

Pedal to Platform

Understanding Operational Efficiency of Bicycle Parking Facilities at Railway Stations in the Netherlands

Master of Transport, Infrastructure and Logistics

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Understanding Operational Efficiency of
Bicycle Parking Facilities at Railway Stations in
the Netherlands

by

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In partial fulfilment of the requirements for the degree of

Master of Science

in Transport, Infrastructure and Logistics
at Delft University of Technology

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Project Duration:	December, 2024 - May, 2025
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Faculty:	Faculty of Civil Engineering, Delft

Cover: Gemeente Maastricht, 2020



Preface

With great pleasure, I present this thesis as the final step of my journey at TU Delft. It marks the completion of not only my Master but also a transformative period in which I have grown both professionally and personally.

The topic of this thesis, bicycle parking at railway stations, touches on subjects that have long fascinated me: the societal role of transport, the impact of sustainability, and the challenge of designing systems that genuinely work for people. From a young age, I have been driven by curiosity, always eager to understand how things work. That same curiosity now guides me in exploring complex systems and in striving to contribute to a future where mobility is not only efficient and sustainable, but also centred around the needs of people.

This thesis process has taught me more than just academic or technical skills. One of the most important lessons I have learned during this thesis is the importance of creating structure for myself, setting my own frameworks, defining what is enough, and knowing when and how to ask others for help. It is a skill I will carry with me beyond this research.

I would like to thank my supervisors at NS Stations, Gert de Wit and Susan de Vos, for their consistent motivation, especially during moments when I struggled to see the finish line. I would like to thank Gert in particular for helping me tackle the data and for remembering the ins and outs of his thesis, which was really helpful, and Susan for showing me how the findings could really matter within the organisation and in practice. Special thanks also go to the NS bicycle parking facility personnel who generously shared their time and insights during the interviews.

To my graduation committee, Niels van Oort, Jan Anne Annema, and Nejc Geržinič, thank you for your valuable feedback and guidance. In detail, Jan Anne, your input from an economic and qualitative research angle helped shape the broader relevance of this work. Nejc, you not only challenged me to translate my findings into something meaningful, but also motivated me throughout the process and helped me realise that it's okay to speak up when things become overwhelming. Niels, thank you for guiding the process and for introducing me to NS in the first place.

This thesis also marks the end of my seven-year adventure at TU Delft, an experience that has shaped me far beyond the lecture halls. My time here was enriched by involvement in various student associations that each taught me something unique. Through Practische Studie, I developed valuable organisational skills, learning how to manage events and responsibilities for large groups. At Virgiel, I found not only friendship but also a space for fun, relaxation, and connection. And with SVRC, rugby pushed me both physically and mentally, teaching me to stand my (wo)man, communicate clearly under pressure, and trust in teamwork. I am deeply grateful to the friends who stood by me, challenged me, and helped me grow into the person I am today. You have taught me the strength of being myself, and the power of true, lasting friendship.

Finally, I would like to thank my family for their constant support and belief in me throughout the highs and lows of these academic years. They reminded me of my strengths, especially in moments when I lost sight of them myself, surrounded by all the brilliant minds in Delft. Their encouragement kept me grounded and gave me the confidence to keep going. I could not have done this without them.

Delft, June 2025

Irene Bosman

Executive Summary

Dutch railway stations are under increasing pressure to provide more bicycle parking to meet rising demand. As cycling remains an important form of transport for the first and last miles of a journey, making efficient use of existing bicycle parking infrastructure is crucial. However, many facilities are struggling with outdated designs, overcrowding and changing user behaviours, particularly the increasing number of non-standard bicycles. This research examines how bicycle parking facilities at railway stations can be made to operate more efficiently in order to serve a greater number of users within the constraints of limited space. The main research question is therefore:

What strategies can enhance the usage efficiency of bicycle parking facilities at railway stations in the Netherlands based on their operational dynamics?

In this context, efficiency is defined as the ability to serve the maximum number of users with the least strain on capacity. This is measured by three indicators: occupancy, turnover and parking pressure. Occupancy is the ratio of occupied spaces to capacity, while turnover is the number of bicycles parked within a given time period. Parking pressure is the proportion of parking spaces in use within a given time period. These indicators reflect how intensively a facility is used and determine whether demand is well matched to supply.

Facility characteristics, such as design and location, influence user decisions, which in turn affect overall efficiency. These interactions are illustrated by the conceptual diagram in figure 1. This shows how these interactions flow from macro-level infrastructure to micro-level user actions and back to system-wide outcomes.

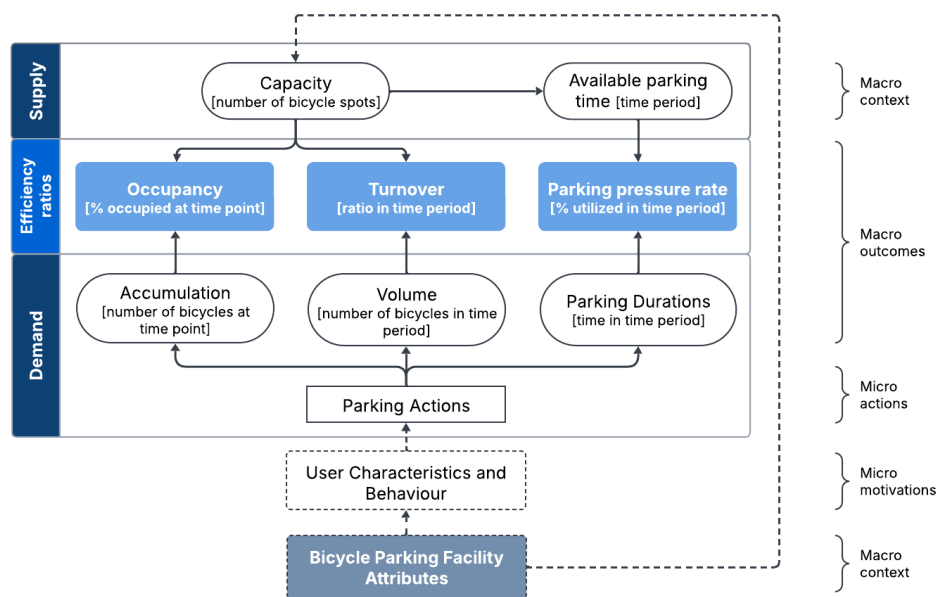


Figure 1: Conceptual diagram of usage efficiency

To explore the operational dynamics of these facilities, the study combines a data-driven analysis with contextual insights gained from interviews with facility staff. The quantitative component draws on check-in and check-out data from 2023–2024 to calculate usage metrics across 97 bicycle parking facilities. A time-series clustering approach was employed to categorise the facilities into usage-based groups, and statistical tests were used to validate these distinctions. Qualitative interviews enriched the analysis by providing first-hand insights into daily operations, user behaviour and challenges.

The clustering analysis revealed six distinct usage patterns, each of which was found to be associated with different user patterns as a results of different overall user behaviour and operational contexts. There was significant variation in efficiency between clusters, highlighting mismatches between infrastructure and actual use. Two clusters emerged as particularly efficient, while others revealed issues such as long-term bicycle storage, abandoned bikes and a lack of enforcement.

Figure 2 shows these usage patterns per cluster. The usage patterns are analysed using a representative average week to capture typical demand. The average week consists of a period of four weeks in September and October, excluding irregular periods such as holidays, and averaging occasional events and possibly weather effects.

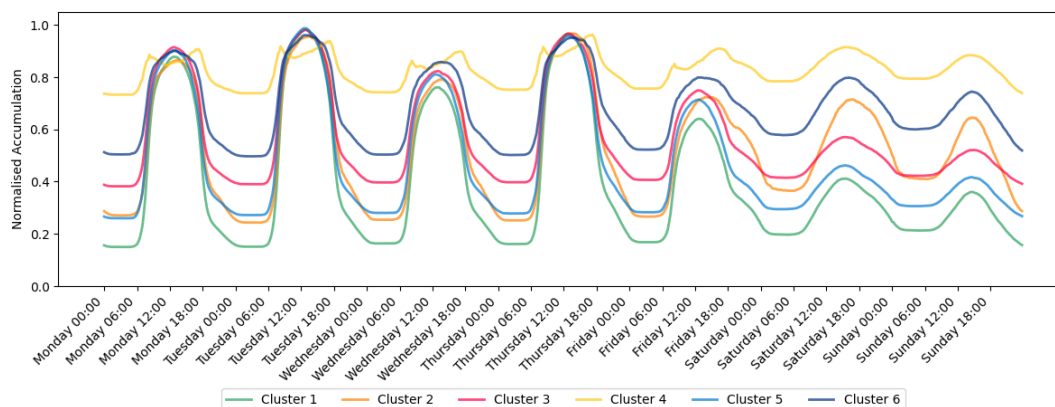


Figure 2: Average usage patterns per cluster of the representative weeks

The graph illustrates the following usage trends:

- Clusters 1 and 5 demonstrate sharp weekday rush-hour peaks, reflecting intensive home-end commuter use during work-related travel.
- Cluster 2 shows elevated nighttime occupancy and increased weekend use, likely driven by large urban areas with significant student populations and longer parking durations.
- Cluster 3 displays also a home-end commuter-oriented pattern, but elevated night-time occupancy suggests extended parking durations.
- Cluster 4 facilities show less high peaks and deep troughs, a more steady usage, indicating balanced traffic. The double peaks during the day suggests two-way flows, reflecting different types of users.
- Cluster 6 shows a usage trend that combines increased weekday activity with significant weekend usage, reflecting a vibrant urban environment.

