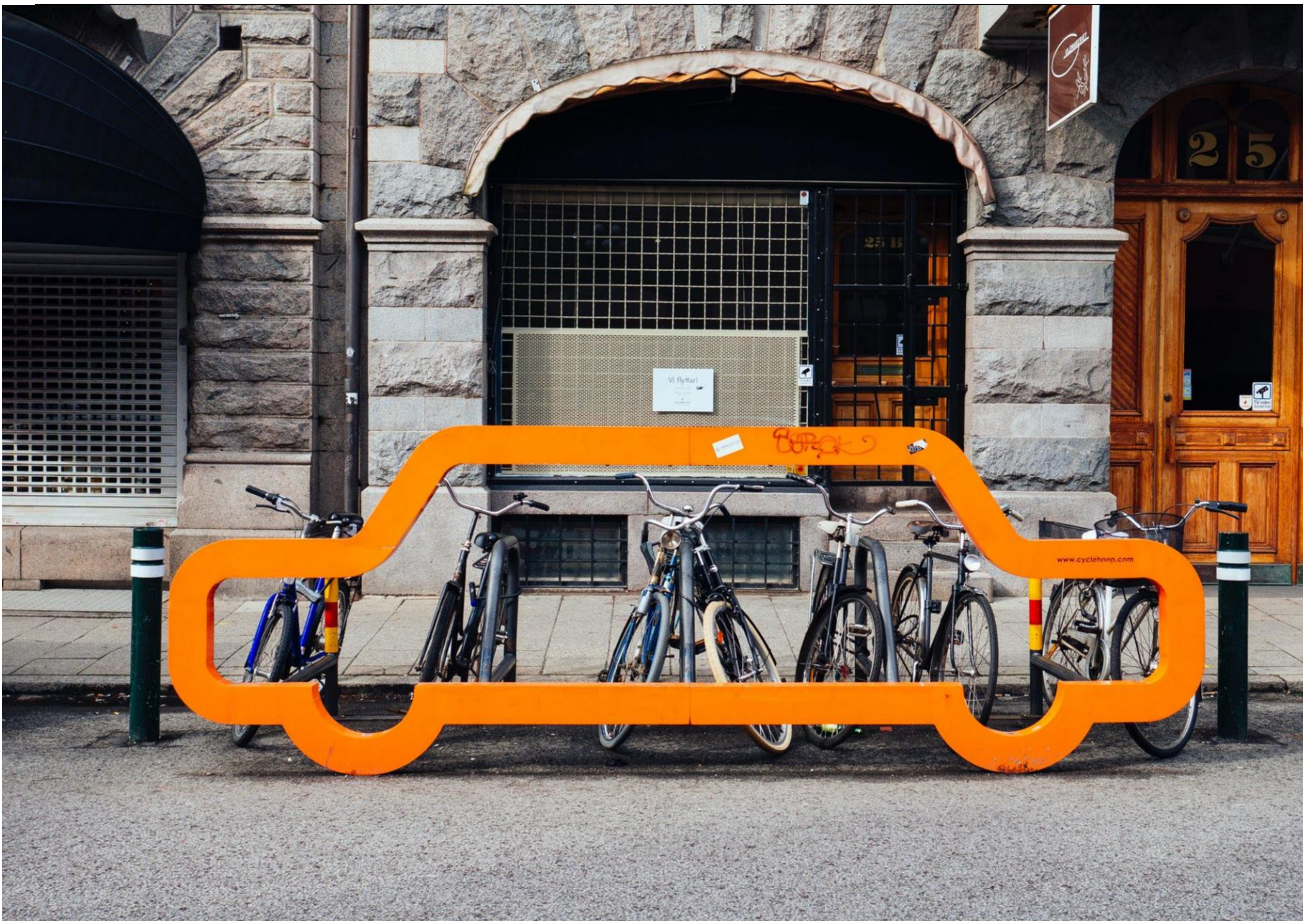
Master Thesis

Converting car parking to bicycle parking:
A GIS-Based Method Using a Location-Allocation Model

Bingyu Zhang



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Converting car parking to bicycle parking

A GIS-Based Method Using a Location-Allocation Model

By

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at the Delft University of Technology

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The Resilient City Hub

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Preface

This report marks the end of my two and half years studying in TU Delft. Because of the interest of human behaviour, transport is my favourite infrastructure topic. It deals with people's daily life and have the interaction with people. That is why I want to study something about bicycles in the Netherlands. In a cycling country, studying cycling infrastructure, why not!

During the roller coaster of my graduation project, I have gone through many challenges. From knowing nothing about GIS, now I can use it to do analysis with various geoprocessing tools. And all the days that I spent to compare the GIS data with street map to manually check their errors, finally offering me many insights of people's real behaviours that cannot be read from the data. Everything worth the effort.

Here I would like to thank my supervisors who are always kind and helpful during the past months. I would like thank Bert for his expertise and always helpful suggestions. Kees for all the time and effort he spent to help me from improving my research design to thesis writing. And if without Benjamin and the Resilient City Hub, it is impossible for me to get the opportunity to study this research question in the Municipality of Leiden. Also, many thanks give to Wouter for sharing his expertise on everything he knows about bicycles parking and being supportive all the time.

I would also like to thank all the colleagues and experts that have helped me with the interview, data collecting, workshops or the coffee and tea during my internship at Gemeente Leiden: Peter Matzken, Amit Akbar, Remco Bruijnes, Jan Smit, Ronald Haverman, Jacob de Vries, Stan van de Hulsbeek, Edwin van der Gracht, Viola van Alphen and everyone in the office 2.35. In addition, I would like to thank Carolien for all the days we spent together working on our thesis at the office and all the warm encouragement from her. Thanks to my friends for their company, dinners, suggestions and encouragement during the rough days. Special thanks to Xiaolin and Yichen for their late-night peer review. Last but not least, thank my mom and dad for supporting me studying in the Netherlands.

Bingyu
Delft, March 2019

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Summary

Many cities worldwide are promoting cycling as a solution for sustainable urban mobility problems. To achieve this goal, providing sufficient bicycle parking facilities is one of the key determinants. In the Netherlands, there is a shortage of bicycle parking facilities. The Dutch cities are ambitious to solve this problem and provide sufficient bike parking facilities to cyclists. However, the main difficulty is the lack of space, especially in the city centre. The 'car-free' city concept is more and more popular these days. This provides cities with the opportunity to use converting car parking to bicycle parking as a solution for bicycle parking shortage. Yet there is no precedent study and much uncertainty exists.

Based on the number of cyclists, how many car parking spaces are needed to accommodate the bicycle parking demand can be calculated. However, not only the required number of bicycle parking facilities but the location of bicycle parking is also important and cannot be obtained through some simple calculation. Therefore, this study aims to develop a method that can be used to allocate bicycle parking facilities to the optimal car parking locations. The Location-allocation model is aimed to locate the new facilities at the optimal locations that can best serve the demand with minimum transport cost. With the support of geographical information system (GIS), location-allocation problems can be solved accurately and efficiently because of its helpful geoprocessing and display functions, availability of data and the ability to handle a large volume of data and calculation.

The main research question is as follows:
"How to optimize the trade-off between bicycle parking and car parking using a GIS-based location-allocation method?"

Subquestions were designed in order to answer the main research question step by step. They are: What are the spatial requirements for bicycle parking, car parking and sidewalks? What are the challenges faced by municipalities of converting car parking to bicycle parking? What are the possible scenarios based on the number and characteristics of converted car parking spaces? Under each scenario, how much residential bicycle parking demand can be satisfied and how will it affect shopping area bicycle parking capacity? Under each scenario, how much car parking demand cannot be satisfied? Under each scenario, how much nuisance of randomly parked bikes can be reduced?

The city centre of Leiden is used as the study case due to its high bicycle ownership, low car ownership and scarce space. Because of the high demand-low supply characteristic, the result of this case study can also be used to examine the spatial feasibility of using car parking space to solve the bicycle parking shortage problem. The study scope is focused on residential parking demand and visitor parking demand in the shopping area. First, the residential bicycle parking demand was analysed using location-allocation. After allocating residential demand, its impact on the shopping area bicycle parking shortage was discussed. This sequence is because residents occupy a large number of bicycle parking facilities in shopping area during shopping peak hour. Only if the residential bicycle parking shortage around the shopping area

is relieved, the bicycle parking shortage for shopping area visitors can be relieved.

Before the location-allocation analysis, a literature review was conducted to investigate the requirement on the public space from the three main stakeholders i.e. cyclists, car owners and pedestrians. With the acknowledge of those requirements, the stakeholders' gains and losses from the conversion of car parking space can be assessed based on whether their requirements are met. According to the result, cyclists want enough capacity to park their bicycles as close as possible to their home or other destinations. With no enforcement on bicycle parking violation, when the parking facility is located outside of the acceptable walking distance, which is 50 metres, there is a high risk that the bicycle parking facility will not be used. And when there is no bicycle parking facility, cyclists often randomly park their bicycles on the sidewalks. This hinders the walkability of pedestrians. The sidewalk should have at least an obstacle-free width of 1.5 metres to allow people in wheelchairs to use it comfortably and safely.

Then, a literature review on public reaction to Oslo's car parking ban policy was conducted to investigate if there was any difficulty of implementation of the policy. The lesson learnt from Oslo is that the car parking ban should not be implemented within a very short time and on a very large scale. Residents need time to adapt to the new policy and the communication with local people is important. Then, through several exploratory interviews with civil servants who are working on bicycle parking and car parking at the municipality of Leiden, their concerns about converting car parking to bicycle parking were collected. One challenge is that the current car parking occupancy at night is already very high in some neighbourhood. The other is that the nuisance of randomly parked bicycles is common in the city centre while the sidewalks are too narrow to install bicycle parking facilities.

To apply the location-allocation, the demand and facility data were needed. Through pre-geoprocessing, the 'population address data' was used for calculating the bicycle parking demand. According to Dutch building regulation and laws, buildings before 1950 were not obligated to providing indoor bicycle parking facilities. Based on this knowledge, People live in buildings built before 1950 are assumed to have the demand for public bicycle parking facilities. The bicycle parking demand in the shopping area was also collected and categorised to different user groups, parking duration and parking location.

Then, the facility data, i.e. car parking space data was collected. Based on the result of the literature review and interview with local city planners, three scenarios with different numbers and characteristics of converted car parking spaces were designed. Scenario 1 favours car owners. Only the car parking space which is empty during the night was used as bicycle parking candidate. Scenario 2 favours cyclists. In this scenario, as much as possible of car parking spaces were converted to bicycle parking. This scenario will show the maximum capacity of using car parking spaces to solve the bicycle parking shortage. Scenario 3 favours pedestrians. Under this scenario, those car parking spaces, which were located next to or opposite to a sidewalk narrow than minimum width of 1.5 metres, were removed. The spared spaces could be used for widening the sidewalk.

There are different problem types of location-allocation model. In this study, the goal was to satisfy as much bicycle parking demand as possible with minimum walking distance and the bicycle parking facilities have a capacity limitation. Based on these characteristics, 'maximum capacitated coverage' is the proper model. First, the current bicycle parking demand was allocated to existing bicycle parking facilities. Then the demand could not be satisfied by existing bicycle parking facilities were allocated to car parking spaces according to each scenario. After solving the location-allocation model, the number of satisfied demands, the number of used car parking spaces were obtained.

The demand points that cannot be satisfied by existing facilities and car parking under each scenario were used to illustrate the density map of unsatisfied demand using point density in ArcGIS software. How much bicycle parking demand has been satisfied by car parking spaces under each scenario can be visually observed from the map and the results were also presented by quantitative data.

For the residential area, under scenario 1, only 17% of the bicycle demand can be satisfied and the car parking space occupancy is 90%. Under scenario 2, 82% of the demand can be satisfied but after conversion, the car parking space capacity will drop to 81%. Under scenario 3, 65% of the demand is satisfied and only 69% of the car parking demand can be satisfied. 668 car parking spaces were removed for widening sidewalks.

As for the shopping area, half of the bicycle parking facilities were occupied by residents during the shopping peak hour. After car parking conversion, if the bicycle parking demand of residents living in the shopping area can be satisfied by car parking spaces, then the facility in the alleys can be used by more short-term parking visitors. Based on the results, the capacity can increase 511 under scenario 2 and scenario 3. Combine with the supporting measure of adding capacity by replacing bicycle parking racks, the total capacity can accommodate all the short-term parking demand. Under scenario 1, there was no possibility of increasing bicycle parking capacity around the shopping area.

Given the fact that Leiden is a city with high bicycle parking demand and low possibility of providing facility supply through car parking due to the low car ownership, under scenario 2, 82% of the residential demand and all the short-term shopping area bicycle parking demand can be satisfied by converting car parking space. This result proves that using car parking spaces to solve the bicycle parking shortage is effective. For cities with lower bicycle parking demand and more car parking spaces, the result could be even better.

However, if a city wants to convert car parking to bicycle parking, three things are important. First is good communication with residents. It should be confirmed that the residents have the bicycle parking need and they will actually use the converted space, or it will be a waste of public space. Secondly, it is important to have bicycle parking regulation. This study was based on the presupposition that cyclists will park their bicycles in the designated area if it is within proper walking distance. Without enforcement on bicycle parking violation, there is a risk that the new facilities will not be used. And in the shopping area, the regulation should take parking duration into consideration. Third, some of the car parking demand cannot be satisfied after the conversion. There are two ways to reduce the on-street car parking demand, one is to use several measures to reduce car ownership. The other is to engage car owners to use alternative car parking facilities, including the parking garage, P+R parking, collaboration with private parking, etc.

As for academia, currently, the academic studies on bicycle parking behaviour is too limited. There are no studies on city centre maximum walking distance for bicycle parking per trip purpose or per parking facility type. The data that was used in this study was acquired from the survey on short-term bicycle parking. This data is probably not the best data for residential bicycle parking. The regulation on bicycle parking is also a huge knowledge gap. There was only one study in Japan and there is no study in a Dutch circumstance yet. For converting car parking to bicycle parking, there are several interesting aspects to be investigated in the future, for example, what will be the environmental impact, economic impact and travel mode impact can be studied in the future.

Since this is a data-driven method, there are some limitations. First of all, the data used for analysis was not perfect that some data was collected at the different time. And the demand is estimated by the population living in the old building due to the lack of data on the building's indoor bicycle parking availability. The commuter's bicycle parking demand is not included in the scope because of the lack of data. And if time possible, some interview or survey can be used to investigate residents' bicycle parking behaviour, their opinion on using on-street parking facilities, etc.

Content

List of Tables

List of Figures

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1. Introduction

1.1 Problem definition

Many cities worldwide are promoting cycling as a solution for sustainable urban mobility problems. To achieve this goal, providing bicycle parking facilities is one of the key determinants (Noland and Kunreuther, 1995; Pucher, 1998; Abraham et al. ,2002; Dickinson et al. ,2003; Stinson and Bhat, 2004; Hunt and Abraham, 2007; Martens, 2007; Pucher & Buehler, 2008; Van der Spek & Scheltema, 2015). According to Scheltema's theory (2012), bicycle parking capacity is one of the pre-conditions for successfully providing cyclists with public space. Without adequate parking facilities, cyclists will park their bicycles improperly anywhere (MKB Delft,2012). Randomly parked bicycles in a city hinder the mobility of pedestrians and reduce the aesthetic of the city (Pucher & Buehler, 2008). Thus, sufficient bicycle parking facilities are essential for cycling promotion and urban planning.

In some countries, such as the Netherlands and Denmark, cycling has already been a mainstream mode of transport, especially for trips shorter than 4.4 kilometres (Pucher & Buehler, 2008). However, this widespread of the bicycle leads to new problems. For example, in many European cities, the shortage of bicycle parking facility has become an issue (Larsen, 2015). At specific times and location, the capacity of bicycle parking has reached its maximum capacity (Van der Spek & Scheltema, 2015). In the Netherlands, cities are ambitious to solve this problem. Currently, in the Netherlands, there are 450,000 bicycle parking spaces near train stations while another 600,000 are planned in 2030 (Bitibi,2017). Correspondingly, more parking facilities in the inner city will also be planned. For example, Amsterdam plans to provide 80,000 extra bicycle parking places in the city by 2040 (Gemeente Amsterdam, 2015).

However, it is not easy to provide sufficient bicycle parking facilities as the streets are already very crowded. Cyclists are competing with cars, pedestrians, buildings and plants for more space (Van der Spek & Scheltema, 2015). In the historic city centre, this competition is even fiercer as the public space is scarcer than the new urban districts.

Therefore, cities who want to promote cycling while having no space for sufficient bicycle parking are facing the problem that it is very difficult to provide more space for bicycle parking infrastructure. Especially bicycles are often be given lower priority. The bicycle infrastructure was often being planned in a manner that keeps bicycles "out of the way" of motorized traffic(García-palomares, Gutiérrez, & Latorre, 2012). Compared to motorized individual transport, the urban space that allocated to bicycle infrastructure is very few(Gössling, Schröder, Späth, & Freytag, 2016).

Van der Spek and Scheltema put forward some possible solution of bicycle parking shortage, one is to replacing car parking space. The opportunity of implementing this solution lies in the 'Car-free city' concept, which has been put forward by many cities around the world (Cathcart-Keays, 2015). Oslo is the first city that announced to ban city centre private car usage by banning on-street parking space (Cathcart-Keays, 2017). In addition, the on-street car parking pricing has been discussed by many spatial economic studies (Vickrey, 1969; Arnott et al., 1991; Verhoef et al., 1995; Shoup, 2004; Borger & Wuyts, 2007; Proost & van Dender, 2008; Van Ommeren, Wentink & Dekkers, 2011) and studies proved that the cities are providing car parking space on-street at too high welfare costs (Van Ommeren, Wentink and Dekkers, 2011).

A parked bicycle occupies much less parking space than a car: one car parking space can accommodate eight to fourteen bicycles (see **Figure 1**). Therefore, converting car parking to bicycle parking seems to be a possible solution to solve the bicycle parking shortage problem and this conversion can also improve the public domain quality (Van der Spek & Scheltema, 2015).

The shortage of bicycle parking facility leads to the random parking of bicycles. The randomly parked bicycles impede the pedestrians on the sidewalk (Pucher & Buehler, 2008). And converting car parking space means less car parking capacity. Yet there is no study about the trade-off between car parking and bicycle parking. The parking behaviour of cyclists and car owners also varies. It is uncertain that whether a car parking location acceptable by car owners can also be accepted by cyclists. These factors make the feasibility of parking space conversion a complex problem.

Figure 1 An example of converting car parking to bicycle parking in Utrecht (Municipality of Utrecht,2010)

1.2 Knowledge gap

Currently, not only policymakers but also scholars are increasingly interested in cycling. However, studies about bicycle parking is still limited (van der Spek & Scheltema, 2015). Especially for conversion of car parking and bicycle parking, much less is known. Until now, Lee and March (2010) published the only study about converting car parking space to bicycle space. They used a survey to investigate the economic impact of relocating car parking to bicycle parking and the scope was restricted to the retail area. On the one hand, the residential bicycle parking shortage problem was not in their study scope whereas this problem is faced by many Dutch cities (van der Spek &

Scheltema, 2015). On the other hand, in their study area, car usage is much higher than bicycle usage. In this case, converting a small amount of car parking space is already enough for accommodating bicycle parking demand. However, in the Netherlands, some cities have a very high cycling rate, thus the bicycle ownership is much higher than car ownership. Taking Leiden as an example, in the city centre, 90% of residents own bicycles while only 21% of them own cars (Gemeente Leiden,2017). The bicycle parking demand is very high while the car parking spaces that can be converted are not that much.

In practice, there are examples of converting car parking to bicycle parking space from Europe to the United States (Gemeente Utrecht, 2010). But these conversions are usually sporadic. Oslo was the first city who announced to remove all the on-street parking spaces in their city centre for the cycling infrastructure and other facilities for pleasant city life. Their cycling network was still under construction and the rise of cycling rate still needs to be awaited (Bliss, 2018).

But in the Netherlands, there are already cities with high cycling rate. And there is no precedent academic study or practical example of replacing car parking with bicycle parking on a large scale yet. Therefore, much uncertainty is existing in this innovative public space relocation between bicycles and cars.

