section 4.3. Additionally, it shows which CROW should be linked to it, but are excluded due to the key figures not being based on surface area size. An additional row is added showing which CROW functions are not matched because they got a footnote of 'inaccurate key figures' in the CROW publication. An extra column shows CROW functions that were initially not included, but for which the parking memo published by The Hague contained key figures based on surface area size. The functions listed in this column were used in addition to the originally included CROW functions during the case study of chapter 5.

Tabel C.2: Mapping between BAG functions and CROW functions

BAG functions	Included CROW functions	Excluded CROW functions	Additional from parking memo
Bijeenkomstfunctie	Bibliotheek, biscoop, filmtheater/filmhuis, theater/schouwburg, musicaltheater, casino, dansstudio, wellnesscentrum, sauna/hammam, indoorspeeltuin/kinderspeelhal, discotheek	Bowlingcentrum, bijtencentrum/snoo-kercentrum, golfoefencentrum, golfbaan	
Celfunctie		Penitentiaire inrichting	
Gezondheidszorgfunctie		Huisartsenpraktijk, apotheek, fysiotherapiepraktijk, consultatiebureau, consultatiebureau voor ouderen, tandartsenpraktijk, ziekenhuis	Ziekenhuis/medisch centrum, verpleeghuis, arts/maatschap
Industriefunctie	Bedrijf arbeidsintensief/bezoekersex-tensief, bedrijf arbeidsexpensief/bezoekersexpensief		
Kantoorfunctie	Kantoor (zonder baliefunctie), commerciële diensverlening (kantoor met baliefunctie), bedrijfsverzamegebouw		
Logiesfunctie		Camping, bungalowpark, hotel	Hotel/hostel werknemers
Onderwijsfunctie	Kinderdagverblijf	Basisschool, middelbare school, ROC, HBO, universiteit, avondonderwijs of vrijetijdsonderwijs	Primair onderwijs, middelbaar onderwijs, ROC, HBO/WO
Sportfunctie	Fitnessstudio/sportschool, fitnesscentrum, sporthal en sportzaal, tennis-hal, squashhal, zwembad (overdekt), zwembad (open lucht), kunststijbaan	Stadion, skihal	

Tabel C.2: Mapping between BAG functions and CROW functions

BAG functions	Included CROW functions	Excluded CROW functions	Additional from parking memo
Winkelfunctie	Supermarkt, groothandel algemeen, stadsdeel-, wijk-, buurt- en dorps(winkel)centrum, kringloopwinkel, bruin- en witgoedzaken, woonwonenhuis/woonwinkel (overig), woonwonenhuis (zeer groot), meubelboulevard/woonboulevard, winkelboulevard, outletcentrum, bouwmarkt, tuincentrum, groencentrum	Binnenstad of hoofdwinkel(stads)centrum	
Woonfunctie		<i>Not based on CROW</i>	
Overige gebruiksfunctie		Opslagruimte (particulier), volkstuin, crematorium, begraafplaats	
CROW footnote inaccurate		Groothandel specialist, weekmarkt/-klein wijk-, buurt- en dorpscentrum, museum, zwemparadijs, sportveld, stadion, ski- en snowboardhal, jachthaven, kinderboerderij, manege, dierenpark, attractie- en pretpark, plantentuin, padelhal, Café/bar/cafetaria, Restaurant, evenementenhal/beursgebouw/congresgebouw, religiegebouw, verpleeg- en verzorgingstehuis, gezondheidscentrum	

# D

## Parking demand workday morning

The ten neighbourhoods with the highest and lowest estimated residential parking demand for a workday morning in The Hague are included in Tables D.1a and D.1b.

**Table D.1:** Highest and lowest residential parking demand workday morning The Hague

(a) Ten neighbourhoods with highest residential demand workday morning

Neighbourhood	Res demand
Leyenburg	3459
Houtwijk	2841
Kraayenstein en Vroondaal	2424
De Vissen	2241
Statenkwartier	2157
Hoge Veld	2136
Schildersbuurt-West	2109
Dreven en Gaarden	1971
Laakkwartier-Oost	1953
Zeeheldenkwartier	1893

(b) Ten neighbourhoods with lowest residential demand workday morning

Neighbourhood	Res demand
Oostduinen	0
Tedingerbroek	0
Zuiderpark	30
Vlietzoom-Oost	39
Rivierenbuurt-Zuid	99
Vliegeniersbuurt	102
Bosjes van Pex	111
Haagse Bos	129
De Reef	186
Vlietzoom-West	207

The ten neighbourhoods with the highest and lowest estimated non-residential parking demand based on the CROW key figures for a workday morning in The Hague are included in Tables D.2a and D.2b.

**Table D.2:** Highest and lowest CROW parking demand workday morning The Hague

(a) Ten neighbourhoods with highest CROW demand workday morning

Neighbourhood	CROW demand
De Rivieren	4106
Kerketuinen en Zichtenburg	3977
Leyenburg	3531
Kortenbos	2893
Vliegeniersbuurt	2694
Binckhorst	1956
Rosenburg	1951
Laakhaven-West	1767
Zuidwal	1539
Houtwijk	1417

(b) Ten neighbourhoods with lowest CROW demand workday morning

Neighbourhood	CROW demand
Lage Veld	17
Arendsdorp	20
Componistenbuurt	21
Parkbuurt Oosteinde	23
Waldeck-Zuid	31
Marlot	34
De Bras	35
Spoorwijk	36
Haagse Bos	49
Duindorp	57