The relationship between cluster grouping and facility efficiency is visualised in figure 3, which plots turnover against parking pressure for a representative week. Facilities above the diagonal trend line are relatively efficient, exhibiting high turnover for their level of pressure, while those below indicate inefficiencies such as long parking durations with limited user exchange. Clusters 1 and 2 are the most efficient. Cluster 1 tend to be medium-sized facilities at production stations with short parking durations and clear home-end weekday commuting patterns. Cluster 2 comprises large, guarded facilities at attraction stations, characterised by high weekend turnover and the shortest average stays. Cluster 3 mainly includes small, unguarded facilities with limited services, showing low turnover and long stays despite moderate pressure, signalling lower efficiency. Cluster 4 is the least efficient, with the longest parking durations and highest pressure. Frequent issues like orphaned bicycles contribute to congestion. Clusters 5 and 6 reflect intermediate and less efficient usage. Cluster 5 includes small, unguarded home-end commuter stations with moderate turnover. Cluster 6 shows dual-use patterns typical of attraction stations, high pressure but long average stays, indicating reduced efficiency.

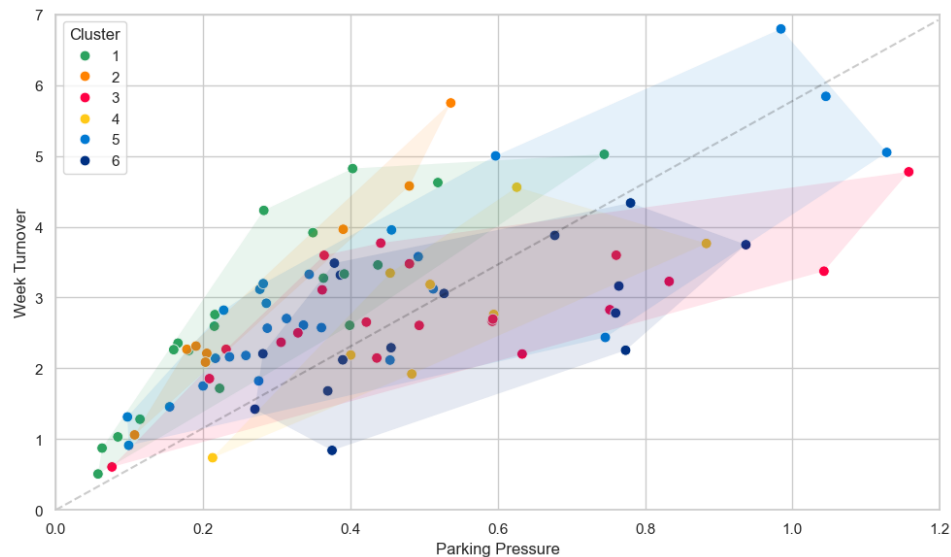


Figure 3: Usage efficiency clusters through turnover and parking pressure

Qualitative findings complement the quantitative patterns and inform targeted interventions. Guarded facilities (clusters 1, 2, and 4) are associated with higher perceptions of security and cleanliness, while self-service facilities (clusters 3, 5, and 6) often face challenges in user discipline, layout clarity, and enforcement. Subscriptions may distort true occupancy levels, and the rising prevalence of non-standard bicycles increases pressure on infrastructure. These findings, together with the conceptual diagram and interview insights, shape the following overarching strategies for enhancing bicycle parking efficiency:

Monitor efficiency throughout the facility's lifespan: Efficiency should be measured not only in terms of occupancy, but also in terms of turnover relative to parking pressure. Regular monitoring of this ratio allows early detection of inefficiencies. Interventions such as time limits or pricing adjustments can then be applied to maintain or restore efficient usage.

Strengthen enforcement: Long-term and abandoned bicycles reduce facility efficiency. Effective strategies include improved digital recording, consistent monitoring and clear responsibilities between stakeholders (NS, ProRail and municipalities). These measures influence both user behaviour and system capacity.

Match design and policy to usage context: Facilities need to be tailored to local demand. As urban hubs require well-integrated, guarded services, smaller stations benefit from compact, intuitive designs. Where long-term use is prevalent, responses include revising parking time limits, changing pricing and subscriptions or improving enforcement. Where use is low despite pressures in the public surrounding, better signage and shorter walking distances can encourage use.

Accommodate diverse bicycle types: Current facilities often lack suitable racks for non-standard bicycles, bicycles with crates/children's seats or cargo bikes. These users park informally, reducing order and space efficiency. Solutions include innovative rack designs tailored to these types, placed in convenient and visible locations based on local demand and space availability.

Improve user experience of self-service facilities: There is a lower sense of security and a higher risk of theft in self-service facilities. Measures to improve security include passive surveillance (e.g. with adjacent services such as bicycle repair shops), robust signage and intuitive layout design to prevent misplacement and misuse by users. These improvements can enhance both perceived and actual security, increasing user confidence and facility efficiency.

These overall strategies can be further specified into cluster-targeted approaches that address the distinct usage patterns and contextual characteristics:

- **Cluster 1 Efficient Weekday Commuter Facilities**
Challenge: Underutilisation during weekends despite high weekday turnover.
Strategy: Encourage off-peak use by offering free or discounted weekend access, increasing overall facility utilisation.
- **Cluster 2 Efficient Urban Hub Facilities**
Challenge: Space constraints and high demand limit scalability.
Strategy: Implement dynamic space allocation (e.g., dual use of shared bicycle areas), support with real-time information, improved signage to sustain high turnover.
- **Cluster 3 Inefficient Commuter Facilities**
Challenge: Long parking durations, abandoned bicycles, and lack of oversight.
Strategy: Increase monitoring through manual checks, improve signage, and reduce long-term parking to free up capacity by for example strict enforcement.
- **Cluster 4 Congested Mixed-Use Facilities**
Challenge: High congestion due to second bike use and limited enforcement.
Strategy: Conduct facility-specific analysis as interviews with staff for tailored action, strengthen enforcement, review parking time limits, and adjust subscription policies.
- **Cluster 5 Intermediate Efficient Commuter Facilities**
Challenge: Limited use outside peak hours and weak enforcement presence.
Strategy: Improve perceived safety and signage, partner with local services, and increase monitoring to enhance off-peak attractiveness without disrupting (home-end) commuter flow.
- **Cluster 6 Inefficient Mixed-Use Facilities**
Challenge: High demand with long parking durations and insufficient turnover.
Strategy: Similar to cluster 4, strengthen enforcement, review subscription use, and investigate causes to design appropriate interventions.

This study improves our understanding of bicycle parking at railway stations by focusing on operational efficiency and the extent to which facilities serve users in the context of limited space and resources. Instead of examining perceptions or satisfaction, it analyses real usage patterns to reveal where systems are effective and where they are not. The results show that context is important: inefficiencies may be manageable in small stations, but active design and management are essential in high-demand urban hubs to maintain functionality.

The findings demonstrate that context matters. While inefficiencies may be tolerable or even negligible at smaller stations, in urban centres, limited space and high demand require active, data-driven management. High performing locations such as Utrecht Centraal show that complex, high pressure environments can function efficiently with good coordination, adaptive policy and user focused design. In contrast, dual function facilities serving both access and egress often experience conflicting user demands and time patterns, requiring a more integrated planning approach.

This study identifies parking pressure and turnover as key performance indicators, providing station operators and policymakers with practical tools. When incorporated into visual dashboards, these indicators support proactive management, allowing stakeholders to detect inefficiencies early and respond with targeted strategies, such as enforcement, pricing or infrastructure adjustments. The findings also emphasise the importance of accommodating various types of bicycles, enhancing the user experience of self-service facilities, and aligning design and policy with local demand.