1.3 Research objective

The objective of this study is two-fold. On the one hand, how much space is needed for solving the bicycle parking shortage can be easily calculated based on the number of cyclists. Then how many car parking spaces are needed to accommodate the bicycle parking demand can also be calculated. However, not only the required number of bicycle parking facilities, but the location of bicycle parking is also important and cannot be obtained through some simple calculation. Therefore, this study aims to develop a method that can be used to allocate bicycle parking capacity facilities to optimal car parking locations. Based on the result, it can help cities to have a better view of the bicycle parking shortage problem and make a better decision on their public space distribution. The alternative bicycle and car parking facilities, such as off-street parking garage or neighbourhood parking, is often with a high construction cost. Based on the result of converting car parking to bicycle parking, the necessity of providing off-street parking can be evaluated based on if there is a high bicycle parking demand that cannot be satisfied by car parking.

On the other hand, the aim is to examine if converting car parking to bicycle parking is a good solution for bicycle parking shortage. Based on the case study in a city with high bicycle ownership and low car ownership, this research shows how effective it is for solving bicycle parking shortage problem.

1.4Research questions

In order to achieve the research objective, the main research question is:

How to optimize the trade-off between bicycle parking and car parking using a GIS-based location-allocation method?

The sub-questions are:

1. What are the spatial requirements for bicycle parking, car parking and sidewalks?
2. What are the challenges faced by municipalities of converting car parking to bicycle parking?
3. How much is the residential bicycle parking demand in the city centre of Leiden?
4. What are the possible scenarios based on the number and characteristics of converted car parking spaces?
5. Under each scenario, how much residential bicycle parking demand can be satisfied and how will it affect shopping area bicycle parking capacity?
6. Under each scenario, how much car parking demand cannot be satisfied?
7. Under each scenario, how much nuisance of randomly parked bikes can be reduced?

1.5 Research scope

1.5.1 Geographical range

In historic city centres, space is scarcer, and many residential buildings do not or hardly provide their inhabitants with in-door parking facilities (van der Spek & Scheltema, 2015). Although the train stations also face the bicycle parking shortage problem (Molin & Maat, 2015; Bitibi, 2017), they are excluded from this study. Because parking behaviour at train stations is very different from city centre parking behaviour that the significantly high demand is concentrated at one destination. The shortage of bicycle parking around train station problem cannot be easily solved by replacing car parking spaces. Instead, it is possible to solve the bicycle parking shortage problem around the train station area through a new pricing policy (Molin & Maat, 2015). Therefore, train station bicycle parking is out of the study scope.

1.5.2 User group

Different user groups will be affected by bicycle parking in the city centre, including inhabitants, visitors and shopkeepers (MKB Delft, 2012). Inhabitants concern bicycle parking facilities at the home side. Visitors concern commercial and retail centres, and recreation areas (Rybarczyk & Wu, 2010). It is often difficult for visitors to find an available bicycle parking facility as many racks are occupied by local residents (Van der Spek & Scheltema, 2015). In the historic city centre, the shopping street is often without on-street car parking space due to the narrow streets. However, in the surrounding streets, there are car parking spaces. This study will investigate that if the residential bicycle parking demand in the shopping area is satisfied by car parking space, how will it affect visitor bicycle parking.

Commuters are excluded from this study. Based on the opinions of experts, the parking duration of commuters is usually long, therefore many companies and schools have their own car or bicycle parking facilities for their employees or students. It is undeniable that many employees working in the historic city centre, for example, if a shopping area has no access to the private bicycle parking facility, it will be difficult to collect the demand and capacity data of these private parking facilities. Therefore, the commuters will be neglected. However, if the data are available, then this user group could be taken into consideration in the future.

1.5.3 Presupposition

According to van der Spek and Scheltema(2015), the enforcement on bicycle parking violation is significant for reducing random bicycle parking. This study is not aimed at investigating how to regulate people to properly park their bicycles in the designed area. Thus, a presupposition is that, with certain regulation or measures, cyclists will park their bicycle at the designated area when the location of the bicycle parking facility is located within a proper distance.

1.6 Scientific and practical relevance

As stated in section 1.2, less is known about what if a city converting car parking space to bicycle space in their city centre. It can be analysed in various aspects, including environmental, economic, human health, etc. However, all the analysis should be based on how much car parking spaces will be converted. It is also unknown if all the car parking spaces are suitable to be used as a bicycle parking space. Therefore, this study can be used as the first step for further studies. Public space allocation is the most direct impact of converting car parking spaces to bicycle parking spaces. Developing a method that can quantify the improvement of bicycle parking capacity and sidewalk width and also the decrease in car parking capacity, then many possible studies can be implemented in the future.

In the past car-oriented age, the importance of bicycle parking management is often neglected by city planners due to its high flexibility (van der Spek & Scheltema, 2015): Cyclists were assumed to find a place to park by themselves from the scarce public space. Now, the situation will be changed. With the popularity of 'car-free city' concept, many cities are ambitious about shifting from car-oriented city to a car-free city. In the foreseeable future, cities need a valid method to evaluate the impact of the switch in advance. With a method to quantify the lost from the car owners and gains from the cyclists and pedestrians, the city planners can have a picture of the result in advance and design mitigation measures or find alternative facilities to relieve the pressure from car owners and retailers.

This method can also reveal the district where bicycle parking demand cannot be satisfied by on-street parking. Then the more expensive options, for example, public garages or neighbourhood parking garage, can be implemented.

1.7 Research method

In this study, a data-driven approach is proposed for quantifying the result of public space relocation between car parking, bicycle parking and sidewalks based on GIS (Geographic Information System) location-allocation analysis. The research methodology is explained as follows.

1.7.1 A case study in Leiden: why Leiden

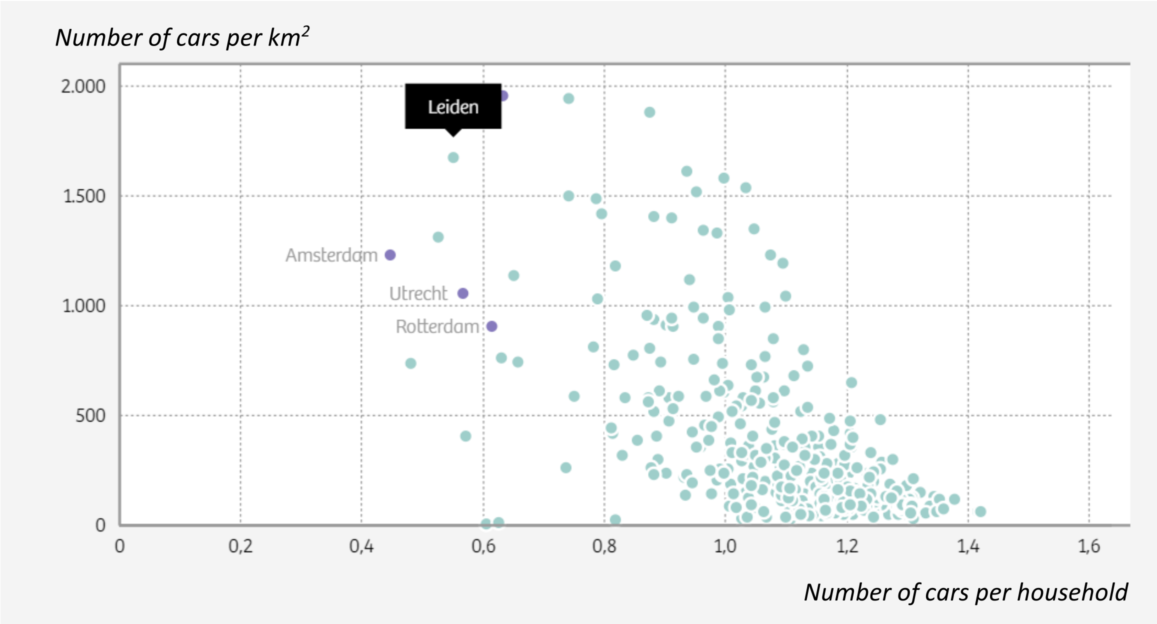

Figure 2 Cars per household versus cars per km^2 in the Netherlands (Data: CBS; Source: Frederik, 2018)

In this report, the city centre of Leiden will be used as the study case. Leiden is a typical historic city in the Netherlands with high cycling usage and low car ownership (see **Figure 2**). In its compact city centre, 90% of residents own bicycles while only 20% of them own cars. There is a huge demand for more bicycle parking due to its high cycling rate and a large amount of old building without in-door bicycle parking storage space. This demand is difficult to be satisfied by installing parking facilities in the pedestrian area because of the scarce space. In their latest planning scheme, Leiden aims at providing its residents with a car-free city centre. Therefore, Leiden is a very good example of Dutch cities to study.

1.7.2 Methodology

When planning public facilities, not only the required size of space is important, but also it is important to know where to locate the facilities. The Location-allocation model is aimed to locate the new facilities at the optimal locations that can best serve the demand with minimum transport cost (Azarmand & Neishabouri, 2009). Therefore, solving the location-allocation problem is important when implementing public facility planning. Scholars have developed different algorithms to solve different type of problems (Azarmand & Neishabouri, 2009). Associated with GIS, the location-allocation algorithm can be applied accurately and efficiently(Pratt, Moore, & Craig, 2014; Yeh & Chow, 1997). Using the built-in extension that included in some GIS software is one of the simplest ways to solve the location-allocation problem(García-palomares et al., 2012). At the same time, GIS is able to quantify and visualize the bicycle parking capacity allocation result. So the policymakers can have a better view of the problem and solutions(Yeh & Chow, 1997).

In order to solve the bicycle parking allocation problem and to assess how it affects car parking and sidewalks, a five-step methodology is designed as **Figure 3**.

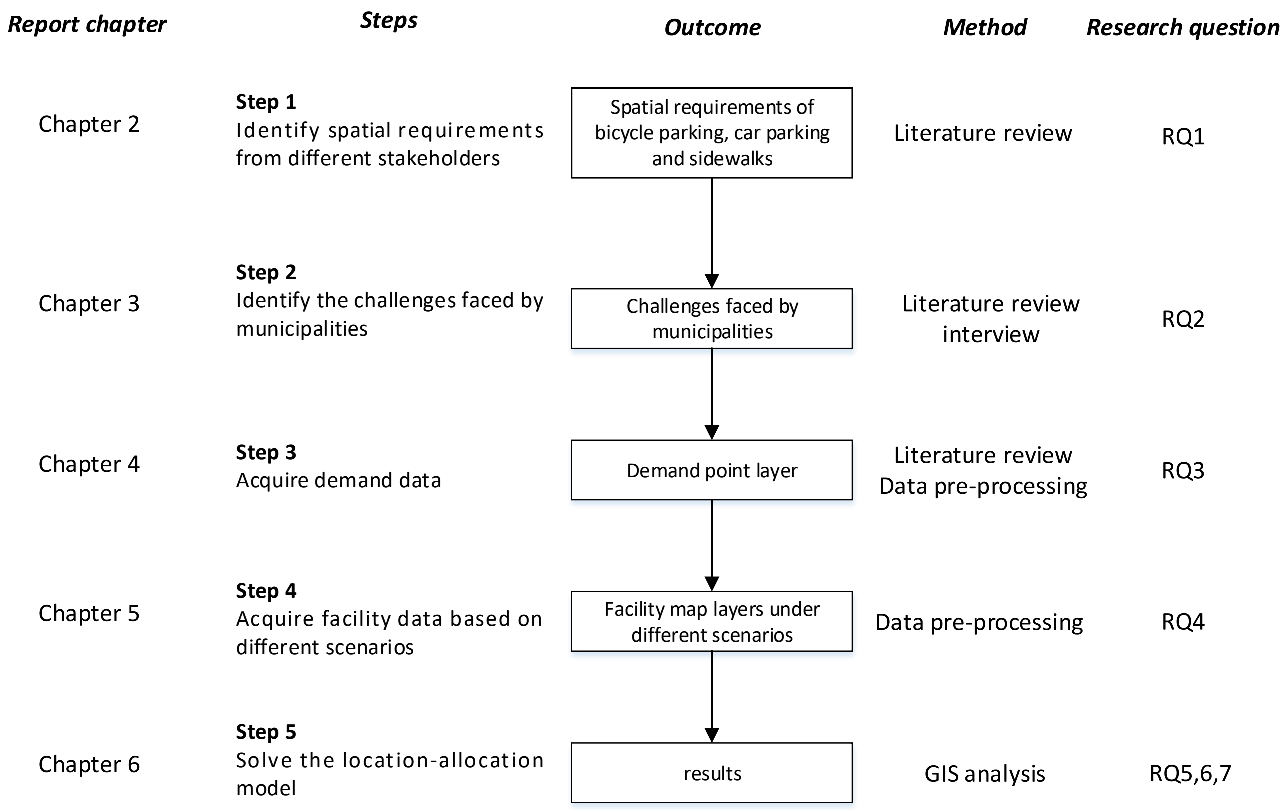

Figure 3 Research approach

Step 1 Identify user requirement from different stakeholders

From the public space user perspective, converting car parking to bicycle parking affects three main stakeholders: cyclists, car owners and pedestrians. Each stakeholder has different requirements for public space. It is important to first understand their needs, then the criteria for sufficient facility location will be known and different stakeholders' gains and losses can be assessed. A literature review was used to investigate users' spatial requirement on bicycle parking, car parking and sidewalk former academic study, survey and guidebooks.

Step 2 Identify the challenges faced by municipalities

Firstly, a literature review on public reaction to Oslo's car parking ban policy is conducted to see if there was any difficulty of the implementation of the policy. Then, through several exploratory interviews with civil servants who are working on bicycle parking and car parking at the municipality of Leiden, the problems that they are facing during planning bicycle parking and car parking and their concerns about converting car parking to bicycle parking are collected.

Step 3 Acquire demand data

There are three main categories of data that are needed for location-allocation analysis. They are facility demand, candidate facilities and the street network. In this step, demand data is prepared. Bicycle parking behaviour in the residential area and shopping area are different. Thus, the needed data is also different. The raw data will be collected then pre-process the data in GIS software to translate it to bicycle parking demand

Step 4 Acquire facility data

First of all, the current bicycle parking facilities data is collected. With this data, before car parking location-allocation, how much bicycle parking demand can already be satisfied by racks is discussed. Then where and how big is the capacity gap will be known.

After that, scenarios are designed based on different number and characteristics of car parking spaces. Converting to a complete car-free city not only depends on physical feasibility but also is affected by political consideration (Banister, Akerman, Stead, Nijkamp, Dreborg & Steen, 2000, p120). Changing transport modal choice rapidly is not very feasible. This is somehow represented by the ambiguous of the term 'car-free' (Toppn& Pharoah, 1994). Bologna was sneered as 'a car-free city with 60000 cars' (Toppn& Pharoah, 1994). It is very difficult to have a real car-free city centre. Therefore, it is practical to design different scenarios with intermediate car-free targets (Banister, et al, 2000, p120).

Step 5 Location-allocation analysis

Geoprocessing tool 'Network Analyst' in GIS software ArcGIS is used to solve the residential bicycle parking space allocation problem. Through GIS software, the location-allocation algorithm can be efficiently applied(Pratt et al., 2014; Yeh & Chow, 1997).

With different location-allocation goals, there are different problem type which solved by a different algorithm. The problem types are 'minimize impedance', 'maximize coverage', 'maximize capacitated coverage', 'minimize facilities', 'maximize attendance', 'maximize market share' and 'target market share'. Their characteristics are listed in Appendix 1.

In this study, impedance, i.e. walking distance, is important for the parking facility. And the coverage is also important as it relates to the effectiveness of the using of car parking space. For parking space, it has a parking capacity, thus 'maximize capacitated coverage' is the chosen problem type. By solving this type of location-allocation problem, the system will try to find the optimal solution so that the impedance is minimized, and the coverage is maximized while the located demand weight cannot surpass the facility capacity.

To solve the 'maximize capacitated coverage' problem for the bicycle parking, some attributes need to be set, including facility capacity, demand weight, impedance cut-off, barriers, etc. This will be discussed in Chapter 6.

As for the shopping area, the location-allocation method is different. The bicycle parking is more complex and there is often no car parking space on the shopping street. In this study, the shopping area demand is categorised based on the user group, parking duration and current parking location. The strategy is to first satisfy residential demand by converting car parking space so that the bicycle parking pressure around shopping street can be partially relieved. Then more short-term parking visitors are available to on-street bicycle parking facilities. The long-term parking visitors should be engaged to use the off-street parking facility.

The bicycle parking allocation problem will be solved using the designed method. The result of satisfied bicycle parking demand, chosen facilities will be obtained. Under each scenario, the bicycle parking demand that cannot be satisfied by car parking will be illustrated by a density map. To compare each demand density map, the effect of car parking converting, and the streets remain problematic can be visually presented.

To compare the sidewalk width and streets with high unsatisfied bicycle parking demand, the sidewalk with random bicycle parking problem can be observed. In addition, how many car parking spaces will be used as bicycle parking under each scenario is known. The new capacity for car parking in the city centre can be obtained.

1.8 Structure of the report

The report is structured as follows: in chapter 2 the literature review is used to identify user requirement for car parking, bicycle parking and sidewalk from car owners, cyclists and pedestrians. Chapter 3 investigates the challenges of converting car parking to bicycle parking based on the literature review and the exploratory interview with bicycle parking and car parking experts in the municipality. Chapter 4 defines the needed data for calculating the demand for location-allocation analysis and how to pre-process the raw data that can be translated to bicycle parking demand. In Chapter 5, combined with the result of the literature review and interview, three different car parking converting scenarios are designed. Then it shows how to create bicycle parking facilities layers under each scenario. In chapter 6, the method for bicycle parking allocation in the residential area and shopping area is presented and the results will be given in chapter 7. The result implications for politicians and academia are in chapter 8. Finally, the conclusion and research limitation are given in chapter 9.

2. Literature review

In the cities, the public space is used for parking, movement and other functions (see **Figure 4**, Lee & March, 2010). This study is aiming to solve the bicycle parking shortage at the expense of car parking space. So, the public space used for car parking and bicycle parking is directly affected. At the same time, sidewalks are often used as on-street bicycle parking. Therefore, the sidewalks are also taken into the study scope. Their users are cyclists, car owners and pedestrians.

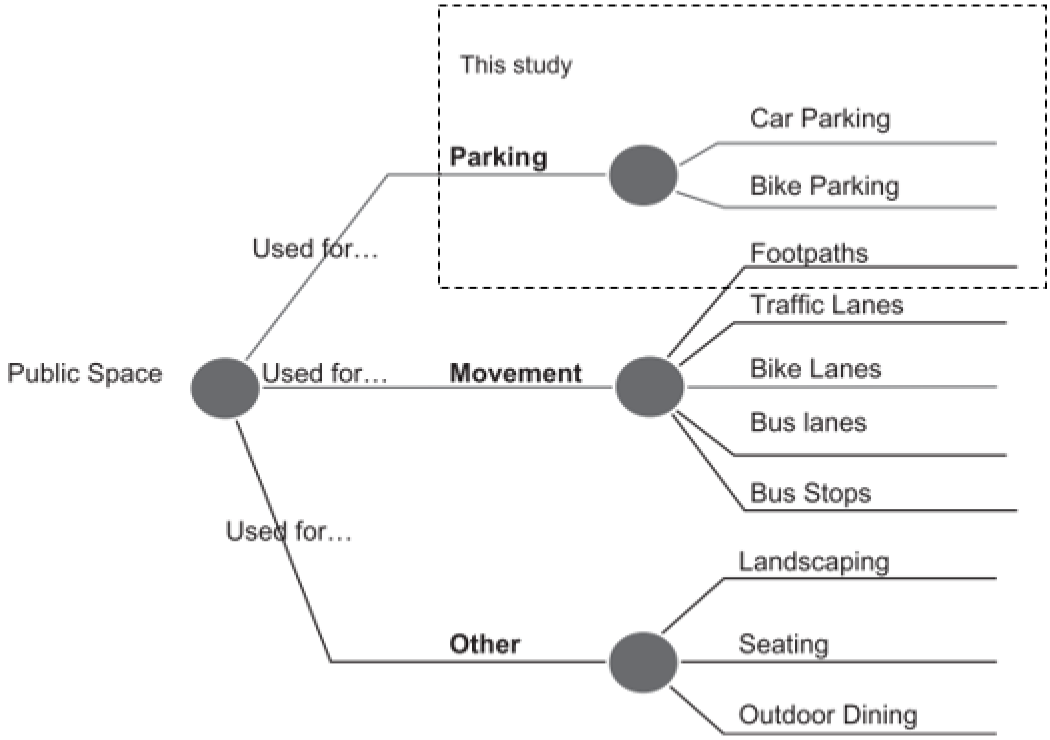

Figure 4 Use of public space(Lee & March, 2010)

With limited public space, cyclists, car owners and pedestrians are competing with each other for more space. In order to assess these stakeholders' gains and losses from the conversion of car parking space, the requirements on public space from cyclists, pedestrians and car owners were discussed in this chapter.