However, limitations include incomplete data on subscription use, the exclusion of short-term parking and unattended facilities, and potential bias arising from clustering decisions made for interpretability. Furthermore, staff perspectives were prioritised over direct user input, and the role of shared mobility requires further exploration in future studies.

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Introduction

In a world where urban populations are growing rapidly, cities face increasing challenges in meeting the transport demand. Public transport systems play a crucial role in ensuring the efficient movement of people within and between cities, helping to reduce congestion, cut emissions and improve urban mobility. In the Netherlands, cycling is the most important means of access to train travel, accounting for about half of the daily train users (ProRail, 2024). Cycling has many advantages over other modes of transport. It is a highly sustainable mode of transport, contributes to a reduced environmental impact, improves public health and takes up less urban space than cars (Handy et al., 2014).

The multimodal combination of bicycle and a high level of transit, such as trains, can improve door-to-door accessibility and the speed of the overall travel time. According to a case study of (Zuo et al., 2020), it triples the transit access distance compared to walking and additionally improves the transport equity, highlighting the importance of integrating these modes. Well-designed bicycle parking facilities at stations are key to enable the integration and ensure a smooth and efficient journey for daily commuters and other travellers.

However, parking facilities are often designed long before they open, with a lifespan of at least forty years (PwC, 2020). This can result in infrastructure that is outdated and unable to meet demand by the time it is utilised. According to Jonkeren et al. (2018), there is even a latent demand for bicycle parking capacity in the Netherlands. This indicates that due to the high occupation of bicycle parking, individuals choose not to cycle to the train station, because they know they cannot park their bikes at the station. The introduction of additional capacity will consequently lead to an increase in users.

Furthermore, rapidly evolving travel patterns, such as the rise of shared mobility (Jorritsma et al., 2021), the growing popularity of e-bikes, shifts in commuting patterns (Arendsen et al., 2023) and the increasing size of bicycles (Broer, 2016), often outpace the ability of existing bicycle parking infrastructure to adapt. These emerging trends can lead to inefficiencies in usage such as overcrowding, abandoned or 'second' bikes taking up valuable space, and a mismatch between parking supply and demand. Some examples of known inefficiencies are shown in figure 1.1. As governmental organisations continue to prioritise sustainable transport solutions and the use of public transport increases (Rijksoverheid, n.d.), the challenge of providing efficient and future-proof bicycle parking becomes more pressing.



(a) Long-term bicycle parking

(b) non-standard bicycles

(c) Subscriptions

Figure 1.1: Examples of parking facility dynamics at Stationsplein Utrecht Centraal (Own source, 2024)

1.1. Problem Analysis

In recent years, the integration of cycling with rail travel combined with the topic bicycle parking has emerged as an important component in the promotion of sustainable urban mobility and has been the subject of research. This combination increases the accessibility to public transport, reduces environmental impact by cutting down car dependency, and promotes healthier lifestyles (Kager et al., 2016). Several studies highlight the importance of convenience and accessibility in the user preferences. For example, Arbis et al. (2016) and Gavrilidou et al. (2020) show that cyclists prefer parking facilities close to station entrances, with minimal walking time and visible security measures. User perceptions of service quality, accessibility, security, and the clarity of parking infrastructure explain 70% of the user experience and play an important role in shaping satisfaction and willingness to use parking facilities (Hoskam, 2020). Pricing and enforcement mechanisms have also been shown to shape parking behaviour, with moderate pricing generally not deterring users and well-enforced policies effectively reducing inappropriately parked bicycles (Fukuda & Morichi, 2007; Molin & Maat, 2015). In addition, the review of Martens, 2007 revealed that investments in well-designed, high-capacity infrastructure, such as guarded parking facilities, not only improves user satisfaction but also encourage cycling as an access and egress mode for rail travel. In chapter 3 the relevant literature on this topic is further explained in a comprehensive literature review.

However, while cycling is typically regarded as a space-efficient mode of transport in comparison to cars, the considerable scale of its use in the Netherlands raises questions about the ability of bicycles alone to meet spatial efficiency demands in dense urban contexts (Ton and van den Heuvel, 2023). As station areas struggle to accommodate growing numbers of bicycles, it is critical to assess whether current parking strategies can sustain this level of cycling, or whether alternative solutions, such as shared bicycles or innovative spatial designs, are needed to further optimise land use. This is further elaborated by Schakenbos and Ton, 2023, who concludes that in order to facilitate the combination of the bicycle and train travel, the solution lies not only in creating capacity, but also in steering demand and catching the right traveller on the right mode of transport.

Research Gap

Despite previous findings on the importance of convenience, accessibility, pricing policies, and infrastructure investment in shaping user satisfaction and parking behaviour, significant gaps in knowledge remain. In order to find a more efficient way to use and provide bicycle parking that meets the growing number of cyclists, a more detailed understanding is needed of how the facilities are used and how user preferences and behaviour influence this overall usage. Existing studies, such as Hoskam (2020) and Martens (2007), provide important insights but often focus on users and specific aspects, leaving broader questions about the overall usage of the bicycle parking facilities unanswered. In addition, while policy and enforcement are often identified as critical factors, their practical impact on usage patterns and user satisfaction is under-researched. This gap is particularly critical given the growing demand for cycle-rail integration and the spatial challenges faced by urban railway stations. Further research into the operational dynamics of bicycle parking facilities is essential to ensure that they efficiently meet user needs, promote sustainable multimodal transport and support urban space optimisation. Moreover, little attention has been paid to the impact of long-term trends in bicycling on the facilities, such as the adoption of e-bikes, fat bikes or cargo bikes or the implications of increasing urban density. In conclusion, the essence of addressing these research gaps lies in the thorough analysis of bicycle parking facility usage and the development of infrastructure to accommodate evolving trends in cycling and urban dynamics.

This research seeks to fill this gap by exploring the operational dynamics of bicycle parking at railway stations. By addressing the gap, the study aims to inform future improvements in efficiency of the usage of bicycle parking facilities at railway stations, ensuring that they can effectively support the growing trend of cycle-rail integration.

1.2. Usage Efficiency

In order to fill the gap for future improvements of efficiency of the usage, it is necessary to determine what usage efficiency in bicycle parking means. This section explores the concept of efficiency in the context of bicycle parking at railway stations.

NS, together with ProRail and local municipalities, provides bicycle parking facilities to encourage train use by making it easy for travellers to access railway stations by bicycle (Rijkswaterstaat, n.d.). This initiative aligns with the concession agreement between NS and the Ministry of Infrastructure and Water Management, which states: "NS shall reasonably ensure, together with other parties, sufficient bicycle parking spaces in the station areas and for optimal utilisation of the available bicycle parking spaces in the station area." (Article 27.1, Ministry of Infrastructure and Water Management, 2025).

In addition to facilitating multimodal travel, bicycle parking plays a crucial role in maintaining urban order by preventing randomly parked bicycles from obstructing pavements and public spaces. Poorly managed bicycle parking can create accessibility issues for pedestrians, reduce the visual appeal of station areas, and contribute to urban disorder (Pucher and Buehler, 2008). According to van der Spek and Scheltema (2015), when designated parking facilities are available and enforcement is in place, cyclists are more likely to use them.

Efficiency, in general terms, refers to the extent to which an activity achieves its intended goals while minimizing resource usage (Harvey, 2024). The goal of bicycle parking at railway station is as described to provide as many travellers as possible with a bicycle parking spot to encourage more people to use public transport, specifically the train. Thus, in the case of railway station bicycle parking, we define efficiency as:

Providing as many travellers as possible with a bicycle parking spot while minimising resource usage—specifically, the required parking space and the total number of parking spots needed.

While cost considerations play a role in infrastructure decision-making, this study focuses on optimising the efficiency of existing bicycle parking rather than conducting a cost-benefit analysis. Cost plays an important role in efficiency as it is also a form of resource. The financial aspects of bicycle parking, including construction and maintenance, are outside the scope of this study.

1.3. Research Goal and Questions

As urban populations grow and sustainable transport strategies become increasingly important, the integration of cycling and rail offers a significant opportunity to improve urban mobility in the Netherlands. Despite the proven benefits of cycling and its prominent role in accessing public transport, current bicycle parking facilities at railway stations face challenges in meeting the growing demand. This research aims to fill existing knowledge gaps by investigating the intricacies of the operation of bicycle parking facilities and their effectiveness in promoting multimodal transport solutions.