2.1 Literature Review Methodology

As this study aims to investigate the spatial impact of converting car parking to bicycle parking, the focus of requirements were spatially related factors. For parking facilities, it is mainly related to capacity and location requirements. For sidewalks, it is mainly related to pathway width. Other factors that affect the comfort of using parking facilities and sidewalks were ignored. For example, the lighting of the parking facility and the pavement of sidewalks.

Both scientific papers and grey literature, including city surveys, government reports and regulations, were investigated. For bicycle parking scientific papers, keywords were searched in Google Scholar, including 'bike', 'cycling', 'bicycle', 'bicycle parking', 'cycle parking', 'bike parking'.

Using Google Scholar can avoid bias in favour of any specific publisher. There are a lot of grey literature that contains the most related data and guidelines, and many of these reports are only available in Dutch, so 'fiets' (Dutch: bicycle) and 'fietsenstallingen' (Dutch: bicycle parking) were searched on website CROW Fietsberaad, which is a non-profit knowledge partner for Dutch government bodies, contractors and consultancy firms.

Based on the searching result, most academic studies about cycling were concerning route choice, factors affecting bicycle use and sharing bicycles. The 'factors affecting bicycle use' studies focused on studying the factors like built environment, cycling network infrastructure, socio-demographic factors, attitudes and how these factors influence cycling. Interestingly, much of previous studies focused on the determinants for commuting to work. Residential bicycle parking was seldom covered. The searching result indicated that specific bicycle parking studies are very limited (see **Table 1**). The snowballing method was used to extend the literature study. The method is that all the studies in the reference list were explored to see if there were relevant studies which did not show up in the database search result.

Table 1 Scientific studies specific to bicycle parking

Topic	***Studies***
Bicycle parking security	(Chen & Sun, 2018)(Gamman, Thorpe, & Willcocks, 2004)
Bicycle parking behaviour at the train station	(Molin & Maat, 2015)
Illegal bicycle parking behaviour	(Fukuda & Morichi, 2007)
Bicycle parking management	(Van der Spek & Scheltema, 2015)
Bicycle parking facility design	(Larsen,2017)
The economic impact of replacing car parking with bike parking in the retail area	(Lee & March, 2010)
Private bicycle parking for sharing bicycles	(Yin & Mu, 2012)

Among these studies, three studies are the most interesting ones. Van der Spek and Scheltema's study (2015) give an overview of the current bicycle parking situation, problems and possible solutions. Converting car parking space to bicycle parking space is one of the possible solutions that be put forward by them. Molin and Maat's study is also aimed to solve the bicycle parking shortage problem while their scope is bicycle parking at train stations, so it is very different from residential bicycle parking shortage problem. Lee and March's study is converting car parking to bicycle parking, but they focused on economic impact and the scope is bicycle parking in the retail area. Thus, it is also different from residential bicycle parking. In these studies, the optimal location of bicycle parking is absent. Thus, several bicycle parking guidelines, surveys and manuals were investigated.

'Parking' and 'car parking' were used for searching car parking requirements for both academic literature and grey literature. Then, the papers were assessed by the relevance to car parking capacity and location. There were some findings on car parking location and capacity. As for sidewalk requirements, 'sidewalk', 'pedestrian', 'walkability', 'sidewalk width' were searched. The focus was on the pathway width and the factors that would affect the sidewalk width.

2.2 Requirements for bicycle parking

2.2.1 Enough capacity and facility type

According to Scheltema (2012), the bicycle parking capacity is the dissatisfier of 'Successful public space for cyclists'. If the bicycle parking capacity is not sufficient, cyclists will be unsatisfied on public space planning. This is also the starting point of this study. However, due to the flexibility of bicycles, the need for good and enough bicycle parking facilities are often neglected. Some city and transport planners believe that cyclists can find a space for parking in the scarce public space anyway, so it is unnecessary(Van der Spek & Scheltema, 2015). However, this is often difficult in a compact city with scarce public space(Van der Spek & Scheltema, 2015).

For short-term parking, the ease of use is very important(Association of pedestrian and bicycle professionals, 2015). Therefore, short-term bicycle parkers usually use on-street parking facilities. For long-term bicycle parking, parkers usually have the need for security control (Association of pedestrian and bicycle professionals, 2015). This cannot be provided by bicycle racks. However, it is better than no facility at all.

2.2.2 Maximum walking distance

Even though there have been no scientific papers on the walking distance between bicycle parking facility and final destination, there are studies on car parking that can be referred to. The walking distance between parking facilities and ultimate destination is one of the most important factors for car parking planning in many studies (e.g. Smith & Butcher,2008; Van Der Waerden,2012; Van Der Waerden, Timmermans & de Bruin-Verhoeven,2017).

According to Fruin and Cantilli (1971), human's largest tolerated walking distance is more related to the walking situation than energy. They gave a list of variables related to maximum walking distance, including the types of users, frequency of occurrence or use, the familiarity of the user with the facility, the perception of security, the expectations and concerns of the user, the degree of weather protection provided along the path of travel, the perception or absence of barriers or conflicts along the past of travel, and the cost of alternatives to walking, etc.

Many people prefer cycling rather than driving is because of the difficulty or higher expense to park their cars (Ministerie van Verkeer & Waterstaat, Fietsberaad, 2009). As one of the strengths of cycling is the flexibility of parking (Blauw research, 2009), it seems logical that cyclists prefer a smaller walking distance from parking to their destination than car drivers. Unfortunately, studies on bicycle parking walking distance are very limited. According to the UK study by Taylor and Halliday(1997), for short-term bicycle parking(less than two hours), 86% of cyclists said the distance to the destination is the decisive factor for parking location. 75% of the cyclists prefer short-term parking that locates *within 50 metres* of their destination.

Unfortunately, there is no academic study about the preferred walking distance for on-street bicycle parking at residential context. Since long-term parking cyclists are willing to trade a longer walking distance for higher parking security (Association of Pedestrian and Bicycle Professionals, 2010), when on-street parking facility cannot provide weather protection and theft protection, the walking distance should be similar with short-term parking, i.e. 50 metres. If a bicycle locker (fietstrommel, see **Figure 5**[1]) is installed on-street, then a farther walking distance is probably accepted. However, there is no study can be used to confirm it.

Figure 5 Bicycle box

In conclusion, the acceptable walking distance for on-street bicycle parking is 50 metres based on available data. This is not an absolute result, as stated in the beginning, many factors affect people's willingness to walk. However, this number reflects the majority of the cyclists' perception and can be used to evaluate the location of an on-street bicycle parking.

2.3 Requirements for car parking

2.3.1 Parking on-street or off-street

There are mainly two types of car parking facilities: on-street parking, i.e. curb parking, and off-street parking, which includes parking lots and garages (Kodransky & Hermann, 2011). Cities are providing car parking space on-street at too high welfare costs (Van Ommeren, Wentink and Dekkers, 2011). When on-street parking is free and occupied and off-street parking is expensive, it is common to see drivers cruising on the street to find an available parking space. Cruising makes congestion and pollution problems worse (Shoup, 2006). Therefore, many researchers believe that it is beneficial to eliminate cruising and encourage more people to use off-street parking.

If more car parkers use off-street car parking facilities instead of on-street car parking facilities, more public space can be used by slow traffic, including cycling and walk. There are some studies investigating how to encourage the use of off-street car parking. Shoup (2006) asserted that people's choice between curb parking and off-street parking is depended on parking price, fuel price, parking duration, whether the driver is alone in the car, and their time value. He suggested that the government should set curb parking price at least equal to the off-street parking, to

[1] Photo retrieved from: https://www.utrecht.nl/fileadmin/_processed_/2/3/csm_Fietstrommels_Wittevrouwen_KJ_Bakker_4906f80934.jpg

prevent drivers cruising for an available parking space. Gragera and Albalate's research (2016) found that besides parking price, curb parking allowance (providing curb parking spaces) and time limits also play a role for garage parking demand. But they stated that pricing has a much larger and more efficient effect on behaviour shift from curb parking to garage parking. Many other studies (ko & Rowse, 2009; Kobus, Gutiérrez-i-puigarnau, Rietveld & Van Ommeren, 2013; Gragera& Albalate,2016) gave the similar conclusion that rising on-street parking price will push more people to switch from on-street parking to off-street parking and eliminate cruising. As a result, it will relieve traffic congestion and reduce air pollution.

According to the city survey of Leiden (2017), most of the car owners are parking their cars on-street. And for residents, in the city centre, the on-street car parking has the same price with garage parking. If more on-street car parking space is planned to be converted to bicycle parking space and it is expected that residents have to park their cars in the public garages, then the price of on-street car parking should rise.

2.3.2 Maximum walking distance

There are more academic studies on maximum walking distance for car parking than bicycle parking. Based on Fruin and Cantilli's study (1971) which has been discussed in Section 2.2.2, Smith and Butcher (2008) developed a recommended gradation of maximum acceptable walking distance for different levels of service (LOS) under five different walking conditions (see **Table 2**). For shopping centre parking on an average day, the LOS A (ideal performance) should be reached whereas on busy Saturdays a level B (good) should be maintained. For certain events, for example, a music festival, people expect the parking will be crowded and distant, then a LOS D (below average but minimally acceptable) can be tolerated. This study also stated that when there are frictions on the path (traffic light, street to cross), the maximum distance may be reduced by around 25% or more. Because the way from home to on-street car parking place is usually outdoor uncovered, the ideal occasion will be 122 metres walking. One thing should be noted that this study was in the U.S, the city size is much larger than Dutch cities. Thus, the accepted walking distance could also be larger.

Table 2 Maximum acceptable walking distance for levels of service A to D[2] (Smith and Butcher, 2008)

Level of Service / Conditions	A	B	C	D
Climate Controlled	305 m	732 m	1158 m	1585 m
Outdoor/Covered	152	305	457	610
Outdoor/Uncovered	122	244	366	488
Through Surface Lot	107	213	320	427
Inside Parking Facility	91	183	274	366

Besides of LOS method, Van Der Waerden, Timmermans and de Bruin-Verhoeven (2017) studied the maximum walking distance between parking and destination in the Netherlands. Their result is based on different trip purpose (see **Table 3**). For weekly shopping (grocery shopping), it is around 100 metres. For Work, it is around 50 metres and for non-weekly shopping (e.g. clothes

[2] Original paper used foot as distance unit. In this study, the unit is converted to metre for the consistency of the article.

and shoes), it can be 500 metres or more. They also found that the most influential factors in trip-related characteristics are trip frequency and stay duration. The travellers with higher trip frequency and longer stay duration are willing to walk a longer distance.

Table 3 Maximum acceptable walking distance for the different trip purpose

(Van Der Waerden, Timmermans & de Bruin-Verhoeven ,2017)

Trip purpose	Maximum acceptable walking distance
Weekly shopping	100 m
Non-weekly shopping	500 m or more
Work	50 m
Social activities	No specific preference

For the residential context, the acceptable walking distance is over 100 metres (Christiansen, Fearnley, Hanssen& Skollerud, 2017). In the Leiden city centre, the car parking distance at home around half is larger than 75m (Gemeente Leiden, 2013).

2.3.3 Optimal car parking occupancy

For cities using car parking permit to prevent cruising for parking, what is the optimal occupancy is an important question. From the aspect of economics, residential parking has external cost and benefit (Zakharenko, 2016). De Vos and van Ommeren (2018) did a case study in Amsterdam residential area and proved that the optimal car parking occupancy in a residential area is 100%. When the parking occupancy rate is higher than 85%, the walking distance increases. But compare the cost of walking the extra distance to the cost of empty parking space, the cost of extra walking distance is limited.

Currently, many cities set their residential night parking occupancy below 85% to avoid the negative effect of cruising (de Vos and van Ommeren, 2018). However, in a residential area, the optimal car parking occupancy should be almost 100%. With this knowledge, the car parking space which currently is empty during the night could be utilised as bicycle parking.

2.4 Requirements for sidewalk

Besides of bicycle parking and car parking requirements, sidewalk requirements are also important because the space of sidewalks are often be squeezed by randomly parked bicycles and car parking spaces. Sidewalks are often the location where people park their bicycles. Thus, solving the bicycle parking shortage can have a positive impact on the quality of sidewalks.

The existing car parking also directly affect the quality of sidewalks in historical city centres. Before the pedestrianization of European cities in the 1980s (Schiller, Bruun& Kenworthy, 2010, p53), there was a trend to plan urban space mostly for cars while pedestrians only had a much lower priority on the streets (McCluskey, 1987, p100). Therefore, in the historical urban area, the sidewalks are usually quite narrow.

Some cities overcame the overrun of cars and become the walking city now, for example, Copenhagen in Denmark (Schiller et al.,2010, p238). Copenhagen is famous for its people-oriented city centre, where 80% of the travelling is on foot and another 14% is cycling (Gehl & Gemzøe, 2004). Since 1967, Copenhagen has gradually removed parking spaces to make more public space for pedestrians (Gehl & Gemzøe, 2004). The requirements from pedestrians should not be neglected in a car-free city. Therefore, the sidewalk requirements are discussed in this section.

2.4.1 Minimum width

Aghaabbasi, Moeinaddini, Zaly Shah, Asadi-Shekari, and Arjomand Kermani (2018) sufficiently studied the capability of walkability audit tools for assessing sidewalks. According to their study, the width of the sidewalk is considered as an important factor in many sidewalk audit tools. The effective width of the sidewalk is related to the comfort and enjoyment of walking. In this study, the main goal is not improving the quality of sidewalks. Because of that, only the minimum width of sidewalks is investigated. It is the basic requirement on the sidewalks.

According to '*Accessibility for the disabled: a design manual for a barrier-free environment*' (SOLIDERE & ESCWA,2003), the minimum width of a two-way wheelchair traffic passage is 1.50 m while the preferred width is 1.80 metres, which is the minimum width allowing a wheelchair to pass an oncoming wheelchair.

There is no national law or regulation on sidewalk width. Cities can have their own standard or regulation. In the case study area, Leiden published its road design requirements in its 'Handbook on quality of public space 2017-2025' (Gemeente Leiden, 2017). In the city centre, the priority should be given to pedestrians. The minimum width of the sidewalk is 2 metres. If this is not feasible, an obstacle-free width of 1.5 meters must be retained. On shopping street, the minimum width is 2.5 metres.

In conclusion, sidewalks are expected to be ***at least*** 2 metres wide. If space is too scarce, then at least 1.5 metres wide should be reserved.

2.4.2 Obstacle-free and parking free

When installing street furniture, a clear width should be retained at least the minimum width level (CROW,2012). A bicycle is averagely 1.8 metres long. A parked bicycle, which can be seen as an obstacle for sidewalks, should only be parked when a sidewalk is at least wider than 3.8 metres to retain an obstacle-free width of 2 metres for the pedestrians. If space is very scarce, then the sidewalk with parked bicycles should be at least 3.3 metres wide to left 1.5 metres wide for pedestrians.

As for car on-street parking lane, according to Leiden's public space design handbook and ITDP's *Streets for walking & cycling* guidebook (UN-Habitat & ITDP, 2018), the on-street parking lane should not exist when the street space is too narrow. On-Street parking should have the lowest priority after public transport and other non-motorised travel (UN-Habitat & ITDP, 2018). In a car-oriented city, this is often opposite to reality.

2.4.3 Enforcement on the bicycle parking violation

When there is no enforcement on the bicycle parking violation, the random bicycle parking on the sidewalks can be serious (Van der Spek & Scheltema, 2015). Cars are seldom permitted to be parked outside the designed parking area, in other words, the drivers must park their vehicles in the designated area. In the Netherlands, parking violations will cause a fine and sometimes wheel clamps and vehicle removal.

However, at the same time, the Dutch bicycle parking regulation is much more permissive. The municipalities can impose the ban for bicycle parking in certain areas in their General Local Ordinance (in Dutch: APV- Algemene Plaatselijke Verordening), which are usually around the train station, on the market street or on a pedestrian-oriented shopping street (see Figure 5). On other streets, cyclists have the right to park their bicycles at any locations they prefer. The municipalities can only remove the improperly parked bicycles directly when they are parked in a dangerous way, for example, blocking the emergency exit.

Under such a permissive regulation, cyclists want to park as closest as possible to their destination without any burden (Van der Spek and Scheltema, 2015). However, when space is scarce, the closest location is probably not a good location for bicycle parking. In this case, bicycle parking can be a nuisance to pedestrians(Pucher, Dill, & Handy, 2010). According to the Leiden Survey in 2017, 71% of the pedestrians have experienced the hindrance from parked bicycles. 24% of pedestrians said they have regularly experienced the hindrance from parked bicycles.

Therefore, with the enforcement on the bicycle parking violation, pedestrians' walkability can be protected better.

2.5 Conclusion

In this chapter, the requirements of bicycle parking, car parking and sidewalks from their users were discussed. The result is concluded as a conceptual framework as shown in **Figure 6**. For bicycle parking, enough capacity is important. However, the parking facility has to be provided within a reasonable distance. Because of the often-absent enforcement on bicycle parking violation, cyclists are more likely to park at a location closer to its destination without using parking facility than park in the racks at a farther location. Based on the former study, the walking distance from parking to the destination should be less than 50 metres, which is less than many car parking's walking distances in the Leiden city centre. So, there is a high possibility that car parking located farther than 50 metres will not be used by cyclists.

As for car parking spaces, the sufficient capacity near the destination is important as well. However, due to the strict car parking regulation, car owners have to accept longer walking distance than bicycle parking when space is scarce. Half of the car parking space is farther than 75 metres to residents' home address. This means many car parking spaces are too far for cyclists to park their bicycles.