The aim of this research is to optimise the efficiency of bicycle parking, ensuring that these facilities can robustly support the bike-rail integration that is central to alleviating urban congestion. By analysing usage patterns and operational dynamics, the study aims to uncover strategies to improve facility utilisation and accommodate emerging cycling trends while addressing spatial constraints at urban rail stations.

The research questions guiding this investigation are to explore the operational capabilities of bicycle parking facilities, assessing both their strengths and areas of inefficiency. By framing these questions, the study outlines a path towards understanding and improving the functional effectiveness of these critical transport hubs.

In pursuit of these objectives, the main research question of this research is:

What strategies can enhance the usage efficiency of bicycle parking facilities at railway stations in the Netherlands based on their operational dynamics?

In order to find the answer to the main research question, the sub-questions will be used to draw conclusions, a flowchart of this structure can be found in figure 2.1.

1. How can usage efficiency be expressed in operational dynamics of bicycle parking facilities?
2. What are the usage patterns of bicycle parking facilities at railway stations, and how do these patterns vary by time and location?
3. What operational dynamics of bicycle parking facilities, both efficient and inefficient, can be observed and how can they be related to the usage patterns?

1.4. Outline

This thesis systematically explores the operational dynamics of bicycle parking facilities at railway stations in the Netherlands, focusing on enhancing usage efficiency. The research starts with the methodology, described in chapter 2, which explains the methods of the quantitative and qualitative analysis of this research. Chapter 3 reviews the existing literature and provides insights into bicycle-train integration, user behaviour, and facility characteristics. In chapter 4, the findings are combined in the development of a conceptual diagram of usage efficiency. The following chapter describes the data processing steps in detail. Chapter 6 presents the results of this research. Chapter 7 summarises the conclusions and then discusses the findings and interprets them in relation to existing literature. Recommendations for practice are next presented, and finally methodological limitations and recommendations for future research are discussed.

Methodology

Although bicycle use and infrastructure are widely studied, research focusing specifically on the efficiency of bicycle parking usage remains limited. To help bridge this gap, this study adopts a mixed methods approach, integrating both quantitative and qualitative analyses. This chapter begins by outlining the quantitative steps of the research. It then describes the qualitative component, which consists of semi-structured interviews with key personnel involved in bicycle parking operations. These interviews offer in-depth insights into operational challenges and user feedback that may not be captured through quantitative analysis alone. The resulting insights from the interviews are integrated into relevant sections of the report to enrich and contextualise the findings.

The initial step is to explore the concept of efficiency in the context of bicycle parking and to determine a method for its assessment. The second research question aims to address the usage aspect of the main research question by conducting an analysis of the usage of different bicycle parking facilities. The final research question seeks to establish a link between the observed usage patterns and the operational aspects, efficiencies and inefficiencies, with the objective of developing effective strategies that will lead to more efficient bicycle parking. In figure 2.1 the process of answering the research questions is presented.

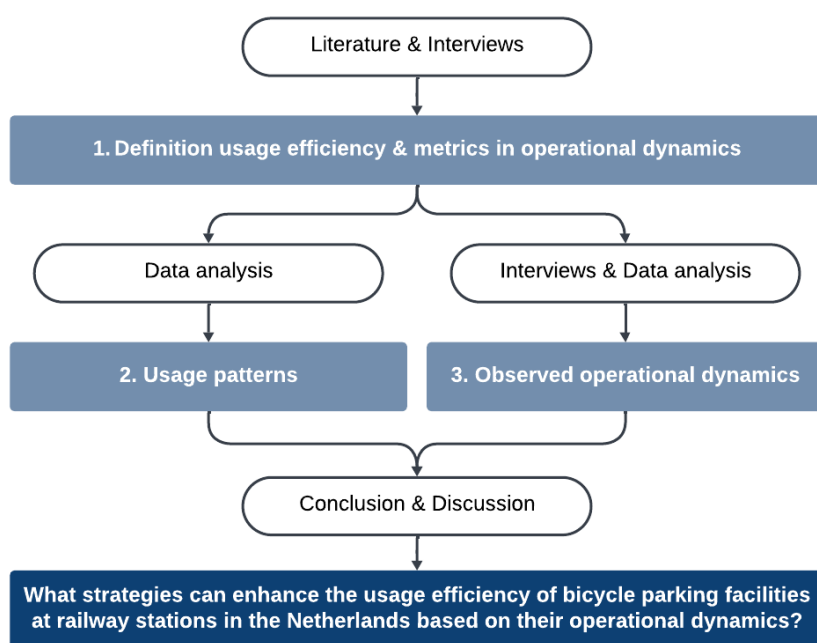


Figure 2.1: Flow chart research questions and methods

2.1. Quantitative Analysis

The quantitative analysis in this study aims to assess the operational dynamics of bicycle parking facilities in terms of usage efficiency, representing the balance between demand and supply. The analysis seeks to evaluate the level of efficiency of these facilities and thereby identify influencing factors that could inform strategies to improve operational efficiency. The demand-to-supply indicators are explored and explained in chapter 4. This data-driven approach aims to identify trends, measure usage levels, and highlight (in)efficiencies that could impact the effectiveness of bicycle parking.

2.1.1. Data Description

The primary dataset for this research consists of check-in and check-out (CiCo) transactions from cycle parking facilities at NS stations, sourced from the NS central data storage. This repository records all transactions that occur at facilities managed by NS. An attempt was made to obtain the dataset of ProRail, which records parking durations for each parking space, in order to broaden the analysis. However, this data was ultimately not made available. As a result, the research relies on the dataset of NS, which, despite certain limitations, provides a rich and consistent basis for assessing usage patterns across the majority of managed bicycle parking facilities.

In order to eliminate as much as possible the potential bias due to COVID-19 interruptions, the dataset focuses exclusively on records from 2023 and 2024. In addition, data from December 2022 is included to account for bikes parked at the start of 2023, taking into account the maximum 28-day parking period, ensuring a comprehensive representation of parking activity at the start of the year.

The dataset used consists of two key tables: the first detailing individual parking activities and the second describing parking facility attributes. These are linked by the location name of the facility and include key attributes such as parking prices, start and end timestamps, duration, staffing details, facility addresses, bicycle and service availability and certain capacity metrics.

Illustration of the structure of the dataset with the parking actions:

Table 2.1: Data format parking actions at NS bicycle parking facilities

Start date	Start time	End date	End time	Duration	Location name
YYYYMMDD	Minutes count	YYYYMMDD	Minutes count	Minutes	Name

2.1.2. Data Processing Steps

The quantitative analysis consists of several steps, selected to build an understanding of how bicycle parking facilities are used, and to evaluate their operational efficiency. Alternative methods were considered at each stage, but the final approach was chosen for its suitability to the available data and research objectives:

- **Data exploration:** Initial data preparation involved cleaning, filtering, and structuring the data to allow for consistent analysis across different facility types and locations. These data processing steps are described in chapter 5. The analysis begins with an examination of parking durations in order to understand usage intensity and identify any outliers or irregularities. This step establishes a baseline for defining and interpreting usage patterns in the subsequent steps.
- **Temporal usage analysis:** Variations in facility usage over time are examined to uncover weekly and seasonal trends, which are largely shaped by commuter behaviour. Bicycle parking facilities at railway stations exhibit clear temporal patterns aligned with broader commuting rhythms (Jonkeren et al., 2021), a topic that is further discussed in chapter 3. These patterns are essential for identifying mismatches between facility capacity and actual demand. To capture representative usage while avoiding distortion from irregular periods, the analysis focuses on a selected “average week”

an averaged period of four weeks starting in the second week of September. This is a period when occupancy is typically high and stable across most facilities, as discussed and demonstrated in more detail in chapter 5. This approach ensures the findings reflect typical demand under peak-period conditions, which facilities must be designed to accommodate. While alternative approaches such as comparing full-year patterns for each facility were considered, they risked overemphasising occasional anomalies (e.g. temporary closures, local events, or weather spikes). Since the objective is to understand structural demand under regular operating conditions, not extreme or atypical usage, the average week approach was deemed more appropriate.

- **Clustering of temporal usage patterns:** To identify meaningful similarities and differences between bicycle parking facilities, a clustering analysis is conducted using time series comparison methods. Given the large number of facilities distributed across the Netherlands, it would be impractical to analyse each one individually. Clustering allows for a higher-level comparison by grouping facilities that exhibit similar usage patterns over time. These patterns follow consistent weekly cycles, making them ideal for time series analysis. The time series comparison techniques and clustering methods are discussed in the following section, including a justification for the selected method.
- **Efficiency evaluation:** Finally, the analysis applies performance measures that capture usage efficiency. Specifically, it uses indicators that reflect the relationship between demand and available supply. These metrics, which are introduced earlier in this section and are discussed in more detail in chapter 4, assess how effectively bicycle parking facilities accommodate users. By quantifying how space is utilised over time, they provide a basis for evaluating whether facilities are under- or over-utilised. To better understand the drivers behind efficiency outcomes, several contextual variables are also examined, including facility type, location characteristics and enforcement practices. This step offers deeper insight into the operational dynamics that shape usage patterns and facility performance.