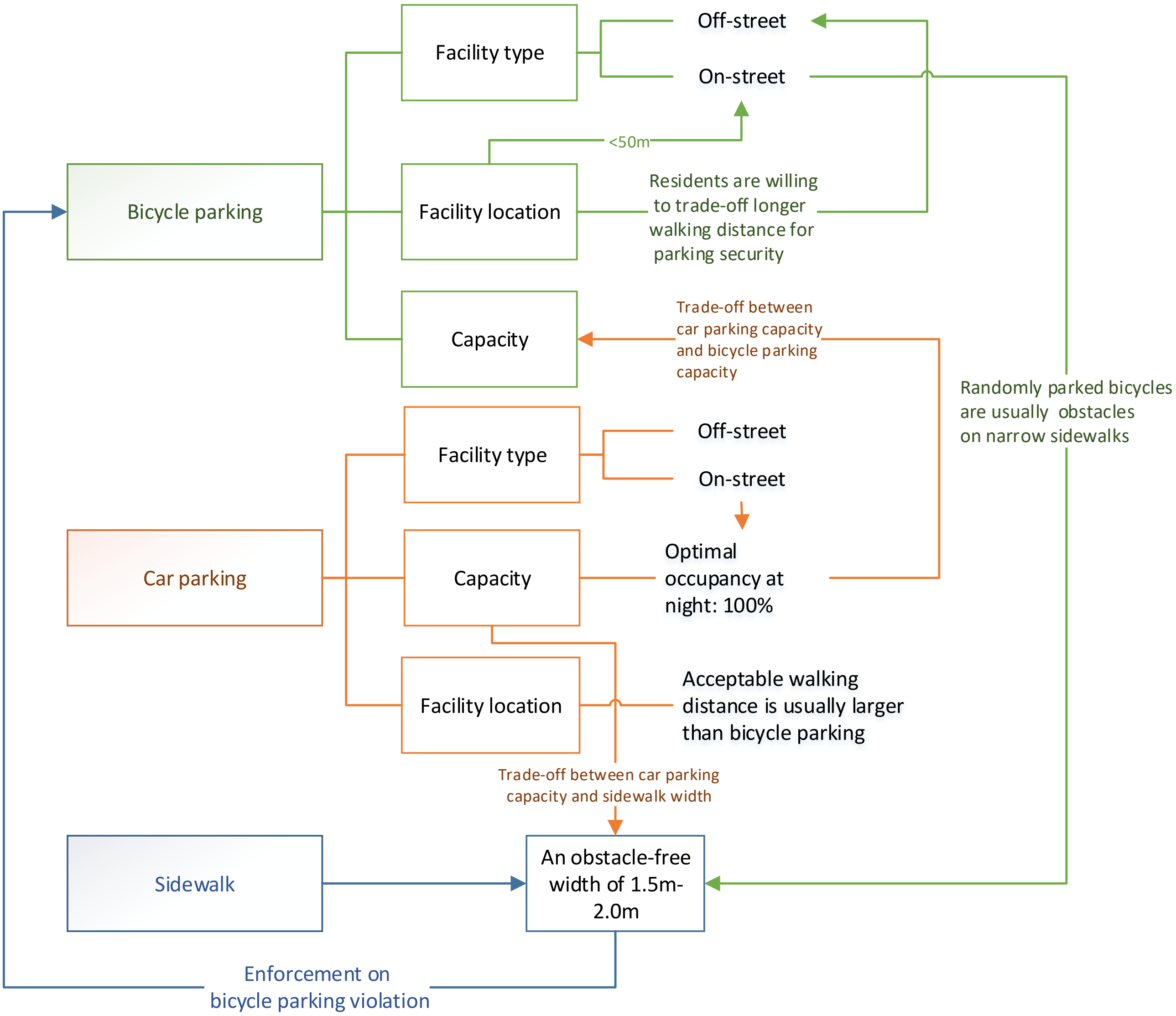

Figure 6 Conceptual framework of spatial requirements on residential bicycle parking, car parking and sidewalk

In addition, according to de Vos and van Ommeren's study (2018), the optimal car parking occupancy rate at night in a residential area should be almost 100%. This is an innovative finding that many cities are trying to control its parking occupancy at 85% (or 90% in Amsterdam). If a city wants to set residential on-street parking occupancy at 100%, it allows some car parking space to be utilised as bicycle parking. And it is possible to raise on-street parking price to push car owners to switch from on-street parking to off-street parking facilities so that more space can be used by cyclists.

For sidewalks, the most important requirement is the width. The minimum width of the sidewalk should be 1.5 meters and preferred to be 2 metres. In the shopping street, this width should be 2.5 metres. When the bicycle parking capacity is low, the problem of random bicycle parking on the sidewalk is more likely to occur. The enforcement of bicycle parking violation will help to reduce the nuisance. However, to avoid the discourage on bicycle usage, providing sufficient bicycle parking facilities is the pre-condition of enforcement of bicycle parking violation. And in some cases, the car parking lane co-exists with sidewalks narrow than the minimum width. In this case, the car parking space should be removed for widening the sidewalks.

3. Challenges faced by the municipality

Converting car parking space to bicycle parking space means some car owners will lose their parking space or they have to walk a longer distance to park their cars. Therefore, it is assumed that there will be some objections to this policy. In order to obtain information on the possible challenges of removing car parking space, first a literature study on Olso's car-free policy is conducted. Oslo was the first city who announced to implement a car parking ban in the city centre area. The way how the public react to their policy is investigated. Then, civil servants who are working with bicycle parking and car parking at the municipality of Leiden were interviewed in an exploratory way. The problems they are facing on bicycle parking planning and the challenges of converting car parking to bicycle parking were asked.

3.1 Public reaction to converting car parking space

A literature review was conducted to investigate the 'car parking ban' case in Oslo. Because this is the only example of converting car parking space to cycling infrastructure or other public city life facilities. Although the implementation of the policy has not been fully finished yet, the public opinion on this policy has already been put forward. The news that reported residents' opinion on the car parking ban in Oslo were searched through search engine *Google* in category *News*.

Even though in Oslo, only 12% of people own a car and 7% of people commute by private cars (Cathcart-Keays,2017), when the city announced to ban on-street car parking in the city centre, some car owners and retailers strongly protested against it (Cathcart-Keays,2017; Bliss,2018). According to the report, car owners felt that they were bullied (Berglund,2016). City's trade association was afraid that Oslo would become a dead city (Cathcart-Keays,2017).

One common thing was pointed out by a few news that before the announcement, there was no communication with residents and retailers in advance. And the target is also as ambitious as frightening for many car owners and retailers (Cathcart-Keays,2017; Berglund,2016). The Oslo' trade association said that shop owners and visitors need time to adapt to this big change (Cathcart-Keays,2017). The deputy mayor of Oslo Andersen said he is confident about the measures promoting cycling in Oslo and said "It's been under-communicated how much space cars take up. It will be so much more comfortable walking and biking around the area when people get priority rather than cars." (Bliss,2018). However, 'under-communicated' seems to be one of the reasons why some people were fiercely against the car parking ban. After many meetings, shopkeeper's association were happier with the plan of carefully changing the city in a street-by-street way (Cathcart-Keays,2017).

The backlash of Oslo's plan has shown the importance of communication with residents and retailers and it is important to give people time to adapt to the new policy, so transitional goals should be settled.

3.2 Interview: problems faced by the municipality

In Leiden's *Policy Agreement 2018-2022*, Leiden claims to develop the city to be a cycling city with a car-free city centre. The definition of the 'car-free' is still under consultation with local residents and retailers. But for sure, the future mobility development in Leiden will be in favour of public transport, pedestrians and cyclists. The city is planning to cancel parking space on streets that have a high pedestrian flow and making more street get rid of car traffic.

This section will discuss the challenges that are faced by the municipality to implement the 'cycling city with car-free city centre' policy based on the interview with bicycle parking policy advisor and car parking policy advisors at the Municipality of Leiden. Several consultations with bicycle parking policy advisor Wouter Haver about the bicycle parking problems in the city centre of Leiden; and car parking policy advisors Amit Akbar and Remco Bruijnes were asked about 'what are the barriers against converting car-parking space to bicycle parking space?'.

3.2.1 High residential car parking demand in the city centre

Based on current car parking data, the residential parking pressure is high in most neighbourhoods in the city centre. 60% of the neighbourhood has an on-street occupancy higher than 85%. The long-term goal is to decrease car ownership; thus, the parking pressure can decrease. However, in the short-term, it is still important to take care of the residential parking demand.

The municipality wants to compensate for the loss of on-street parking capacity by garage capacity. Currently, the garages are quite empty during the night. However, according to the interview, the garages are originally designed for visitors. In the city centre, the current garages' occupancy on a Saturday afternoon is already close to 100 percent. If the residents are engaged to park in the garages, the capacity for the visitors to park their cars in the city centre will largely drop. On the one hand, if with a bundle of measures, the car traffic reduces, then visitor parking pressure will also drop. On the other hands, the municipality is planning to involve private party, for example, university and companies, to open their parking facilities at weekends for city visitors in the future to solve the problem. However, both of these cannot be achieved overnight. The trip mode transformation needs time, so does the collaboration with private parties.

3.2.2 Narrow sidewalks versus random bicycle parking

The sidewalks in Leiden city centre are quite narrow. Randomly parked bicycles can make it worse. Based on literature review, enforcement on parking violation is important for avoiding wild bicycle parking. Some Dutch cities have already implemented enforcement on bicycle parking violation at the city centre. However, the feedback is not always good. The nuisance in Utrecht has largely reduced (Van der Spek and Scheltema, 2015) while cyclists in Amsterdam are complaining about having a strict rule but no sufficient bicycle parking space. With current regulation, sometimes they find nowhere to park their bicycles (Witteman,2018). The municipality of Leiden wants to promote cycling, so they are careful with measures which could frustrate cyclists. Currently, the bicycle parking shortage is serious in the city centre. So, if there are strict rules on bicycle parking, then many cyclists will find no place to park. If cycling should not be discouraged, it seems logical to provide sufficient parking space first, then enforce people to behave well.

This leads to a dilemma: when space is scarce, what if we expand the sidewalk to standard, but it is not wide enough for accommodating bicycles? Will it be occupied by randomly parked bicycles and make it be blocked again? At this situation, the access to off-street bicycle parking (e.g. neighbourhood parking or public garage) and enforcement on bicycle parking violation seem to be important.

Based on the interview and the result of the literature review, the space conflict between bicycle parking, car parking and sidewalks can be described as **Figure 7**.

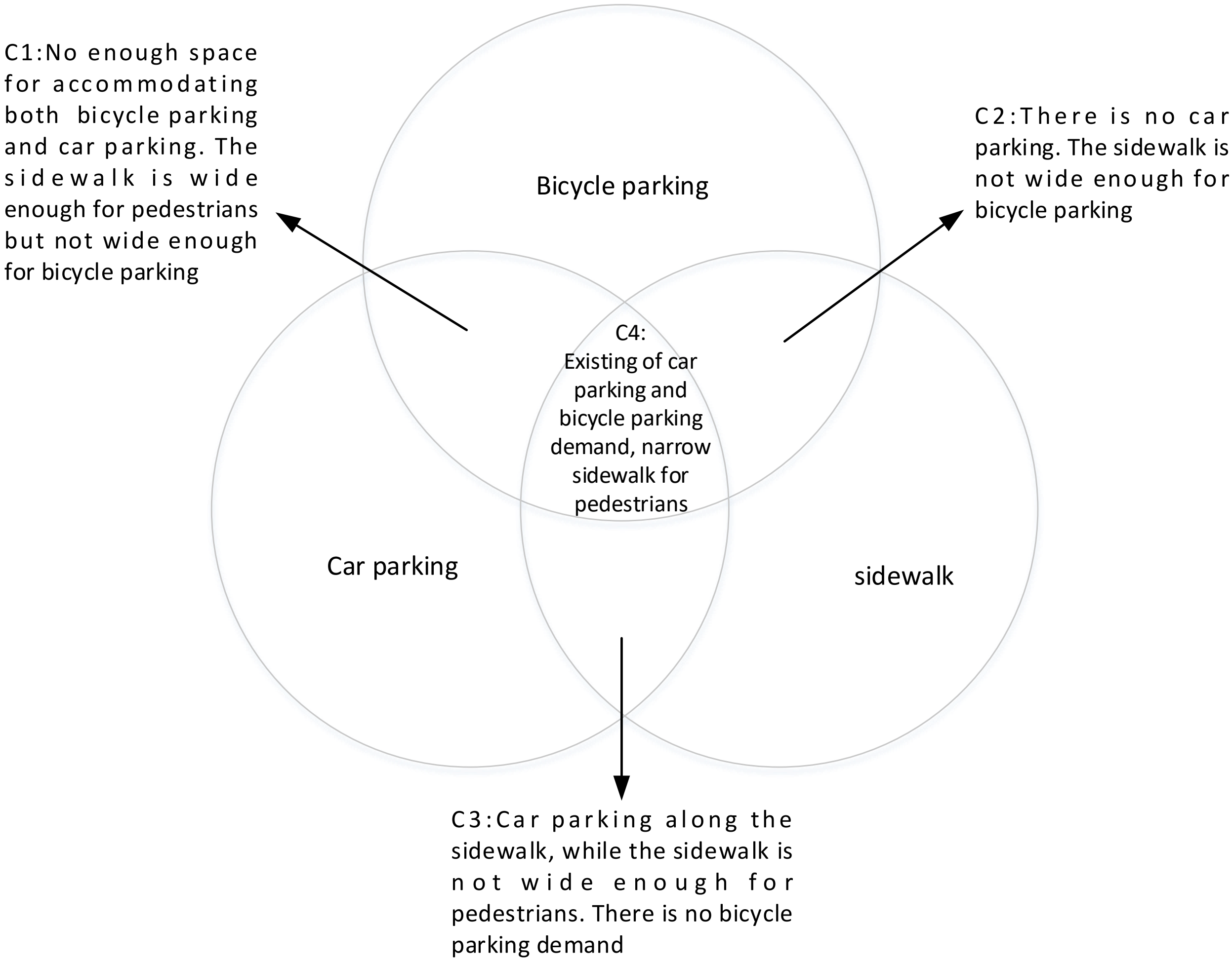

Figure 7 Space distribution conflict between bicycle parking, car parking and sidewalk

4. Bicycle parking demand

To solve the location-allocation problem, the demand points and facility candidates are input data. In this chapter, how to calculate the bicycle parking demand is discussed. The studying area is the city centre of Leiden. It is an area of 179 hectares with 21,458 population (data source: BRP,2018; CBS,2018). Currently, there are 4020 regular car parking spaces. The on-street bicycle parking capacity is 6366, which is around half of the number of parked bicycles on-street that were counted during the night. Compared to bicycle ownership, car ownership is low: 29% of households in the city centre own cars while 90% of the population own bicycles (CBS,2018; City survey 2017).

Since the peak hour of residential bicycle parking and shopping area bicycle parking is different, their parking demand will be analysed separately. Based on the bicycle parking data, the residential parking peak is during the weekday night. The shopping area parking peak is on Saturday afternoon.

4.1 Demand in the residential area

In the Netherlands, not all the homes have their own bicycle shed. Only after 1950, in municipal regulations, there has been regulation about compulsory bicycle storage room at home. In 1992, this was made as national law in Dutch Building Decree (Bouwbesluit). The relevant paragraphs of the regulation are in Appendix 2.

Therefore, most of the old residential buildings are without bicycle storage space. However, some old buildings that have spare space indeed have their own parking storage space. Unfortunately, the data of buildings with or without their own bicycle parking facilities are not recorded by the municipality.

According to the *Guide to Bicycle Parking* (CROW, 2010), the demand can be estimated by different methods, including counting parked bicycles during night and neighbourhood survey. Although there is the data of the amount of on-street parked bicycle at night, it should be noted that the perceived demand may be lower than the demand that develops once quality bicycle parking facilities appear (Association of pedestrian and bicycle professionals, 2015). Therefore, this study will not use the observed demand. Instead, it will use the number of cyclists who have no access to bicycle parking facilities at home. The assumption is made that all the buildings built before 1950 are without bicycle storage space. A margin of +10% is used for the desirable extra parking capacity that allowing people to find an empty place easier and also allows future growth of cycling rate (CROW,2010).

Therefore, the residential bicycle parking demand can be estimated by the formula:

$$\mathrm{D}_i = \mathrm{p}_{1950i} \times \mathrm{r} \times (1 + 10\%) \qquad (1)$$

Where demand point i is the address of a building built before 1950, D_i is the residential bicycle parking demand for demand point i; p_{1950i} is the population number living in that address i, and r is the city's bicycle ownership rate.

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According to the city survey (Gemeente Leiden, 2017), 90% of the population owns bicycles. Thus, in Leiden, the formula (1) can be written as

$$\mathrm{D}_i = \mathrm{p}_{1950i} \times 90\% \times (1 + 10\%) \approx \mathrm{p}_{1950i} \quad (2)$$

So, in Leiden, the residential bicycle parking demand approximately equals to the number of populations living in building without private bicycle parking facilities.

Currently, around 11800 bicycles are parking on-street during the night while the population live in old residential buildings is around 15850. The difference between the residential bicycle parking demand that estimated by the population living in old buildings and the on-street parked bicycle number could be resulted by two facts:1) some old buildings have their own bicycle parking facilities; 2) some residents do not want to park their bicycles on-street because there is no good facility. Therefore, when the parking facility is installed on-street, the true demand could be between currently parked bicycles number and population live in old buildings.

In addition, according to the interviews with local municipality officer, many people own more than one bicycle. The parking behaviour of the second bicycle can be bad as the usage and turnover are low. Therefore, in this study, the parking demand for the second or the third bicycle is ignored.

Some pre-geoprocessing was done to make a 'demand point' data layer that can be used in location-allocation. For example, the population data is recorded in '*address*' dataset while the buildings built year is recorded in '*building'* dataset. Using the geoprocessing tool 'select' and 'overlay', the data layer '*address of the old residential building'* was created, and it contains the data of population living in old residential buildings. This data can be used as 'demand point' in location allocation.

4.2 Demand in the shopping area

Unlike residents, customers usually do not have the option to park their bicycles at a private space, so their parking behaviour is easier to be observed. They usually park their bicycles on-street or in a public garage. Therefore, the counting number is reliable for commercial area visitors. The bicycle parking demand in the study area will be classified by user group, parking duration and parking location. The residential building's entrances are closer to the car parking space at the back side of the shopping street, so it is more likely to be satisfied by the car parking space. So, the residential demand is distinguished from visitor parking demand.

Currently, in Leiden shopping area, space is very scarce. Therefore, the city is providing off-street bicycle garages for cyclists. Parking duration affects the selection of bicycle parking facility type (Van der Spek & Scheltema, 2015). This study only focuses on on-street bicycle parking facilities, which is more often to be used by short-term parking cyclists. Therefore, it is assumed the on-street parking is only designed for short-term parking cyclists while the longer-term bicycle parkers are expected to park in the garages. The demand will be calculated separately based on parking duration.

4.3 Conclusion

The residential bicycle parking demand will be the number of residents who do not have their private bicycle parking facility at home. In this study, this was estimated by the population living in buildings built before the 1950s and the bicycle ownership rate. This is because only after 1950, providing inhabitants with in-door bicycle parking storage space is a compulsory requirement.

As for demand in the shopping area, it was classified into different user groups, parking duration and parking location. And after allocating the residential demand to car parking spaces, how much bicycle parking pressure in the shopping area can be relieved would be analysed.

5. Bicycle parking facilities and Scenario design

In Chapter 2, the requirements for bicycle parking, car parking and sidewalks showed the space conflict between cyclists, car owners and pedestrians. It is very possible that sufficient car parking capacity, sufficient bicycle capacity, and wide-enough sidewalks cannot co-exist when the public space is scarce. In addition, when the bicycle parking demand cannot be satisfied, the nuisance of randomly parked bicycles will affect pedestrians' walkability. In chapter 3, the challenges of converting car parking to bicycle parking were identified. Residents need time to adapt to a new car parking policy. And the current car parking pressure is already quite high. It is needed to providing alternative car parking facilities to car owners. In chapter 4, how to calculate the residential bicycle parking demand was discussed. At the same time, how to calculate and classify bicycle parking demand in the shopping area was also introduced.

In this chapter, the bicycle parking facilities will be discussed. First of all, the current bicycle parking facilities were discussed. With this data, before car parking location-allocation, how much bicycle parking demand can already be satisfied is discussed. Then the location and amount of the capacity gap will be known.

After that, scenarios of different number and characteristics of converted car parking spaces will be designed based on the result of literature review and interview.

5.1 The data on current bicycle parking facilities

The municipality of Leiden has the on-street bicycle parking facility capacity that was collected in October of 2018. This dataset includes bicycle parking facility type, location and capacity.

Currently, the supply of bicycle parking facilities is provided by parking garages and on-street racks. There are also some private parking garages and racks that operated or installed by private party, which were ignored in this study. The night bicycle parking capacity is less than day time parking capacity because the garage is not open during the late night and on market day there is temporary extra bicycle parking facility (see **Table 4**).

Table 4 Current bicycle parking capacity

Location / Time	Bicycle parking capacity		
	On-street	Garage	Total
Weekday afternoon	6366	736	7102
Weekday night	6366	0	6366
Saturday afternoon	6890	789	7679

5.2 Converted car parking space

Based on different bicycle parking facility type, one on-street car parking space can be converted to a bicycle parking space with a capacity of eight to fourteen bicycles (**Figure 8**).