2.1.3. Time Series Comparison

In analysing the temporal usage patterns of bicycle parking facility, employing robust clustering strategies is helpful for capturing the inherent variations in user behaviour across different time series datasets for the parking locations. This study explores three similarity methods for time series, Euclidean, Dynamic Time Warping (DTW), and Soft DTW, to effectively classify facility usage patterns.

Euclidean Distance

Euclidean distance is a foundational metric used to determine similarity between time series data by calculating the straight line distance between points. It provides a simplistic yet efficient method for clustering when data points are uniformly distributed without significant temporal distortion (Kate, 2016).

Given for example for two time series $X = x_1, x_2, \dots, x_n$ and $Y = y_1, y_2, \dots, y_m$ the Euclidean distance is:

$$ED(X, Y) = \sqrt{\sum_{i=1}^n (x_i - y_j)^2}$$

And thus in this research that would be the square root of the difference of all normalised accumulation point per quarter of the average week.

Dynamic Time Wrapping

DTW allows for flexibility in alignment, making it possible to assess how similar two facilities are in their usage trends, even if their peaks occur at slightly different times (Kate, 2016). This method could provide a more robust way to compare parking facility usage,

ensuring that the analysis accounts for shifts in peak demand while maintaining an accurate measure of similarity.

Given two similar time series X and Y , a cost matrix is constructed where each element is $(x_i - y_j)^2$ which represent the cost to align the point x_i with y_j . An alignment between the two series represents the wrapping path $W = (w_1, w_2, \dots, w_K)$ and the DTW distance minimises this alignment costs:

$$DTW(X, Y) = \arg \min_W \sqrt{\sum_{k=1, w_k=(i,j)}^K (x_i - y_j)^2}$$

A constraint to limit the path in the cost matrix is possible (Kate, 2016). In the case of the normalised accumulation of a week, it is important that the alignment does not cross between days of the week, this also improves the speed of the calculation. This constraint is set to one hour to account for small differences in, for example, opening times (facilities open a quarter before the first train and close a quarter after the last train) and small differences in peak times.

Soft Dynamic Time Wrapping

Soft DTW extends traditional DTW by smoothing the cost function, allowing more flexible adjustment between time series. In order to do so, the min operator of traditional DTW is replaced by a smooth one:

$$\min_{x \in S} \gamma f(x) := -\gamma \log \sum_{x \in S} \exp \left(-\frac{f(x)}{\gamma} \right)$$

In this expression, γ is a parameter that balances between approximation precision and smoothness, allowing flexible adjustment in time series analysis, which is set to 0.5 (Cuturi and Blondel, 2018, Blondel Arthur Mensch Jean-Philippe, 2021). The rest of this method is similar to the traditional DTW, where $f(x)$ is the function to be minimised and S the corresponding cost matrix.

The three methods have different strengths when it comes to comparing usage patterns. The most suitable method is selected by evaluating their clustering results using silhouette scores. The method with the highest score is then used in the final analysis to ensure meaningful grouping of facilities based on temporal behaviour. This evaluation method is discussed further in the following sections.

2.1.4. Clustering Method

Using K-means clustering for analysing time series data such as bicycle parking facility usage is advantageous due to its straightforward approach and interpretability. K-means aims to minimise the total within-cluster sum of squared distances, effectively grouping time series with similar patterns around cluster centroids (Kobylin & Lyashenko, 2020). This objective allows for clear and concise representation of typical usage profiles. Moreover, K-means is computationally efficient and scales well to large datasets, making it particularly suitable for time series clustering compared to hierarchical methods. Hierarchical clustering, while flexible, can become prohibitively slow and memory-intensive as the number of time series grows (Aghabozorgi et al., 2015). This reduction of complexity by grouping similar usage patterns makes K-means a suitable clustering method for this research.

Steps in K-Means Clustering Algorithm:

1. Initialisation: Choose k initial centroids randomly, where k defines the number of expected clusters. These centroids are the preliminary cluster centres.
2. Assignment: Assign each data point to the nearest centroid using a specific distance metric (Euclidean distance, DTW or soft DTW). This step groups the time series data points closest to each centroid, forming preliminary clusters.

3. Updating Centroids: Calculate new centroids for the clusters by taking the mean of all data points assigned to each cluster, effectively shifting the centroid to represent the centre of mass of the cluster.
4. Iteration: Repeat steps 2 and 3 until the centroids no longer change significantly, indicating convergence to optimal cluster definitions.

The similarity methods paired with K-means, enables grouping based on nuanced temporal interactions, capturing subtle variations in usage patterns across facilities.

2.1.5. Model Selection and Fit for Time Series Clustering

To achieve a robust cluster analysis and find the best fitting clustering method, the silhouette score is used as a measure of cluster validity, providing insight into how well separated and internally cohesive the clusters are, depending on the distance measure used (Januzaj et al., 2023).

Data processing steps:

1. Implementation clustering method: K-means clustering, which involves calculating time series distances according to the three proposed methods - Euclidean, DTW and Soft DTW. These distances guide the assignment of data points to appropriate clusters.
2. Silhouette score calculation: Calculate the silhouette score for different numbers of clusters to assess cluster quality. The formula is:

$$\text{Silhouette Score} = \frac{b(i) - a(i)}{\max(a(i), b(i))}$$

Where $a(i)$ represents the average intra-cluster distance, and $b(i)$ signifies the lowest mean distance to points in other clusters. In the case of time series comparison, $a(i)$ is the average of all distances within the cluster calculated with the similarity method. And $b(i)$ the lowest distance to the mean of the other clusters.

3. Method comparison and cluster number: Compare silhouette scores across different cluster counts and methods to identify which configuration and distance measure yields the highest score, indicating optimal clustering.

By following these steps, we can effectively use K-means clustering to explore and validate different similarity methods, thereby selecting the most appropriate clustering model tailored to the specific data dynamics of bicycle parking facilities. Through silhouette analysis, the model not only determines the optimal number of clusters, but also improves the understanding of temporal usage patterns, which is critical for optimising facility management and planning. The steps of processing the data for clustering can be found in appendix B.2.

2.1.6. Cluster Validation

To further validate the clustering results and to assess the distinctiveness of the identified groups, statistical tests are performed to examine whether the clusters represented significantly different patterns of facility characteristics and between the different efficiency indicators.

Continuous Variables

For continuous variables such as facility capacity, average occupancy, or turnover rate, the ANOVA (Analysis of Variance) F-statistic is used to test whether the means of these variables differ significantly across clusters (Lamkey, 2023). The F-statistic is calculated as:

$$F = \frac{\text{Variance Between Groups}}{\text{Variance Within Groups}}$$

A high F-value, coupled with a p-value below 0.05, indicates statistically significant differences in means between the clusters, suggesting that the clustering has captured meaningful distinctions in the dataset.

Categorical Variables

For categorical variables, including facility type (e.g. guarded or self-service) and pricing regime, a Chi-squared test is used to evaluate the independence of distributions across clusters. The Chi-squared test compares the observed frequencies with the expected frequencies under the assumption of independence (Tallarida and Murray, 1987). The chi-squared statistic is calculated as follows:

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

where O_i is the observed frequency and E_i is the expected frequency assuming no association between the variable and cluster assignment. The null hypothesis (H_0) states that the variable is independent of the clusters, in other words, its distribution is uniform across the clusters. The alternative hypothesis (H_1) posits that the variable's distribution differs significantly between clusters. A significant result ($p < 0.05$) leads to the rejection of H_0 , indicating a meaningful relationship between the variable and the cluster structure, which provides interpretability to the identified usage patterns.

These statistical tests support the internal validation of the clustering by showing that the clusters differ in ways that are consistent with meaningful, interpretable variables. This reinforces the usefulness of the cluster configuration for answering the research question about usage patterns and helps to contextualise the practical implications for facility design and management.