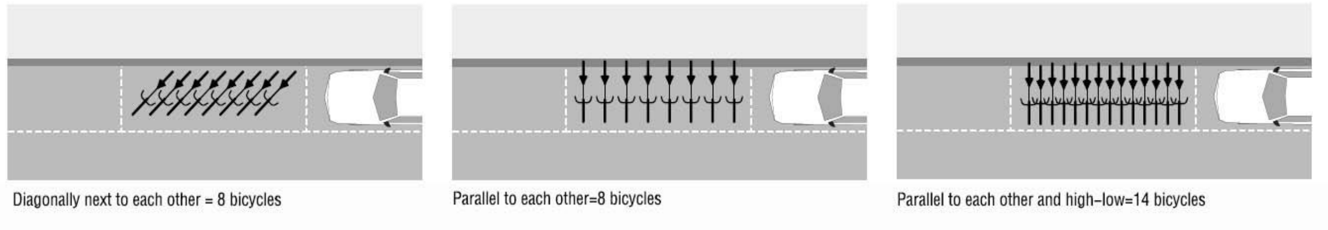

Figure 8 Change a car parking space for 8 or 14 bicycles (Gemeente Utrecht,2010)

In the study area, Leiden currently uses clip and triangle racks for residential bicycle parking. Each car parking space can accommodate five bicycle parking racks of these two types. Therefore, each car parking space can be converted to a bicycle parking space with a capacity of ten bicycles (see **Figure 9** and Appendix III).

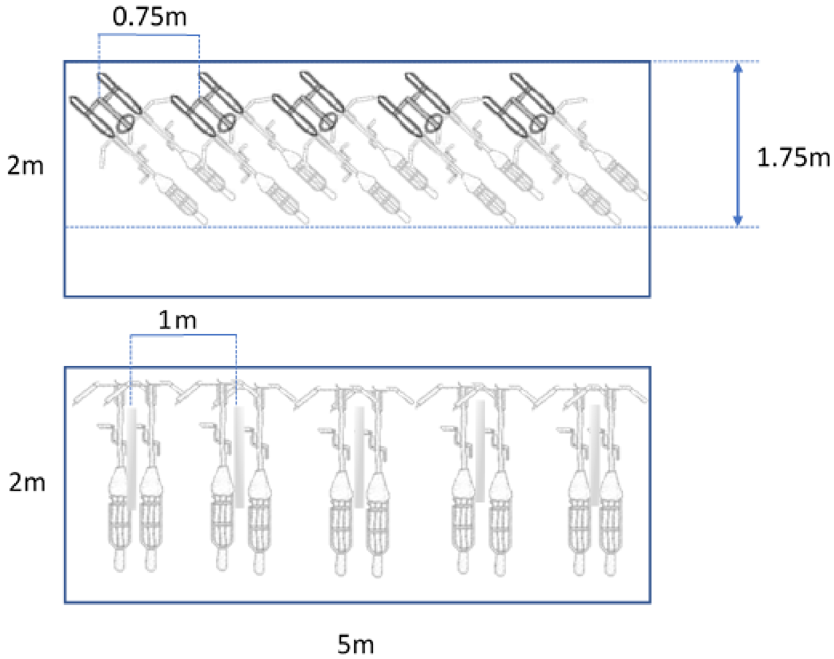

Figure 9 Triangle rack capacity (top) and clip rack capacity (bottom) within a car parking space

5.2.1 Why scenarios?

Based on the literature review, the car owners and cyclists desire enough parking space with short walking distance. And the pedestrians desire the sidewalks with an obstacle-free width larger than 1.5 meters so that it meets the minimum requirement of people in wheelchairs. And the lesson learnt from Oslo is that people need time to adapt to new policies. The parking ban should not be immediately applied at a very large scale. In addition, according to the interview with the civil servants from the Municipality of Leiden, they are facing two challenges, one is that the current car parking pressure is high; the other is that many sidewalks are too narrow to park bicycles while it is difficult to put enforcement on bicycle parking violation with the shortage of proper bicycle parking capacities. Based on comprehensive consideration, the scenarios will be designed in favour of different stakeholders. Thus, the change can be gently started with one scenario in favour of car owners and end up with the scenarios in favour of cyclists and pedestrians.

5.2.2 Scenario design

Based on the information from the literature review and interview. It is necessary to design scenarios favour different stakeholders. One scenario in favour of car owners is needed to be designed and it will be suitable to implement in an early stage. Because it will cause fewer losses for car owners. One scenario in favour of cyclists is designed so that the maximum bicycle parking demand can be satisfied with car parking. The result of this scenario will show the extreme capacity of solving bicycle parking shortage by converting car parking space. And one scenario favours pedestrians. Under this scenario, the priority will give the to sidewalk width. If a city aims to make all its sidewalks meet with the minimum width requirement (1.5 metres), then one day the car parking space will be used to widen sidewalk instead of bicycle parking.

The shapefile data of on-street car parking space in the city centre was first collected from the municipality of Leiden. Then using geoprocessing tools, the car parking that will be used as candidate facilities under each scenario were selected and made into three map layers. These layers will be used as candidate facility in the location-allocation analysis. The detailed information on each scenario is as follows.

Scenario 1: in favour of car owners

In order to ensure that the car parking demand will still be satisfied after car parking converting, under this scenario, only those empty car parking space during the night will be used as new bicycle parking facility candidates. Based on de Vos and van Ommeren's study result, although when car parking occupancy is higher than 85%, the parker's walking distance increases, this cost is much less than the cost of empty space and people's willingness to pay for a car parking space. Therefore, this scenario aims to reduce the empty car parking at night but also make sure that the car parking demand will still be under-covered.

In GIS software, the car parking space that currently is not occupied during weekday nights was selected and made to the first facility map layer. The car parking occupancy data was provided by the Municipality of Leiden.

Scenario 2: in favour of cyclists

Under this scenario, all the car parking space will be used as bicycle parking facility candidates. This scenario will show the maximum capacity of solving bicycle parking shortage by converting car parking in the study area.

Scenario 3: in favour of pedestrians

Under this scenario, car parking along the narrow sidewalks will be removed and space will be used to widen the sidewalk. The difference between scenario 2 and scenario 3 is illustrated by **Figure 10** Comparing scenario 2 and scenario 3 of converting car parking space on the Hogewoerd streetif there is a high bicycle parking demand on the Hogewoerd street, it cannot be satisfied by converting car parking. However, this will lead to another problem that bicycles have no access to parking facilities will park on the sidewalk and block the widened sidewalk again. It is only suitable for roads with the possibility of providing off-street neighbourhood bicycle parking as an alternative bicycle parking facility.

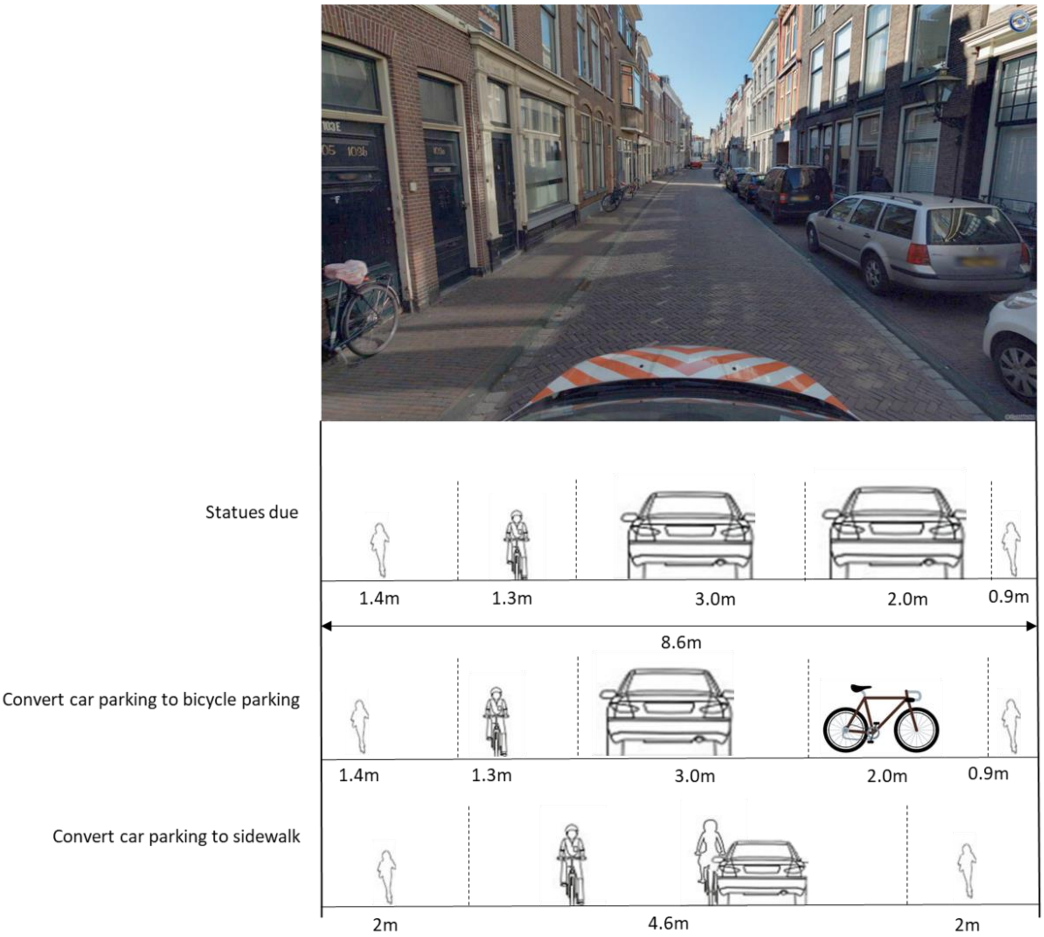

Figure 10 Comparing scenario 2 and scenario 3 of converting car parking space on the Hogewoerd street

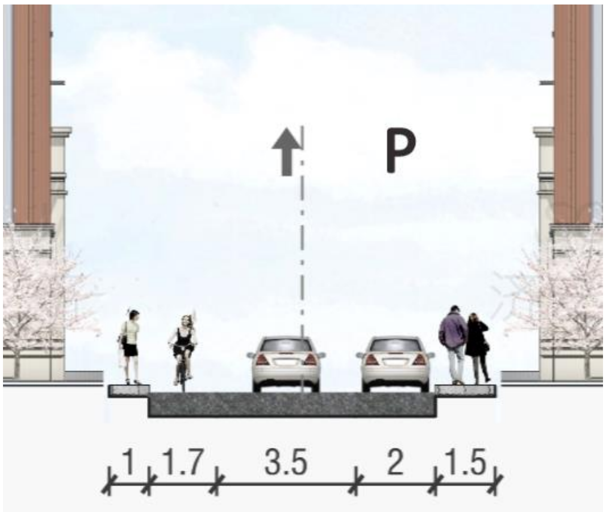

Figure 11 Narrow sidewalk (left side) opposite to a car parking space (right side)

The selection of converted car parking space under scenario 3 is more complicated. Under scenario 3, if a sidewalk is too narrow, and there is regular car parking space existing along the narrow sidewalk, or on the opposite side of the sidewalk (see **Figure 11**), this car parking space should be removed for widening the sidewalk. In this case, the car parking space will not be considered as potential bicycle parking space. The first step is to identify sidewalk narrow than the minimum width. As stated in literature Section 2.3.1, 1.5 metres is the minimum acceptable width of a sidewalk. Then, if there is car parking exists, it needs to be identified. This is analysed by geoprocessing tool 'Near' in ArcGIS, which calculates distance and additional proximity information between features. The searching radium is 5.2 metres (see **Figure 12**). Because in the Leiden city centre, narrow sidewalks are usually located next to one-way roadways. The desirable width for a one-way roadway is 3.5 metres. The bicycles are allowed to pass the road in both directions, and according to former study, bicycle lanes that located next to roadways should be at least 1.7 metres wide (CROW,2015). Therefore, when the road is wider than 5.2 metres, some space of the roadway could be used to broaden the sidewalk narrow than the minimum width. When the roadway is narrow than 5.2 metres, parking lane should be removed. After identifying all the car parking that should be removed for broadening narrow sidewalks, the remaining regular car parking space will be the options for bicycle parking under scenario 3.

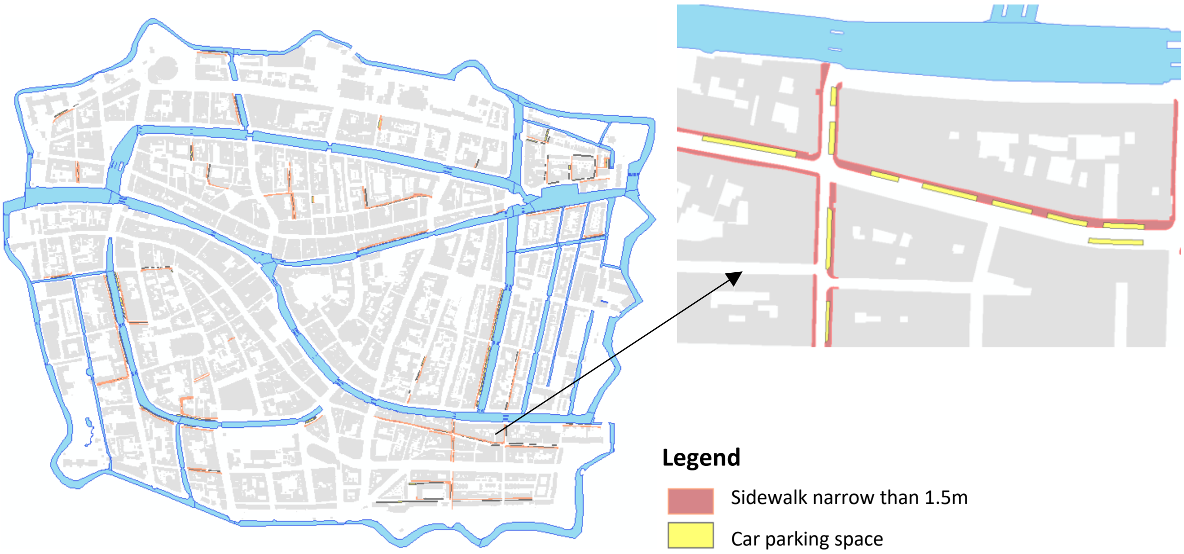

Figure 12 Identify narrow sidewalks and the car parking space close to them

5.3 Conclusion

In chapter 4 and chapter 5, the demand point and facility candidate data has been prepared. Through some pre-geoprocessing, the raw data is converted to a dataset of bicycle parking demand point and three data sets of bicycle parking facility candidates under three scenarios. **Table 5** presents the summary information for the characters of each scenario and the quantity of how many car parking spaces will be utilized as bicycle parking facility candidates.

Table 5 Characters of each scenario and the quantity of converted car parking

Scenarios	Favoured stakeholder	The character of the selected car parking space	The quantity of car parking spaces to be converted
Scenario 1	Car owners	empty ones at night	528
Scenario 2	Cyclists	all regular car parking	4020
Scenario 3	Pedestrians	all regular car parking except those located close to sidewalks narrow than 1.5m	3365

All the data was provided by the municipality of Leiden. And all the needed data is concluded in the table below:

Table 6 List of needed data sets

Data set	Function	Comment
Population	Estimate bicycle parking demand	
Building function	Distinguish residential building from non-residential ones	
Built year	Distinguish residential buildings with and without indoor bicycle parking space	
Number of parked bicycles	Estimate shopping area bicycle parking demand	In the shopping area, at Saturday peak hour
Parking duration	Distinguish between long-term and short-term parking demand	
Bicycle parking facility capacity	Compare with the parking demand to know where and how much bicycle parking demand cannot be satisfied by current facilities	
On-street car parking location and capacity	Identify spaces that can provide more bicycle parking capacity by converting car parking space	
On-street car parking occupancy and current residential car parking demand	Under scenario 1, to identify car parking that is selected as bicycle parking facility candidate, these data are needed to identify car parking space that is empty during the night; the car parking demand will be used to assess how much car parking demand cannot be satisfied after the conversion.	Night occupancy and Saturday afternoon peak occupancy
Sidewalk Width	Under scenario 3, this data is needed to define where the sidewalk is under minimum width so the car parking along it should be replaced; after location-allocation analysis, this data will be used to assess where the unsatisfied bicycle parking demand will hinder pedestrian mobility	

6. Location-allocation model

In Chapter 4 and Chapter 5, the needed data for location-allocation analysis including demand points and new facilities have been prepared. Under each scenario, a different number of car parking spaces was selected to be used as bicycle parking candidates. In this chapter, the detailed location-allocation method will be presented.

6.1 GIS-based Location-allocation model

The Location-allocation model is aimed to locate the new facilities at the optimal locations that can best serve the demand with minimum transport cost (Azarmand & Neishabouri, 2009). It simultaneously locates the facility and allocates the demand point to facilities (ESRI, 2018a). As discussed in section 1.7.2, there are several location-allocation problem types. The goal of each different problem type is different. Most location models are variants of four general classes: median, covering, capacitated, and competitive(Church, 1999). The median (also known as *P-Median*), or *minimize impedance*, aims to locate a fixed number of facilities so that the sum of impedance (travel time or travel distance) between demand points to facilities is minimized. The covering, or *maximum covering*, aims to maximize the total demand points that are covered by facilities within the desired distance. These two kinds of models are the most commonly used location-allocation models(García-palomares et al., 2012). The capacitated models have some restrictions on the facility capacity. And the competitive models are suitable for situations that there are competitors who will affect the location decision making.

In this study, the bicycle parking facility allocation problem should be solved by 'maximum capacitated coverage'. It is a combination of the median, covering and capacitated models. Because the goal is to locate the bicycle parking facilities in a way that the maximum demand can be served with minimum cost (i.e. walking distance) At the same time, the bicycle parking facilities have a capacity limitation, so the allocated demand weight cannot exceed the facility capacity.

Current and Storbeck (1988) proposed two capacitated covering location problem models as variants of maximum covering model. They first proposed a capacitated maximal covering location problem (CMCLP) formulation then reformulated it as a capacitated *p*-median problem (CPMP). Considering the goal of bicycle parking location-allocation includes the minimum walking distance between the home address and bicycle parking facilities, the CPMP formulation is more proper. According to their study, the model can be mathematically formulated as follows:

$$Z = Minimize \sum_{i \in I} \sum_{j \in J} c_{ij}\, a_i\ x_{ij} \tag{3}$$

Subject to:

$$\sum_{j \in J} x_{ij} = 1, \qquad for\ all\ i \in I \tag{4}$$

$$\sum_{i \in I} a_i\ x_{ij} - k_j x_{jj} \leq 0, \qquad for\ all\ j \in J \tag{5}$$

$$\sum_{j \in J} x_{jj} = p \quad (6)$$

$$x_{ij} \in \{0,1\}, \qquad for\ all\ i \in I, j \in J \quad (7)$$

$$x_{jj} \in \{0,1\}, \qquad for\ all\ j \in J \quad (8)$$

Where
I = the index set of all demand points
J = the index set of all potential facility sites
a_i = the expected demand for the service at node i
p = The number of facilities to be sited
k_j= the capacity of a potential facility at node y
d_{ij}= travel distance or time from j to i
S = the maximum service distance or time for the service

$$c_{ij} = \begin{cases} 1, if\ d_{ij} \leq S \\ 0, otherwise \end{cases}$$

$$x_{ij} = \begin{cases} 1, if \text{ a facility at } j \text{ provides service to point } i \\ 0, otherwise \end{cases}$$

$$x_{jj} = \begin{cases} 1, if\ a\ facility\ is\ sited\ at\ j \\ 0, otherwise \end{cases}$$

Constraint (4) will assign all the demand points each to a facility. If there is maximum distance restriction, then C_{ij} will correct the demand points that are covered by a facility out of service distance. Constraint (5) restricts the total number of sited facilities to not exceed the total number of new facilities. Constraint (6) ensures the required number of facilities will be sited. Constraint (7) is optional, it is assumed that the demand cannot be partially assigned to a facility. Constraint (8) prevents partial facilities from being opened.

Current and Storbeck (1988) also noted that these models are NP-hard (non-deterministic polynomial-hard), which means that it is very difficult to examine all the solutions to obtain the optimal solution. For example, if 10 facilities will be selected out of 100 candidate facilities, there will be over 17 trillion possible solutions. Thus, in ArcGIS software, heuristics are used to solve the location-allocation problems. Heuristics cannot provide a perfect solution but will try to obtain a near-perfect solution.

The algorithm used by the ArcGIS Network Analyst extension to solve location-allocation (ESRI,2018b) is as follows: The first step is to generate an origin-destination matrix of the shortest-path cost between all facilities in the network and the location of the demand point. An edited version of the cost matrix is then built by a process called Hillsman editing (details see Hillsman,1984). This editing process enables using the same heuristic solver to solve a variety of different types of problems. The location-allocation solver then generates a set of semi-randomized solutions and applies the vertex substitution heuristic algorithm (Teitz-Bart) to optimize these solutions to create an effective set of solutions (details see Teitz and Bart, 1968).