2.2. Qualitative Analysis

While the quantitative analysis provides valuable insights into the usage patterns and operational efficiency of bicycle parking facilities, it does not fully capture the underlying behavioural and contextual factors that influence these patterns. To address these knowledge gaps, this study incorporates a qualitative component. This mixed methods approach enriches our understanding of facility dynamics by exploring aspects that are difficult to quantify, such as contextual factors, nuances in user behaviour and operational challenges. The qualitative research thus complements and deepens the quantitative findings, helping to identify inefficiencies and opportunities for improvement that may remain hidden in data-driven analysis alone. The following sections describe the design, execution, and thematic focus of the semi-structured interviews, highlighting their role in providing a comprehensive picture of bicycle parking facility operations.

2.2.1. Semi-Structured Interviews

As mentioned to bridge the gap between data and practice, this study employs semi-structured interviews with personnel involved in the daily operation and management of bicycle parking facilities.

Semi-structured interviews are a widely used qualitative research method that combines structured and unstructured elements (Kallio et al., 2016). Compared to structured interviews, semi-structured interviews are better suited for this research due to the exploratory nature of the topic and the complexity of operational challenges within bicycle parking facilities. While structured interviews rely on a fixed set of predefined questions and leave little room for deviation, semi-structured interviews provide the flexibility to explore unanticipated themes or elaborate on insightful responses that may arise during the conversation. The semi-structured format allowed for a balance between having a set of core questions that guide the conversation, while also permitting the interviewer to explore areas of interest that arise spontaneously during the interview (Gill et al., 2008). This is particularly

valuable when examining the operational dynamics of bicycle parking, where individual experiences and insights could uncover deeper issues and encourage participants to share their perspectives in their own words, which provides richer insights into user behaviour and operational challenges. The flexibility of the method also allows for the emergence of new ideas or unexpected insights, which might otherwise be overlooked in more rigid interview formats. Despite this flexibility, the core questions provide a structured framework, making it easier to compare findings across different interviews and identify patterns or trends.

The structure for the semi-structured interviews in this research includes:

- **Introduction:** a brief explanation of the purpose of the interview and the role of the participant, creating a comfortable environment for open communication.
- **Core Questions:** a set of open-ended questions aimed at exploring the primary research topics.
- **Follow-up Questions:** these arise naturally as the participant shares their thoughts. These can either clarify responses or probe deeper into specific aspects of the discussion.
- **Conclusion:** a summary and closing, with the opportunity for the participant to share any additional thoughts or concerns.

Topic Selection

The interview topics were chosen to address the gaps in the quantitative analysis identified and to explore the behavioural and operational dimensions. Although quantitative clustering revealed patterns in facility usage, it could not fully capture the human, procedural and contextual factors that influence these patterns. The importance of user perception is emphasised in literature on travel behaviour. These elements are difficult to infer from numerical data alone. By contextualizing the quantitative part of the research with interviews, the study leverages the strengths of both approaches to provide comprehensive insights. In this research, the semi-structured interviews focused on exploring the following themes:

1. **Role of the interviewee in bicycle parking facilities:** As an introduction and to get an understanding of the participant's responsibilities in relation to the operation and management of bicycle parking.
2. **Facility usage:** While the data showed variation in usage intensity and efficiency, it did not explain why certain practices lead to these outcomes. This theme explores the impact of physical design, enforcement practices, operational procedures on usage and types of bicycles in the facilities, which are not systematically recorded in datasets.
3. **Users:** Quantitative data lacks information about user intent, preferences or feedback. This theme aims to uncover user segmentation (e.g. commuters vs. occasional users), behaviour patterns and qualitative user experiences. These are all factors shown in the literature to influence parking demand and satisfaction. These literature findings are further elaborated in chapter 3.
4. **Future of bicycle parking:** As a conclusion, to gain new insights, the participants' perspectives on the future role of bicycle parking, potential challenges and necessary adaptations to meet changing needs are investigated in this theme.

Participant Selection

A total of 8 participants are internal selected for their practical knowledge and diverse perspectives across different executive roles within the facilities of two distinct regions. This selection includes two district managers, two unit leads, and four facility employees, representing different perspectives of operational layers. Their first-hand experience and insight into the daily operations and strategic management of the facilities offer valuable

contributions to understanding the discrepancies and efficiencies observed in bicycle parking.

- Two district managers: responsible for coordinating and overseeing the performance of multiple bicycle parking facilities (and other station services except train operations) in collaboration with municipalities and ProRail.
- Two unit leads: manage the day-to-day operation of specific locations and oversee the staff teams.
- Four facility employees: engaged in frontline activities such as enforcement, general upkeep and user interaction.

The number of interviews was determined based on the principle of thematic saturation, a point at which additional interviews no longer provide substantially new insights (Rahimi & Khatooni, 2024). Throughout the interviews similar themes and operational challenges kept coming back and thus provided sufficient perspective for this qualitative study.

Results Presentation

Given the dual relevance of the interview findings to both the literature and data analysis, results from interviews are integrated throughout the report. They are directly linked to topics of interest, offering explanations or posing further questions related to the findings (*in blue italic font*). The results help to interpret and enrich the literature and the results of the quantitative analysis.

These methodological steps enable the study to progress from raw usage numbers to a deeper understanding of how bicycle parking facilities are used in practice. By identifying patterns, the findings can inform strategies to improve operational performance and better match supply with demand. The quantitative results are interpreted alongside qualitative insights from interviews to provide a comprehensive overview of the user-driven dynamics of bicycle parking. The following chapters begin by outlining the context of bicycle parking in chapter 3, followed by an exploration of the concept of usage efficiency in chapter 4. Subsequently, the data processing steps for the quantitative analysis are detailed in chapter 5. The results chapter 6 presents the findings of this methodology, including both quantitative and qualitative results, and concludes with strategies aimed at answering the main research question.

Context Bicycle Parking

This chapter provides an explanation of the context of bicycle parking at railway stations to provide a baseline of knowledge about station bicycle parking. It begins with the bicycle-train combination, followed by an examination of the bicycle parking behaviour of the users. Special focus is given to first-mile cycling (the home-end of the trip), since this has the greatest impact on the usage of bicycle parking facilities. The research also includes second bicycles (those parked at the activity-end of the trip), but shared bicycles are out of scope. The next step in the research is to look at the usage of bicycle parking facilities. This chapter also presents some results of the interviews in order to interpret the literature and relate it to reality. This chapter provides the basis for describing the metrics of bicycle parking usage efficiency and developing a conceptual model to answer research question 1 in chapter 4.

To find relevant literature, the search engines Google Scholar and Scopus are used with keywords such as 'cycle rail integration', 'bike train integration', 'bicycle parking behaviour', 'bicycle parking at stations', 'bicycle parking facilities', 'bicycle parking pricing', 'bicycle parking management', 'cycling access/egress mode train' and various combinations of the above keywords. The abstracts of relevant papers are reviewed in order to assess their suitability for inclusion in the analysis. Papers that are consistent with the focus of the study and related topics are selected for further review. Mendeley is used for the efficient organisation and management of sources. This software facilitated the categorisation of papers, the annotation of key points, and the retrieval of references during the writing process. Table 3.1 outlines the primary focus, methodology, findings and limitations of the sources reviewed.

Table 3.1: Summary of reviewed studies on integration of bicycle and train and parking behaviour

Source	Focus	Method	Relevant findings	Limitations & recommendations
Arbis et al. (2016)	Location preferences in bicycle parking and infrastructure implications	Regression data analysis	People tend to park close to station entrances	Data from Australia only, cultural differences may affect generalisability
Fukuda and Morichi (2007)	Bicycle parking behaviour	Discrete choice models	Train users respond to parking infrastructure and enforcement policies	More research needed on behavioural and policy implications
Gavrilidou et al. (2020)	Revealed and stated preferences in parking choices	Discrete choice modelling	Preference for parking close to exits; real-time signage has positive effect	Case study limited to Delft station
Heinen and Buehler (2019)	Bicycle parking behaviour overview	Literature review	Parking availability positively correlates with usage	Comprehensive overview still lacking, more empirical data needed
Hoskam (2020)	Willingness to pay for station bike parking	Stated choice experiment	Users willing to pay more for guaranteed free space	Not all influencing factors identified
Jonkeren et al. (2021)	Users of station parking facilities	Survey data analysis	Mostly used by young commuters in urban settings	NS panel not fully representative of all users

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Source	Focus	Method	Relevant findings	Limitations & recommendations
Jonkeren and Kager (2021)	Parking behaviour at activity-end	Survey	Second bike use is significant and impacts capacity	Frequency of use not captured
Kager et al. (2016)	Typology of station areas and access modes	Spatial network analysis	High-quality access routes stimulate cycling to stations	Framework needs more testing in diverse station types
Martens (2007)	Impact of bicycle parking investments	Literature review	Investments led to growth in use and satisfaction	Outdated (2007), focused only on the Dutch context
van Mil et al. (2021)	Importance of parking in bike-train use	Choice modelling	Users accept longer bike times to avoid transfers	Sample composition and unmeasured factors limit generalisability
Molin and Maat (2015)	Trade-off between price and walking distance	Stated choice experiment	Users are willing to pay for proximity	Limited to Delft station, lacks broader validation
Paix Puello and Geurs (2014)	Influence of parking on mode choice	Choice modelling	Perceived safety and proximity of parking influence rider-ship	Broad interpretation of “parking” as concept
Shelat et al. (2018)	First/last mile access and socio-demographic factors	latent class cluster analysis	Most trips by combined mode are commuters with cycling as access mode	Based on Dutch panel data; deeper behavioural insight needed
van der Spek and Scheltema (2015)	Bicycle parking management practices	Literature review	Emphasises importance of enforcement and facility quality	Lacks concrete management strategies
Ton and van den Heuvel (2023)	Access/egress mode trends at Dutch stations	Cluster analysis of survey data	Growing role of cycling; increasing spatial pressure	Reinforces urgency but lacks operational parking focus
Zuo et al. (2020)	Equity in access to transit via cycling/walking	Equity-focused spatial analysis & case study	Cycling access can triple the catchment area of PT compared to walking and significantly improves transport equity	U.S.-based, results may be context dependent

3.1. Integration of Bicycle and Train

As mentioned in chapter 1, the integration of bicycle and train has become increasingly important in promoting sustainable mobility. By combining the strengths of these two modes, individuals can enjoy an efficient alternative to car travel while contributing to wider societal benefits, including reduced congestion and lower carbon emissions (Shelat et al., 2018; Zuo et al., 2020). The two modes come together at railways stations and parking facilities allow a seamless transition between the two. In the Netherlands, this integration has been particularly well developed and studied, reflecting the country’s strong cycling culture and high reliance on public transport. Research highlights the effectiveness of Dutch bicycle-train integration in supporting sustainable transport systems (Martens, 2007; Kager et al., 2016). However, while the broader concept of bike-train integration has received considerable academic attention, the specific role, usage, and management of bicycle parking facilities remains under-explored.

To understand how users interact with bicycle parking facilities at railway stations, it is essential to explore both their mode preferences (why and when people choose cycling as a means of station access or egress) and their station selection behaviour (how the characteristics of stations and surrounding infrastructure influence where they choose to park and board). These two behavioural dimensions inform how demand is distributed across space and time, and what design or policy measures may influence more efficient usage.

Mode Choice

The studies on mode choice particularly focuses on the selection of cycling as a mode of transportation to and from the station. Research by Ton and van den Heuvel (2023) on the means of access (at the home end of a trip, the production station) and egress (at the activity end of a trip, the attraction station) of train passengers showed that cycling is increasingly used to reach production stations and, for some users, to leave attraction stations as well. The study concludes that the spatial footprint of stations is becoming a challenge. As the Netherlands is densely populated and faces a housing shortage, urban space is becoming scarce, putting pressure on the use of space for parking cars and even bicycles.

To illustrate this, figure 3.1 shows the share of train passengers using a modality of access or egress to or from a station compared to the land use of these different modes at stations in the Netherlands. As earlier discussed in chapter 1, this figure clearly demonstrates the efficiency of cycling compared to driving in terms of spatial requirements. Since bicycle parking requires significantly less space than car parking, cycling is a more sustainable option in space-constrained urban areas. However, with limited space available for some dense urban locations, bicycle parking must also be managed efficiently to maximise its benefits.

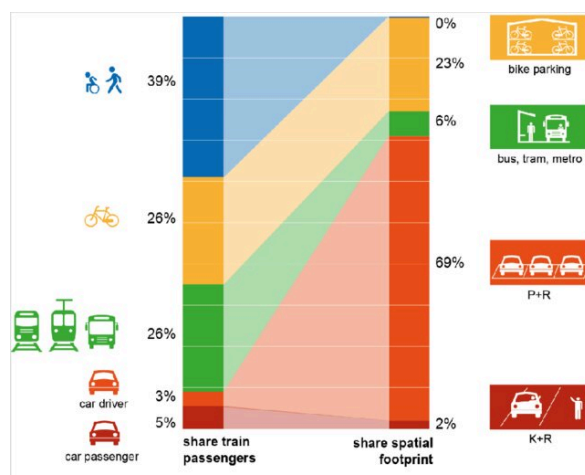


Figure 3.1: Share access and egress modes (Ton and van den Heuvel, 2023)

Paix Puello and Geurs (2014) emphasise the qualitative aspects of integration, such as perceived safety, proximity and cycling comfort. Their findings suggest that users are particularly sensitive to these factors during the egress journey, where the quality of the parking facility can significantly influence their mode choice, while users are less sensitive during the access journey. This highlights the importance of providing high quality, well located parking facilities to support seamless multimodal travel. This is also shown in the fact that investment in bicycle parking infrastructure has a direct and positive impact on user satisfaction and travel behaviour. As noted by Martens (2007), improvements to regular and secure bicycle parking at stations have led to increased use of cycling as an access mode, higher satisfaction levels, and a rise in the number of bicycles parked. This effect is particularly evident in high-density areas with large numbers of students and commuters. Such enhancements not only meet existing demand but also encourage new users to adopt cycling as a mode of transport. This corresponds with the research by Heinen and Buehler (2019), an increased availability of parking facilities is correlated with more bicycle parking. This reflects the importance of bicycle parking facilities at railway stations to steer to more use of the bicycle-train combination as mode of transportation.

Station Choice

Bicycles are predominantly used as a mode of transportation at the home-end, connecting users from their homes or starting locations to railway stations. The preferences of cyclists for integrated travel solutions are influenced by various factors. For instance, van Mil et al. (2021) found through a stated choice experiment that individuals are willing to accept longer cycling distances or parking times if it eliminates the need for transfers. This trend has driven increased demand at major intercity stations, often necessitating the development of larger mobility hubs. Additionally, according to van Mil et al. (2021) factors such as parking time and cost significantly influence user choices, highlighting the importance of tailored parking solutions.

According to Jonkeren et al. (2021), the choice of stations is strongly impacted by the quality of the station and its facilities. Higher-tier stations are preferred for their proximity to major destinations and the superior services they offer, such as frequent train connections and better facilities. These findings support the trend that users are willing to cycle longer distances to avoid transfers and enjoy the benefits of well-connected, well-equipped stations. Furthermore, the study showed that cyclists are more likely to choose stations where high-quality parking facilities are available, further supporting the integration of cycling and train travel.

Summary Integration Bicycle and Train

- The combination of bicycle and train is crucial for sustainable mobility and offers an efficient alternative to the car, while bicycle use is increasing, but space at stations is limited. Efficient use of space and management measures are needed to sustain the promotion of public transport use, further emphasizing the relevance.
 - People will accept longer cycle and parking times if they have to transfer less. Showing of how parking choices are influenced by convenience and journey time, which will affect the bicycle parking facilities. Since user choices directly impact the efficiency of bicycle parking facilities, the next section delves into the behavioural aspects influencing cyclists' parking decisions.
-

3.2. Users

To get a better understanding of usage of the bicycle parking facilities a review of existing literature is done to identify the users and the aspects that influences the users for different usage of the facility. These aspects helped to determine what facility characteristics to check influencing the usage of bicycle parking facilities.

3.2.1. Characteristics

The demographic profile of facility users provides insights into their parking behaviour. Jonkeren et al. (2021) analysed the personal profiles and travel choices of bicycle-train users in the Netherlands based on a 2017 survey of 2,299 train users conducted by NS. The study classified users as 'bicycle-train travellers' if at least 16% of their trips involved this combination, with frequent users exceeding 51%. Findings showed that bicycle-train users are generally younger and more often salaried employees, while retirees were predominantly infrequent or non-users. Differences among entrepreneurs, students, and other groups were minimal, though the student sample size was too small for significant conclusions. Bicycle-train users primarily commuted for work, whereas social and leisure trips were more common among infrequent or non-users. The study also found that bicycle-train users tend to be highly educated, with university graduates being overrepresented among frequent users. Lower education levels were less common in this group, suggesting that education level may play a role in travel behaviour, potentially due to work locations or commuting preferences.

Complementing these findings, Shelat et al. (2018) used a cluster analysis approach to segment Dutch train travellers based on their travel patterns and station access modes. This study also revealed that younger, urban travellers were more likely to use bicycles, particularly in areas with high-quality cycling infrastructure. The results highlight that access mode choice is shaped not only by individual demographics, but also by spatial and infrastructural context. Together, these findings emphasise the need for targeted planning strategies that consider the diverse needs of different user groups.