The metaheuristic algorithm then merges this set of effective solutions to create a better solution. If there are no other improvements, the metaheuristic will return the best solution found. The combination of an edited matrix, semi-random preliminary solutions, a vertex substitution heuristic, and an optimized metaheuristic can quickly produce near-perfect results.

A brief explanation of the principle of maximum capacitated coverage location-allocation model can be illustrated in **Figure 13**. In this example, there are four candidate facilities and five demand points. It is assumed that the capacity of each facility is 1, the weight of each demand point is 1 and the maximum impedance i.e. the maximum facility service distance is 1. Because of the capacity restriction, even though *Demand Point e* is located within the service distance of *Facility B*, it cannot be allocated. Because the *Facility B* can only serve one demand point and the *Demand Point c* is closer to *Facility B* than the *Demand Point e*. Thus, the *Facility* B will only serve the *Demand point c.* And the *Demand point b* cannot be allocated because it is not covered by any facility's service distance. What's similar is that *Facility D* is not located because there is no demand point within its service distance. The *Demand Point d* is located both in the service distance of the *Facility B* and *Facility C*, but it is allocated to the *Facility C*. This is because it is closer to *Facility C* and if it is covered by the *Facility C*, *Facility B* can be used by another demand point, so the coverage can be maximized.

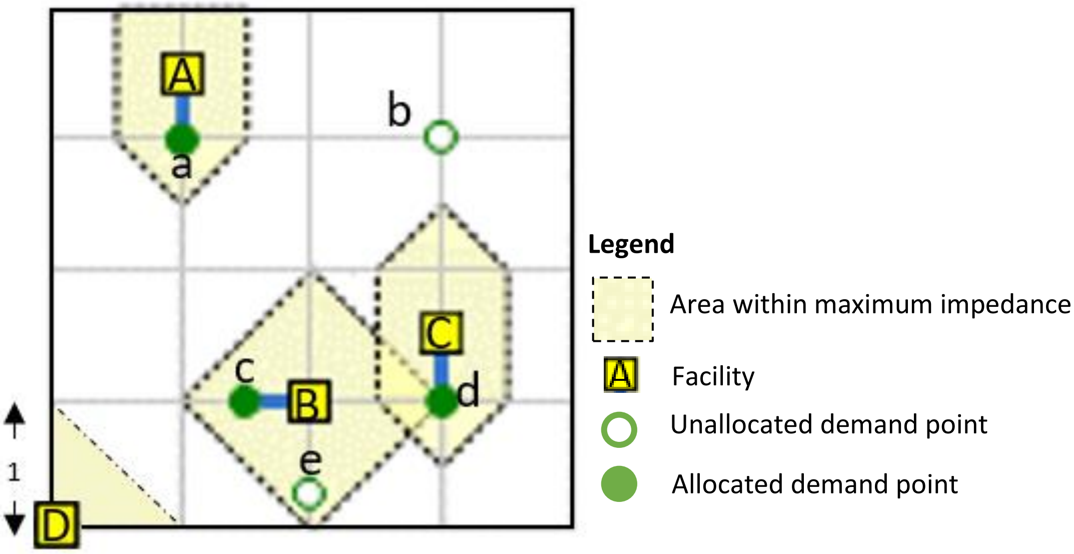

Figure 13 An example of the maximum capacitated coverage location-allocation mode, modified from (ESRI,2018)

6.2 Application of the Location-allocation model

Because of the different parking behaviour and parking peak hour, there are two case studies. One is to investigate the residential bicycle parking in Leiden city centre; the other is to study the visitor bicycle parking in the shopping area, taken Leiden's main shopping street Haarlemmerstraat as the case. It is often difficult for visitors to find an available bicycle parking facility as many racks are occupied by local residents (Van der Spek & Scheltema, 2015). Therefore, the residential bicycle parking demand should be allocated first, then the visitor bicycle parking demand in the shopping area can be allocated.

6.2.1 Residential area

The method to solve this problem has the following steps.

Step 1: Build up the transport network dataset

First of all, in order to perform the location-allocation, the network dataset was built up as **Figure 14**. The network dataset uses the centreline of the actual road network. In this way, the walking distance will be much more accurate than the linear distance. In Leiden city centre, there is no much traffic limitation on pedestrians and cyclists. So, there is no need to set extra attributes such as speed limits or direction limits.

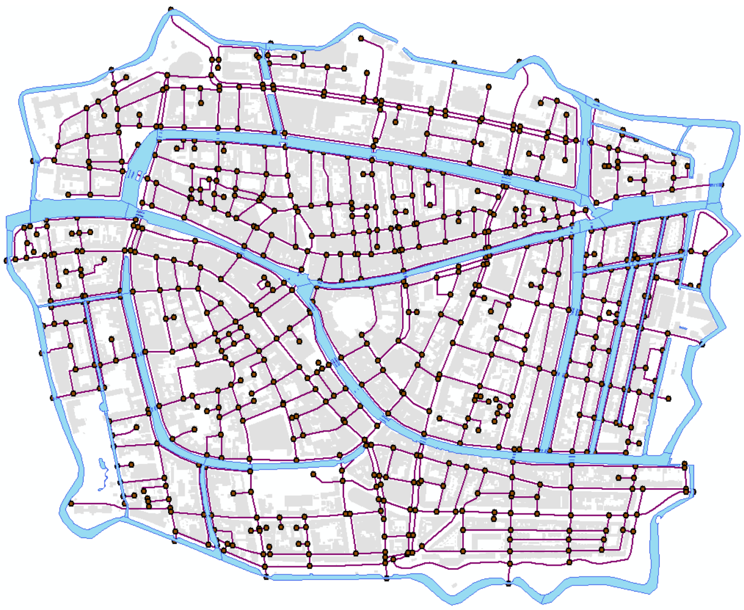

Figure 14 Network dataset of Leiden city centre

Step 2: Creating the location-allocation layer

Four location-allocation analysis layers were created in ArcGIS. One was to allocate bicycle parking demand to existing on-street bicycle parking facilities and the other three were used to allocate the bicycle parking demand that cannot be satisfied by existing facilities to car parking spaces.

For the current bicycle parking situation, the data on bicycle parking facilities and total residential bicycle parking demand has already been prepared and was loaded to the analysis layer (see **Figure 15**). The detailed pre-processing process of data preparation has been discussed in Chapter 4.

It should be noted that three car parking converting scenarios will not use the same demand points for the current bicycle parking situation. Their demand points can only be loaded after solving the bicycle parking location allocation of the current situation. Then the demand cannot be satisfied by street racks can be used as demand for converting.

Several parameters of the location-allocation analysis layer were needed to be set. Based on formula (2) in Section 4.1.1, the population was used as the 'weight' for demand points. In this study, the distance is used as impedance. The maximum acceptable walking distance from bicycle parking to home was used as 'impedance cutoff', which is 50 metres (Taylor and Halliday, 1997).

When a facility is located outside of ‘impedance cutoff’ distance, it will not be chosen. Adding barriers is not compulsory for location-allocation analysis. In the study area, there are many canals and bridges. According to Smith and Butcher (2008), frictions along the walking path will reduce the acceptable walking distance by 25 percent. Therefore, points barriers were set at every bridge (see **Figure 16**) and the added cost is set as 25 percent of the maximum acceptable walking distance 50 metres, which is 12.5 metres extra cost.

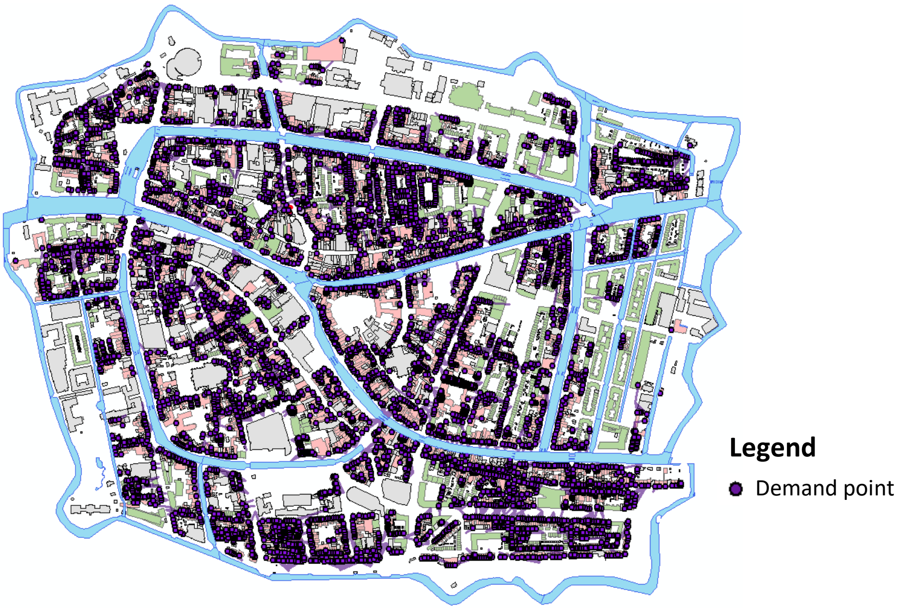

Figure 15 Demand points map

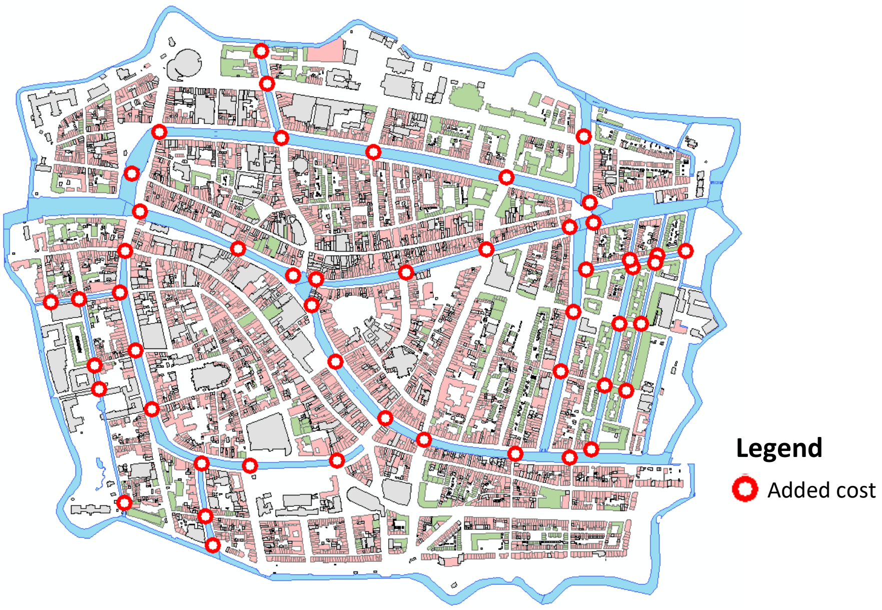

Figure 16 'Added cost' barriers on bridges

Step 3: Perform the analysis and obtain the result

When the analysis layer was ready, the location-allocation analysis for current situation was performed first. This is necessary because the bicycle parking facilities are designed not only for residents but also students, employees, customers, etc. The bicycle parking facilities designed for non-residents might locate at a location without residential parking demand nearby. Using location-allocation analysis, the bicycle parking facility that can be accessed by residents will be identified.

After solving this current situation location-allocation layer, the demand points that cannot be allocated were extracted. These demand points will be allocated to car parking space under different scenarios.

After performing the location-allocation analysis for three car parking scenarios, the result was recorded in the attribute tables. And from the map layers, the results were presented clearly (see **Figure 17**). Based on these map layers, the civil servants can have a view on the car parking space with an effective location.

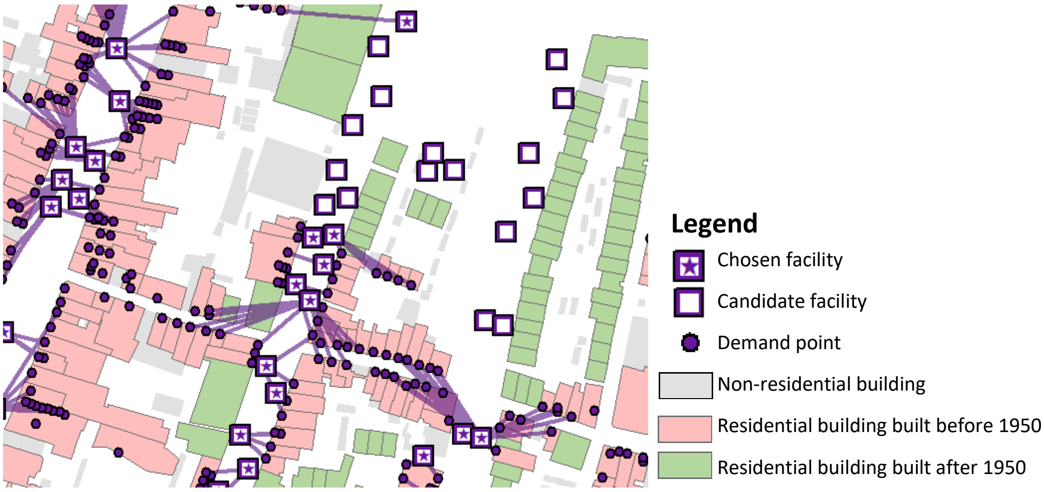

Figure 17 Partial result of location allocation analysis

Density map

After the results were obtained, the capacity gap after converting car parking to bicycle parking can be visualized by a point density map. The Point Density tool calculates the density of point around each output raster cell. Around the raster cell, a conceptual neighbourhood is defined and the number of points that fall into that neighbourhood will be divided by the area of the neighbourhood. The radius of the neighbourhood is computed specifically to the input dataset using a spatial variant of Silverman's Rule of Thumb that is robust to spatial outliers (ESRI,2018). The population field determines how many times a point will be counted, and it was set as the demand that was not satisfied. In this way, the density map can be used as a bicycle parking shortage problem heat map. Through the density map, the area still with a high unsatisfied demand can be noticed. To compare the density map of the current bicycle parking situation with different scenarios, the effect of car parking conversion can be easily presented.

At the same time, the sidewalk width layer can be added on the top of the bicycle parking problem density map, and it can show the problematic area where the sidewalk is narrow, but the bicycle parking capacity gap is large.

6.2.2 Shopping area

In the shopping area, it is often difficult for visitors to find a bicycle parking spot as many facilities are occupied by local residents (Van der Spek & Scheltema, 2015). Therefore, visitors' bicycle parking demand was analysed after residential demand. Only when residents' demand is satisfied, then visitors will more likely to find a bicycle parking facility.

The case of studying shopping area is the main shopping street of Leiden, Haarlemmerstraat. According to car parking analysis (CROW,2003), the shopping area can be distinguished by four categories based on pedestrian intensity. The spot where has the largest pedestrian flow will be used as 100% intensity, then other spots' pedestrian density will be calculated depends on the proportion of the highest passers-by number (see **Table 7**). Based on this standard, the Haarlemmerstraat consists of sections of the top shopping street and sections of the main shopping street. Thus, there is the highest pedestrian flow during shopping peak hour. On Saturday shopping peak hour, more than 1300 bicycles were parked on or around Haarlemmerstraat while the current parking capacity was only 694. The bicycle parking capacity was large, which makes it a good study case.

Table 7 Category of shopping streets (CROW,2003)

Label	Description	Relative pedestrian intensity
A1	Top shopping street	80%-100%
A2	Main shopping street	50%-75%
B1	Premier connecting shopping street	25%-50%
B2	Secondary connecting shopping street	<25%

Parking demand: location, duration and user type

Unlike residential parking, the bicycle parking behaviour in the shopping area is more complex. The user type includes residents, visitors and employees. Their parking duration also varies. The parking duration of residents was long. Nearly 60% of residential bicycles parking had no turn over on Saturdays while half of the visitors stayed less than two hours. Logically, the employees will park their bicycles longer than two hours.

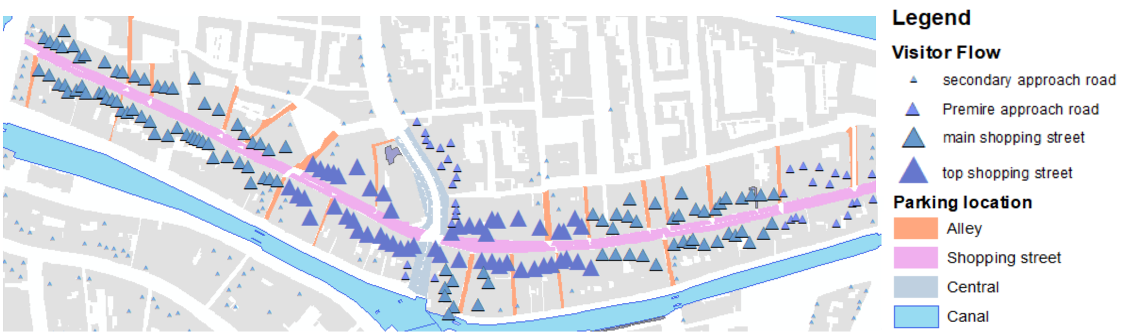

Figure 18 Haarlemmerstraat visitor flow and bicycle parking location

And there are different parking locations. According to bicycle parking data, on Haarlemmerstraat the parking location has mainly three types: in the alley, on the shopping street and in the central area (see **Figure 18**). Although there is a small bicycle garage in the central area, very few cyclists were using it. Alleys were the most popular parking location. However, half of the alley parking capacity was occupied by residents (see **Figure 19**).

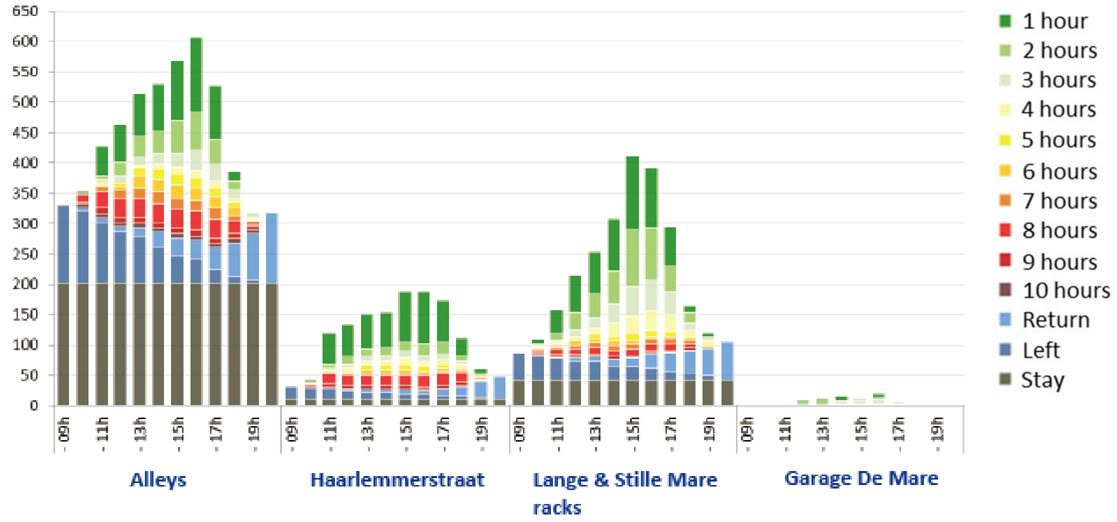

Figure 19 Bicycle parking duration and location on Haarlemmerstraat (Gemeente Leiden, 2016)

According to the city survey (Gemeente Leiden, 2011), few people (9%) carry their bicycles with them and park at every store they visit during their shopping. Instead, more people tend to park their bicycles at a central spot of their shopping (62%). Among them, 38% prefer a rack, and 24% will park at the first good parking spot they saw, no matter with or without racks. The central location is depended on people's visiting area. Haarlemmerstraat is 800 metres long. When a cyclist only visits part of the stores, the central location of her visiting area does not have to overlap the central location of the Haarlemmerstraat. Thus, the alleys could be many visitors' central parking location.

Cyclists who park for shorter time are more likely to prefer parking on-street. Therefore, when space is very scarce, the on-street alley parking should first satisfy short-term parking cyclists.

In conclusion, to analyse shopping street bicycle parking demand and supply, first of all, the bicycle parking demand should be calculated based on user type, parking location and parking duration.

Supply options

After obtaining the demand for bicycle parking and their properties, the possible extra bicycle parking supply options should be considered. Besides bicycle garage, the bicycle parking facilities are usually located on sidewalks (also attached alleys) and in this study, car parking space is also considered.

Figure 20 Sign saying 'it is appreciated if the bicycle is parked in the alley' on a shop window on Haarlemmerstraat

The Haarlemmerstraat is a pedestrian street, so there is no car parking on Haarlemmerstraat. And the shop owners want their shop windows bicycle-free (see **Figure 20**). So, visitors currently parking on the Haarlemmerstraat should also be engaged to park their bicycles in the designated area rather on the shopping street. This also indicates that expanding bicycle parking supply on the street itself is not possible. But car parking around the shopping street was taken into consideration. On this shopping street, there is no car parking space. But around the shopping street, there are some car parking spaces that can be converted to bicycle parking space. These spaces are closer to the entrance of the residential buildings than shopping street. If residents who are currently parking in alleys can park their bicycles in car parking space, then more facilities in the alleys can be used by visitors (see **Figure 21**). After accommodating residents' bicycle parking demand in car parking space, the new alley parking capacity can be calculated and compared with the short-term (less than 2 hours) parking demand.

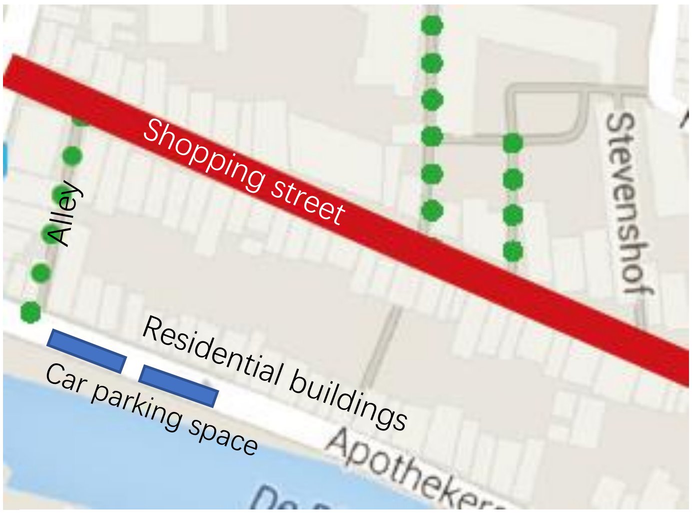

Figure 21 Bicycle parking options and their location

There are two factors that determine if bicycle parking facilities can be installed in an alley: alley width and the existing of private property entrance and windows. When the alley is longer than

80 metres, then the free passage needs to be 3.5 metres wide to allow emergency service pass. If an alley is shorter than 80 metres, then the free passage of 2 metres is needed for wheelchair users to pass. The entrance and windows of residents and shops should not be blocked. And if the alley is narrow that only wall racks are possible to be installed, then the permission from the building's owner is needed.

In conclusion, the shopping area demand and supply need to be analysed based on their different characteristics. This is concluded in **Table 8**.

Table 8 Bicycle parking type and location

Cyclists type	Residents	**Visitors**	
Parking duration	Long	**Short**	Long
Proper Parking location	**The back side of the shopping street**, garage	**Alley, street racks**	Garage

6.3 Conclusion

There are multiple location-allocation. In this study, based on the characteristics of the maximum coverage, minimum walking distance and restricted facility capacity, the 'maximum capacitated coverage' is selected. First, the current bicycle parking demand is allocated to existing bicycle parking facilities. Then the demand cannot be satisfied by existing bicycle parking facilities will be allocated to car parking space according to each scenario. After solving the location-allocation model, the number of satisfied demand, used car parking space and walking distance were obtained. In the shopping area, half of the bicycle parking facilities were occupied by residents during the peak hour. After car parking conversion, if the residents living in the shopping area and its demand can be satisfied by car parking space, then the facility in the alleys can be used by more short-term parking visitors.

7. Results

The result of the analysis will be shown in this chapter. The results for the residential area and shopping area will be presented respectively. For the residential area, the result mainly consists of three parts: bicycle parking capacity gap after converting car parking, capacity gap and sidewalk, and the influence on car parking capacity. For the shopping area, the result is focused on parking capacity at different locations for different types of cyclists.

7.1 Residential area

7.1.1 Effective bicycle parking supply

The residential bicycle parking peak is weekday nights. It can be seen from the data in **Table 9** that the bicycle parking capacity is 6366 during the peak hour, and the facility type is the on-street facility. It is logical that some parking facility installed for students or employees are close to educational institutes and companies but far from residential area. Thus, not all of these facilities can be used by residents at night. Through location-allocation analysis, the demand that cannot be satisfied by current bicycle parking facilities is still very high, which is 11565. The three car converting scenarios were then analysed through location allocation to allocate the demand currently are not satisfied. The results are presented in **Figure 22** and **Table 9**.

Based on the density map of demand points that are not satisfied, the bicycle parking shortage problem can be visually presented. The problem is slightly relieved under scenario 1 while largely improve under scenario 2 and scenario 3. Under scenario 2, all the regular street car parking space have been served as converting options, but still, some area has bicycle parking demand that cannot be satisfied.

Table 9 Residential bicycle parking capacity gap under each scenario

Scenario	Effective capacity added by car parking	Effective capacity/total potential capacity	Capacity gap	Reduced gap
Status quo	-	-	11565	-
Scenario 1	1962	37%	9603	17%
Scenario 2	9435	23%	2130	82%
Scenario 3	7529	22%	4036	65%

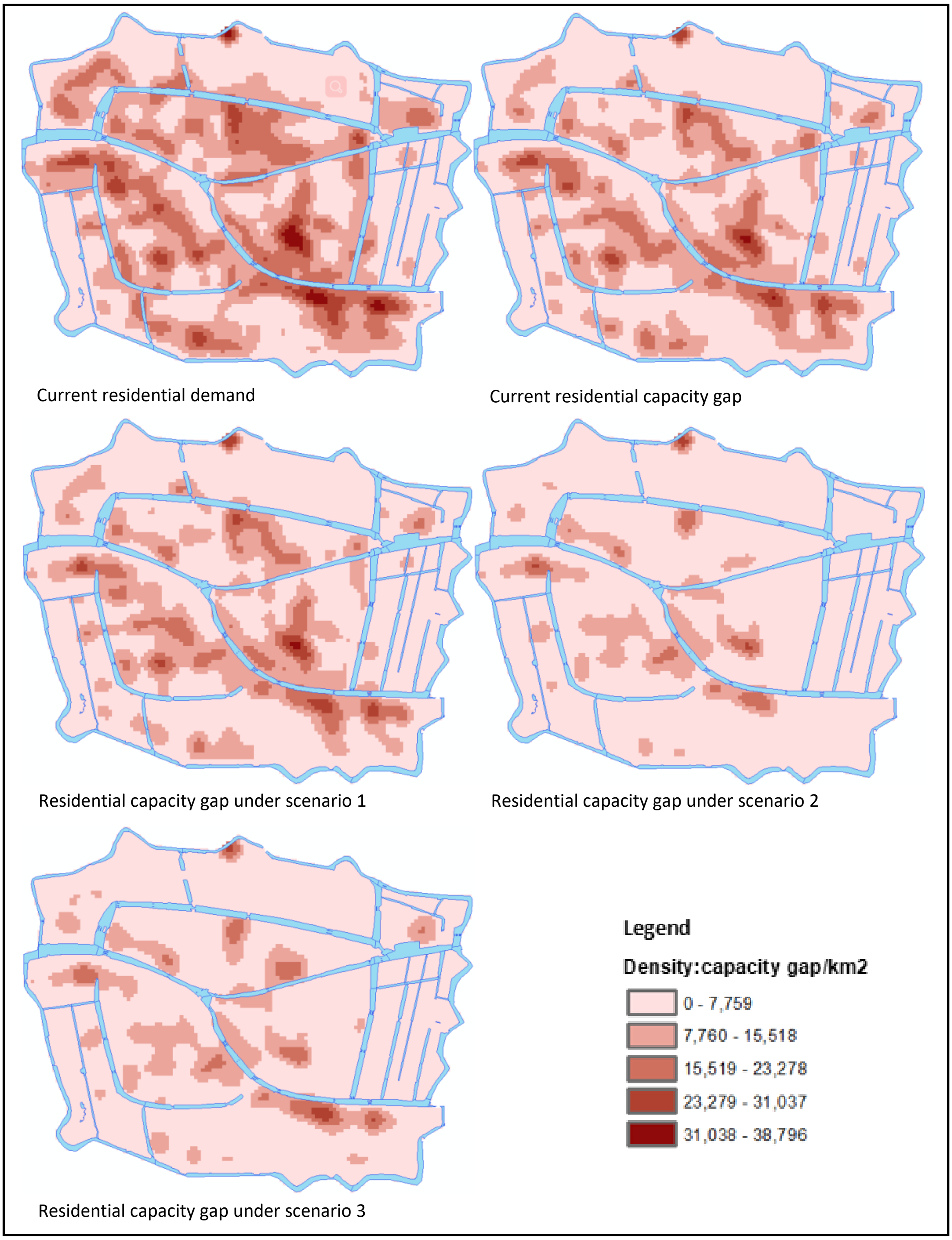

Figure 22 Residential bicycle parking capacity gap in status quo and under each scenario

As for the walking distance, the comparison is between scenario 1 which has the least parking facility candidates and scenario 2 which has the most parking facility candidates. Under scenario 1, only 39% of the demand points are located within 50 metres to facilities(see **Figure 23**). And the average walking distance is 165 metres. With the 50-metre walking distance restriction, the average walking distance is 18 metres.

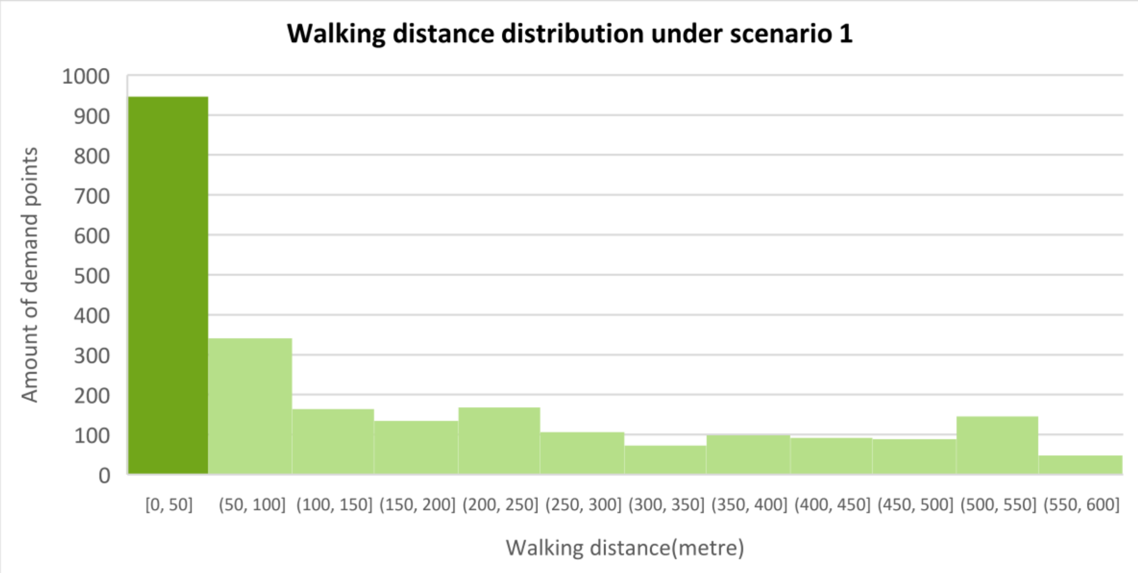

Figure 23 Walking distance distribution when location-allocation has no maximum walking distance restriction under scenario 1

Under scenario 2, 59% of the demand points were located within 50 metres(see **Figure 24**). And the average walking distance is 55 metres, which is much less than the average walking distance of scenario 1. For car parking spaces that are within 50-metre walking distance, the average walking distance is 19 metres. However, when comparing the proportion of parking within 50-metre to the whole candidates, scenario 1 is higher than scenario 2. This is because although under scenario 2, more parking locations are close to the residential addresses, there is often no such a high demand to fulfil all the available capacity. This means that many car parking spaces can be reserved in the residential area. This will be discussed in Section 7.1.3.

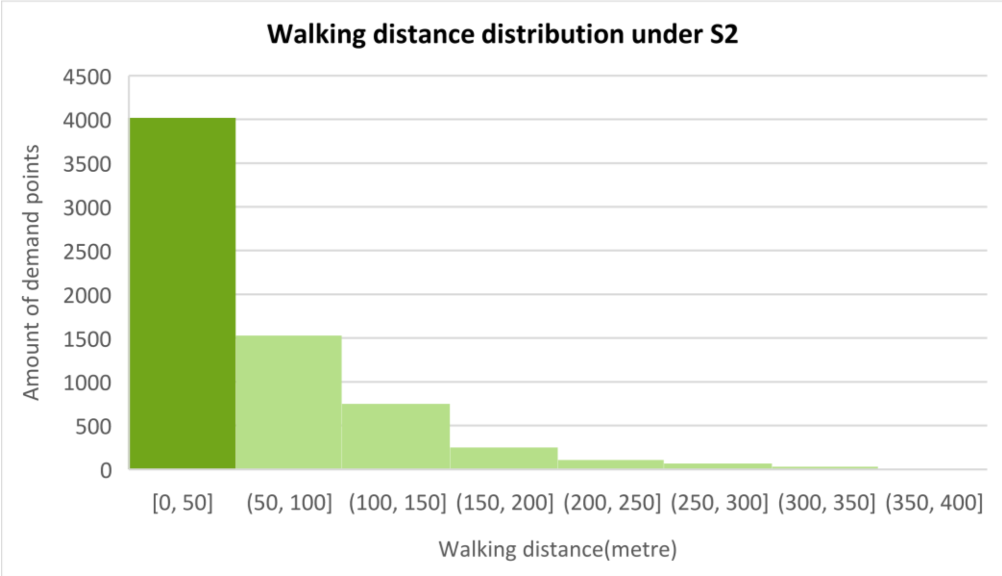

Figure 24 Walking distance distribution when location-allocation has no maximum walking distance restriction under scenario 2

7.1.2 Wild bicycle parking on the sidewalk

After obtaining the map of bicycle parking capacity gap, compare it with the layer of sidewalk width, the spot with narrow sidewalk and high bicycle parking capacity gap is presented (see **Figure 25**). The sidewalk width is classified based on the possibility of installing different type of bicycle parking facility (bicycle parking facility dimension see Appendix III).

It can be seen from the graph that a lot of high demand spot are with narrow sidewalks. It could be predicted that these areas have a high possibility of random bicycle parking on sidewalks, which will lead to hindrances for pedestrians using the sidewalk.

Scenario 3 is designed for good sidewalks. However, when there is bicycle parking demand and no sufficient parking facilities, the widened sidewalk will still be occupied by bicycle parking. Then it is meaningless to replace car parking space to widen the sidewalk. However, in a pure residential area, the car traffic flow is very low. It is common to see residents use sidewalks as bicycle parking and use the traffic lane as the sidewalk (see **Figure 26**). However, for people with specific need, this is still dangerous. If the car parking is removed in a pure residential area, the traffic flow will almost reach zero. It is possible to ban car use and only allow emergency service to drive in. In this situation, residents can use the sidewalk for bicycle parking, plants and benches. And the traffic lane will be closed for cars and be used by cyclists and pedestrians (see **Figure 27**).

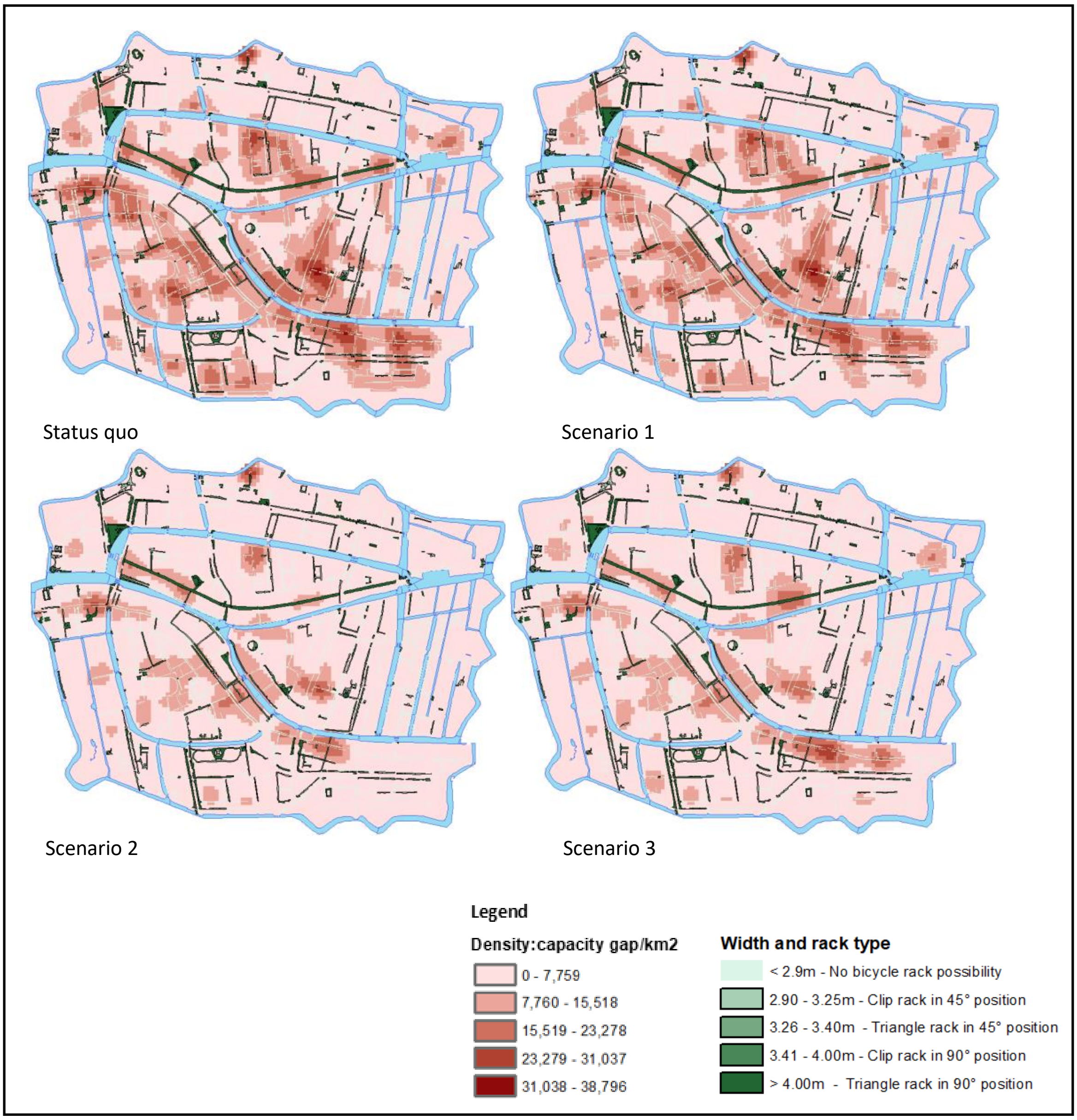

Figure 25 Sidewalk width and bicycle parking capacity gap

Figure 26 Street with residential car parking and no bicycle parking facility

Figure 27 One car-free section on Groenesteeg in Leiden city centre

7.1.3 Car parking capacity

Due to the walking distance restriction, under the first two scenarios, the car parking capacity is still beyond current residential parking demand. However, under Scenario 3, although less car parking spaces were converted to bicycle parking spaces than Scenario 2, another 668 parking spaces were cancelled to make sidewalks meet minimum width standard. After these two conversions, only 69% of the current car parking demand can be satisfied (see **Table 10**).

The alternative car parking location is the garage. During weekday nights, the occupancy of public car garage is very low. However, during Saturday afternoon, the occupancy is higher than 90%. This means allocate car users to park in the garage will lead to less capacity for visitors on Saturday.

On the other hand, the current car garages' service area cannot cover the whole city centre. According to the civil servant working for Leiden, they did a survey about the distance that car users are willing to walk from parking to destination, the maximum distance is 250 metres. As shown by **Figure 28**, some neighbourhoods are not locating within a 250-metre walking distance area.

Table 10 Car parking capacity after bicycle parking conversion

Scenario	Converted car parking space	Car parking capacity after conversion	Available capacity /needed capacity
Scenario 1	272	3748	111%
Scenario 2	1295	2725	81%
Scenario 3	1028	2324	69%

Figure 28 250m service area coverage of car garages in the city centre of Leiden

7.2 Shopping area

7.2.1 Demand

The bicycle parking demand in the study area was classified by user group, parking duration and parking location. The data was collected on Saturday and the demand used peak hour bicycle parking data. The result is presented in **Table 11**. Cyclists who were parking on the shopping street is not welcomed by the shop owners and also cause a nuisance on the busy hour. They will be engaged to park in the alleys.

Table 11 Bicycle parking demand on Haarlemmerstraat during peak hour

User group / Parking location	Residents	Visitors		Total
Parking duration	*long*	*Short*	*Long*	-
Alley	330	203	151	684
Shopping street	30	100	65	195
Central	90	200	110	400
Total	450	503	326	1279

7.2.2 Supply

There is no possibility to install bicycle parking racks on the shopping street itself. The current bicycle parking capacity at alleys is 244. Based on the municipality of Leiden's data, through replacing different bicycle parking racks, the maximum bicycle alley parking capacity can reach 411. And in the central part of the shopping street, there are bicycle parking racks with a capacity of 122. This is smaller than the number of visitors who are parking for a short-term at the central location.

On the back side of the shopping street, there are car parking spaces that have been converted to bicycle parking in residential area analysis. Based on the location-allocation result, the car parking space that was used by residents live on shopping street can be identified (see **Figure 29**).

Figure 29 Parking location allocation result example

Under scenario 1, there is almost no added residential parking capacity around the shopping street. Under scenario 2, the number is 517. Under scenario 3 the result is the same.

Thus, residents who currently park their bicycles in the alleys can park in the car parking spaces. The capacity of the alley is 411, the short-term parking demand of visitors in the alley is 203 and people who park their bicycles on shopping street is 100. The total demand 303 can be accommodated in the alleys with upgraded capacity. And there is still 100 capacity that can be used by people parking in the central rack area. But the pre-condition is that people who want to park in the central part of shopping street also find alley a good location.

Due to the scarce space, it is difficult to expand bicycle parking capacity on-street. Providing bicycle parking in garages may be necessary. The long-term parking demand can be satisfied by a bicycle garage. The garage can also provide weather protection and higher security for the bicycles of residents living around.

8. Implications of the results

8.1 Implication for politicians

According to the result, converting car parking to bicycle parking is an effective solution for bicycle parking shortage. Using 1295 car parking spaces, 9435 bicycle parking capacity can be created to satisfy 82% of the residential bicycle parking demand and largely relieve the visitor parking pressure on the main shopping street. But if a city has a very high bicycle parking demand with low car parking spaces, for example in the city centre of Leiden, the demand-supply gap probably cannot be fully bridged. In this case, the off-street bicycle parking facilities are essential. Based on the unsatisfied demand density map, the area with a high bicycle parking demand, low capacity and narrow sidewalks should have the priority of being provided with off-street bicycle parking.

Based on the result, possible problems on bicycle parking, car parking and sidewalks were concluded in **Figure 30**. These are the factors that the municipality should consider after obtaining the result of converting car parking to bicycle parking.

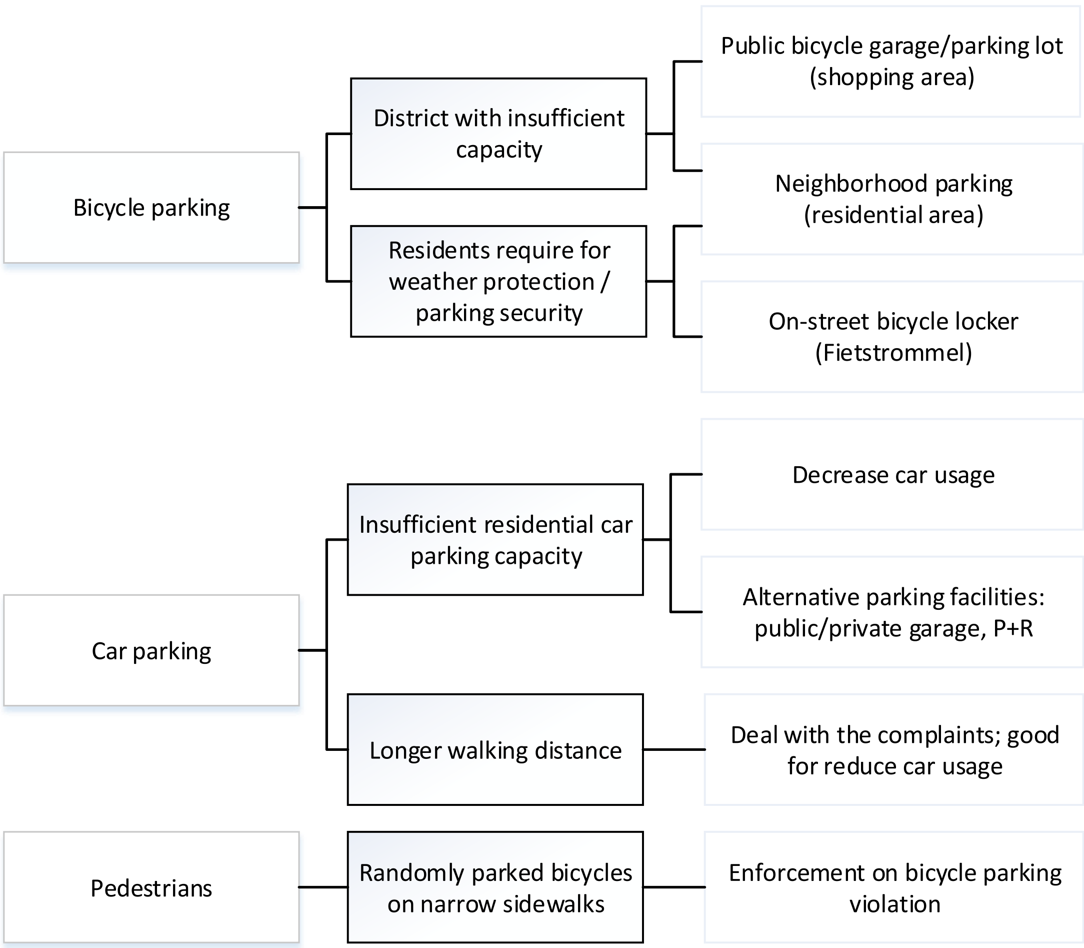

Figure 30 How to deal with the result of replacing car parking to bicycle parking

The study was based on the presupposition that cyclists will park their bicycles in the designated area if it is within proper walking distance. Without enforcement on bicycle parking violation, the new facilities could be empty during the night. And in the shopping area, the regulation should take parking duration into consideration. This is doable by using different tags to record parking duration. But it will cost some human cost because bicycles do not have plates and have to be manually managed.

This study is only based on data and the assumption of people's behaviour. Based on the lessons learnt from Oslo, it is recommended to communicate the project with the residents first to collect their opinions. Especially the on-street parking facilities cannot provide weather protection and a high level of parking security, which is important for residential parking. Pedestrians should also be invited to the meeting. Currently, disabled people are often neglected by parking meetings. However, they should be involved in the discussion of cities' parking policy as they will benefit from the relief of the bicycle parking shortage.

After converting car parking spaces, on some streets the night car parking occupancy will be higher than 85% or even the car parking capacity will be not enough. In these situations, longer walking distance or parking in alternative off-street garage is needed. It causes a negative impact on car owners. However, this is a good thing for a city that want to give slow traffic priority and make driving cars not that attractive. It helps to push people reconsidering their trip mode, especially for the people who use their cars at a low frequency.

There are two ways to reduce on-street car parking demand. One is to use several measures to directly reduce car ownership. This can also be achieved by the development of car-sharing and even automatic driving. The other is to engage car owners using alternative car parking facilities, including the parking garage, P+R parking, collaboration with private parking, etc. According to the interview with car parking policy advisor, the lack of alternative car parking facility is often the barrier to reducing car parking space.

Parking is a habitual behaviour(van der Waerden, Timmermans, & da Silva, 2015). Residents and visitors need time to adapt to the new parking policy. Besides good communication, some pilot project can be used as a trial. Scenario 1 can be used as a pilot project to see if residents will use the on-street bicycle parking facility during the night.

8.2 Implication for academia

Currently, the academic studies on bicycle parking behaviour are too limited. This study used a data-driven method while a user participation method can be used in the future to collect data on people's parking behaviour. In addition, this research only focused on spatial impacts. The environmental impact, social impact and economic impact of converting car parking to bicycle parking are also interesting. If some car owners need to park their cars from streets to garages to make room for bicycle parking, how will this affect the income of car parking and if a new parking pricing policy can be used to encourage the decrease of on-street parking need are interesting to study. Thus, a comprehensive cost and benefit analysis on converting car parking to bicycle parking can be conducted in the future.

The alternative car parking facility can come from private parking, for example, company parking garage. There is already a commercial company who is operating sharing car parking. They open private car parking facilities to city visitors on weekends. The municipality of Leiden is also trying to collaborate with private companies to open their parking facilities to residents and visitors. It is very interesting to investigate questions such as 'how to achieve collaboration? What role should the local government take?'.

As the demand for bicycle parking cannot be fully satisfied by car parking, some alternative solution is needed. Excepted for neighbourhood parking, sharing bicycles could also decrease the need for bicycle parking facilities. The free-floating sharing bicycle parking system has already been operated in some Dutch cities. Through the interview with Mr Ronald Haverman, who is now operating the branch of world's biggest free-floating bicycle company in the Netherlands, he suggested that when a city allows the operating of sharing-bicycles, more space for bicycle parking is used as the total number of bicycles increased. However, after some time, the demand for parking space can drop as some people will give up their second or third bicycles and replace them with sharing bicycles. The turnover of the second or third bicycle is usually low. Thus, if they can be replaced by sharing bicycles which have a higher turnover, less bicycle parking facilities will be used. There is no study to prove this yet.

9. Conclusion, discussion and recommendation

The research question is answered in this chapter. Then the limitations of the study are discussed.

9.1 Conclusion

Cities are promoting cycling as one of the solutions of urban sustainable mobility while bicycle parking shortage problem is faced by many Dutch cities. The increasing popularity of 'car-free city centre' concept offering an opportunity to solve this problem by replacing on-street car parking space with bicycle parking space. The objective of this study was to examine the effectiveness of solving the bicycle parking shortage problem by converting car parking space to the bicycle parking space. In addition, the effect of allocating bicycle parking demand with car parking space on car parking capacity and sidewalk walkability was assessed. As far as I noticed, this is the first study that develops a model to assess how much of the residential bicycle parking demand can be satisfied by car parking space and as a result how much bicycle parking pressure in shopping area can be relieved.

The main goal of this study is two-fold. On the one hand, it aims to develop a method that cities who would like to solve the bicycle parking shortage problem through replace car parking spaces can use to assess the spatial gains and losses. On the other hand, this study intends to use a city with high-demand-low-supply to explore if the bicycle parking shortage can be solved by converting bicycle parking spaces at an acceptable expense of car parking spaces. These two goals have been achieved and the conclusion is as follow.

9.1.1 Converting car parking to bicycle parking using location-allocation model

Taking car parking space from car owners may cause strong objection. Even though many cities want to go car-free and make their cities cycling-friendlier, they are cautious about the decision to ban on-street residential car parking. Therefore, it is significant to develop a method that cities can use to assess how many car parking spaces has to be removed and how much bicycle parking capacity can be created. This will help cities to make a better decision on their public space distribution.

A city can easily calculate how much bicycle capacity is needed for residential bicycle parking demand based on population and cycling rate. However, location is one of the most important criteria of good parking facilities. It is difficult to ask residents to park their bicycles in a spot one kilometre away from their home. Prior to this study, it was difficult to make predictions about how much bicycle parking demand can be satisfied with car parking by 'eyeballing', which would lead to low efficiency and unreliable result. This is the reason to develop a Location-allocation method to allocate bicycle parking demand to car parking spaces. The location-allocation model is commonly used for optimizing the location of public facilities. It can be easily analysed in GIS software such as ArcGIS, TransCAD, etc. Since GIS is widely used by municipalities, this method can be easily adapted.

Because the population and car parking data are usually possessed by municipalities, the residential bicycle parking demand and car parking spaces that used as candidate parking facilities can be easily obtained. As long as there is available data, a city can conduct the assessment of converting car parking to bicycle parking as detailed as one street or one neighbourhood or as broad as the whole city.

In addition, A city can set their own goals based on how much or what kind of car parking can be converted. For example, in this study, the scenarios are designed based on the preference for car owners, pedestrians or cyclists. Based on the result, the amount of bicycle parking demand and needed car parking spaces can be obtained. The city can evaluate after conversion, how much bicycle parking demand still cannot be satisfied and how much car parking capacity have to be sacrificed. Then they can make mitigation measures, such as providing alternative car parking and bicycle parking facilities. This method can also be used to set the goal of 'how much car ownership should be reduced if a city wants to have enough bicycle parking capacity'.

One innovation is that pedestrians were also taken into account in the method. Because bicycles are often randomly parked on the sidewalks and block the way, the pedestrians are also the victim of the bicycle parking shortage. Using a map showing the width of sidewalks, the district with high unsatisfied bicycle parking demand and narrow sidewalks can be easily discovered. Cities can take measures to prevent the problem of randomly parked bicycles and protect the sidewalks' walkability.

Based on the result of satisfied bicycle parking demand, unsatisfied car parking demand and the relieve of the nuisance of randomly parked bicycles on sidewalks, a city can make the trade-off between allocating more public space to bicycle parking or more space to car parking.

In conclusion, using the method developed by this study, the main research question:
"How to optimize the trade-off between bicycle parking and car parking using a GIS-based location-allocation method?" can be answered.

9.1.2 The spatial feasibility of using car parking space to solve the bicycle parking shortage

No previous study has investigated the feasibility of solving the bicycle parking shortage with car parking space. In this study, Leiden city centre was used as the study case. In the city centre of Leiden, there is a high cycling rate, low car ownership, and scarce public space. This means that Leiden is a city with high bicycle parking demand and low car parking supply. The difficulty of using car parking space to satisfy bicycle parking demand is high. Thus, if converting car parking space to bicycle parking space is a good solution for bicycle parking shortage in Leiden, it should also work for other cities with lower bicycle parking demand and more car parking supply.

Under the scenario that all the regular parking spaces were used as new bicycle parking facility candidates, the result showed the maximum bicycle capacity that can be provided by car parking space. 82% of the residential parking demand can be satisfied. This means in Leiden city centre, it is impossible to satisfy all the residential bicycle parking demand by converting car parking space. However, 82% is still a large amount. The car parking capacity can only satisfy 81% of the current parking demand. Thus, either the car ownership needs to be reduced, or some residents need to use alternative car parking facility off-street.

In this scenario, car parking provided extra 517 bicycle parking capacity around the main shopping street. With the upgrade of existing bicycle racks capacity, the short-term parking visitors can be accommodated. The bicycle parking pressure is largely relived. However, extra capacity is still needed to accommodate long-term parking visitors. And extra supporting measures are needed to engage long-term parkers to use off-street parking facilities instead of parking on-street.

For cities with lower bicycle ownership and higher car ownership, more demand can be satisfied as the demand is lower and supply is higher. As for the two scenarios that were designed in favour of car owners and pedestrians, scenario 1 can be used as a pilot project as the losses of car owners are low. And scenario 3 is only effective in the district with low bicycle parking demand or supported by an off-street bicycle parking garage. Or the widened sidewalk will still be occupied by randomly parked bicycles.

In conclusion, a very high amount of bicycle parking demand can be satisfied with car parking spaces, while a small amount of car owners has to change their parking habit from parking on-street to parking off-street. If a city is towards sustainable mobility and determined to boost the bicycle usage while discouraging car usage, then converting car parking to bicycle parking is a good solution. But at the same time, the conversion of car parking needs to be combined with other measures including neighbourhood parking in streets where the bicycle parking demand cannot be satisfied by converting car parking and it needs to be noticed that, the municipality need to prepare alternative options for car owners. It will be very difficult to remove car parking spaces in the neighbourhood which have no access to off-street car parking facilities.

9.2 Limitation

9.2.1 Data limitation

This research used a data-driven approach. However, during the analysis, because of the lack of data, the residential demand is a rough estimation based on the population living in old buildings. In addition, some data were collected at the different time. For example, the bicycle parking occupancy rate was collected in October of 2018 while the car parking occupancy rate was collected in the spring of 2018. The bicycle counting data on Haarlemmerstraat was collected in 2015. The differences in collecting time may lead to some error. The shapefile data from the municipality also have some errors. I have manually corrected all the errors that I noticed to reduce the error as much as possible.

9.2.2 Scope limitation

Commuters are not included in the study scope due to the lack of data. Their parking demand both for car parking and bicycle parking could have an influence on the study result. For example, an empty car parking space at night could be occupied during the day time. If it was converted to bicycle parking, then the daytime car parking will be affected. Therefore, this study would have been more interesting if it had included commuters.

After conversion, the walking distance for car parkers was not taken into the scope. Theoretically, it is feasible to investigate the car parker walking distance based on their parking location and the registered address. This is how de Vos and van Ommeren (2018) did their study on car parking occupancy rate. However, currently in the study area, the scanning car data has not been well used by municipality yet and it would cost a long time to prepare the data. Due to the time limitation, it is excluded from the scope.

9.2.3 Method limitation

This study used a data-driven method. Although some information was collected through surveys, there is no survey about people's opinion on converting car parking to bicycle parking. If this study is combined with some user participative study, for example, survey or interview, then the result could be more accurate and comprehensive.

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Appendix I Problem types of location-allocation models and their characteristics

Problem type / Characteristic	Minimize Impedance	Maximize Coverage	Maximize Capacitated Coverage	Minimize Facilities	Maximize Attendance	Maximize Market Share	Target Market Share
Impedance cut-off	Optional	√	Optional	√	Optional	√	
Minimize distance	√		√				
Maximize demand coverage		√	√		√	√	
Facility capacity restriction			√				
Minimize facilities							√
Demand weight decay				√			
Presence of competitors						√	√
Example	Warehouse	Fire station	Parking	School bus stop	Shops		

Appendix II Regulation on Residential Bicycle parking in the *Dutch Building Decree 2012*

Bouwbesluit 2012, translated by BicycleDutch[3]

Dutch Building Decree 2012
Section 4.5 Outside storage, new buildings

Article 4.30 Regulating article

1. A home must have a space to store bicycles protected from the weather.
2. A home meets the requirement of paragraph 1 if the space is constructed according to the regulations in this section.

Article 4.31 Availability, access and measurements

1. A building with the main function of habitat must have -as a sub-function- a private lockable storage space of at least 5 square meters with a width of at least 1.8 meters and a height over this width of at least 2.3 meters.
2. Notwithstanding paragraph 1, the storage room may be shared, when the habitat function of the dwelling does not exceed 40 square meters and the storage space for each dwelling is at least 1.5 square meters.
3. The storage room has to be directly accessible from the public road or from a shared private area that gives direct access to the public road.

Article 4.32 Rain resistance

The external construction of a storage space as described in article 4.31 has to be rain resistant according to the regulations of NEN 2778.

[3] Original regulation retrieved from https://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012/hfd4/afd4-5
Translation retrieved from https://bicycledutch.wordpress.com/2013/07/11/parking-your-bike-at-home/

Appendix III Bicycle rack dimension

Facility type	Length (including bicycle)	45 ° Length	Heart to heart interval	Preferred location
Clip	1.9 m	1.4 m	0.9-1.0m	Limited space, fewer bicycles
Triangle Rack	2.5 m	1.75 m	0.75 m	Higher demand
Wall Rack	2.1 m	1.5 m	0.75m	Narrow alleys with façade (only feasible when building owner allows installation)