That users of the facilities are indeed mainly commuters, is also indicated by the interviewees (Appendix A), emphasizing that commuters indeed form the largest group utilizing the bicycle parking facilities. This alignment between research and practical observations

underscores the critical role of bicycle facilities in accommodating commuter needs. And thus help to streamline the transition between bicycle and train, reflecting established commuting patterns among frequent users.

3.2.2. Parking Behaviour

In order to improve the efficiency of bicycle parking facilities at railway stations, it is essential to understand the factors that influence the behaviour of the individual cyclists, as these choices collectively determine the overall utilisation of these facilities. A variety of psychological, social and environmental factors have been the subject of recent research, providing insights into the preferences and decision-making processes of cyclists. These topics can also provide insights in how to steer to more efficient use based on the behaviour of users. The most researched and relevant topics in this domain are described: parking location, pricing, enforcement, and experience.

Parking Location

Cyclist tend to prefer to park at convenient locations. This importance of location preference is highlighted by Arbis et al. (2016), whose regression analysis of revealed preference in Australia showed that 80 percent of bicycles parked outdoors are located within 30 metres of the nearest station entrance. This tendency reflects the desire of cyclists to minimise walking distances to their destination while benefiting from the passive surveillance provided by pedestrian traffic, which can deter theft and vandalism. The conclusions of the the study by Martens (2007), which concluded that the walking route from the bicycle parking facility to the public transport stop influences the use of the facility. The findings of these two studies underscore the significance of effective facility location and layout in optimising usage of the facilities.

This finding is consistent with the results of the revealed preference research conducted by Gavrilidou et al. (2020) using a discrete choice model, which demonstrated that cyclists prefer to park in close proximity to the exits of parking facilities in order to minimise walking time. Moreover, users tend to prioritise convenience, with women being more likely to walk up to 50 metres to find a spot in the lower racks than men, who are willing to walk up to 10 metres. This suggests that some users may consider a parking facility to be full when the lower racks are filled. The provision of real-time parking information has also been shown to have a positive impact on the user experience, reducing search time and increasing the utility of parking facilities.

Complementary, Fukuda and Morichi (2007) further expand on the dynamics of parking decisions through a discrete choice model. Their research shows that individuals with lower risk aversion are more inclined to park bicycles on the street, whereas those with higher public morality tend to avoid on-street parking. Furthermore, frequent train station users are more likely to use off-street parking, possibly to avoid enforcement measures such as fines or bicycle removal by authorities. The study also underscores the impact of routine police patrols, which significantly increase the use of off-street parking. Heinen and Buehler (2019) also found that pricing of facilities reduces the likelihood of people to park their. Many people lock their bicycles to urban street furniture that is not intended for parking, which may indicate a supply and demand imbalance.

The insights from the interviews align with findings from the literature, emphasizing the cyclist preference for convenient parking locations. The interviews revealed the tendency for users to park their bicycles shortly after entering the facility, illustrating the desire to minimise walking distances. This theme underscores the importance of facility layout and real-time information in enhancing user satisfaction and optimizing parking usage.

Pricing

Pricing of parking facilities has also been researched and is one of the factors that influences the perception towards parking facilities of users. Research by Molin and Maat (2015) highlights a trade-off between price and walking distance, showing that cyclists are

willing to pay for more convenient parking options closer to station entrances. The study suggests that when a pricing policy is introduced where parking was previously free, the majority of cyclists would continue to park at the station. Of those who would switch to other options, most would walk to their destination, with only a limited number choosing to drive. These findings suggest that pricing could be an effective strategy for managing congested station parking. Further research, such as Hoskam (2020) with the indicated attributes calculated the willingness to pay for parking facilities at stations in a mixed logit model. It showed that people generally prefer guarded facilities. And a longer free parking time has a positive effect on the utility, as well as the presence of surveillance and a repair shop. Pricing and walking time have negative utility, in line with Arbis et al. (2016), Martens (2007) and Gavriilidou et al. (2020). The research of Hoskam (2020) concludes that an increase in cost does not lead to a proportional decrease in usage. Instead, the initial price increase has a much larger impact on user behaviour than subsequent increases.

Enforcement

As briefly mentioned at parking location, cyclist behaviour also depends on enforcement actions in the area. While pricing strategies can provoke certain behaviours, the effective management of parking facilities also requires clear enforcement mechanisms. Ensuring compliance with designated parking rules not only maintains order but also maximises the utility of available infrastructure. This is emphasised by van der Spek and Scheltema (2015), who stated that when bicycle parking is well managed, the nuisance caused by improperly parked bicycles is significantly reduced. In particular, when improperly parked bicycles are seen as an offence, cyclists are more likely to use the designated facilities. This highlights the importance of enforcement, which is consistent with the findings of Fukuda and Morichi (2007), which show that enforcement measures, such as routine patrols to address improperly parked bicycles, are effective in encouraging the use of designated parking facilities. These measures help alleviate congestion at stations while ensuring a more organised and efficient use of space.

Interviews affirmed the observations from the literature regarding enforcement's role in influencing cyclists' parking behaviour. As noted, when areas surrounding a facility are overcrowded with bikes, the facility's occupancy tends to be lower, demonstrating that inadequate enforcement allows cyclists to bypass designated facilities. This corresponds with the finding of the preference of convenience of parking locations.

Experience

The effectiveness of station bicycle parking is not only determined by its functionality, but also by how it matches users' expectations and experiences. Hoskam (2020) conducted in her thesis a factor analysis to identify the key elements that influence the user experience or perception of bicycle parking. The study found that factors such as service quality (staff presence and attitude, sense of security), clarity (effort required to find a space, clarity of information), appearance (maintenance and cleanliness), accessibility (time, cost and ease of use) and bike security (concerns about theft or damage) together explained almost 70% of the overall user experience. Underlining the importance to take these factors into account when design policies for bicycle parking facilities.

Further insights are provided by Barneveld (2022), whose thesis explores the role of both dissatisfiers (e.g. access time and parking cost) and satisfiers (e.g. lighting, shelter, and perceived safety) in cyclists' station choice. A stated choice experiment revealed that dissatisfiers tend to have a stronger overall influence on station choice. Satisfiers significantly shape preferences, but have less impact. The research suggests that tailoring bicycle parking environments to user characteristics, particularly with regard to dissatisfiers, can enhance the user experience.

Interviews reaffirmed the importance of clarity and staff presence in enhancing user experience. Concerns about theft, especially in self-service facilities, are prominent, reflecting how perceived security influences users' satisfaction and choice of parking location.

Summary Users

The demographic profiles of bicycle-train users are often young, highly educated commuters who favour urban areas and large stations. Cyclists prioritise convenient, accessible parking, with pricing and enforcement shaping their choices. Understanding these patterns can help evaluate whether facilities, particularly in urban areas, are effectively meeting demand and encouraging appropriate use, and ultimately inform improvements in their management and design.

- **Parking location:** The walking distance from the facility to the station influences the usage. Cyclists prefer to park proximate to exits, and women are more likely to walk further to find a ground-level spot than men. Real-time parking information and the layout of the parking facilities are key to improving usage. This is important for designing efficient facilities that meet user expectations and encourage more cycling to the station.
 - **Pricing:** Cyclists are willing to pay for convenient parking, particularly near the station entrance. However, pricing policies should balance cost with convenience. Understanding cyclists' willingness to pay and the effects of pricing on parking choices is critical for managing demand in crowded areas and optimizing parking space allocation.
 - **Enforcement:** Effective enforcement, such as regular patrols, encourages cyclists to use designated parking spaces, reducing congestion from improperly parked bikes. This is essential for maintaining order and maximizing the effectiveness of parking infrastructure.
 - **Experience:** Factors like security, service quality, and cleanliness influence cyclists' overall experience with parking facilities. Improving these aspects can lead to higher user satisfaction and greater utilisation of parking spaces.
-

3.3. Facilities

The intersection of user behaviour and infrastructure capacity defines the operational dynamics within bicycle parking facilities. Understanding how these facilities manage the supply and demand for bicycle parking is crucial for optimising their efficiency. Building on insights into user commuting patterns and preferences, this section examines the structural and operational characteristics of bicycle parking facilities at railway stations in the Netherlands.

3.3.1. Operational Aspects

In the Netherlands, a number of organisations are involved in the provision of bicycle parking facilities at railway stations. The main stakeholders are NS stations, ProRail, municipalities and the Ministry of Infrastructure and Water Management. The stakeholders are mapped in terms of how they influence the operational dynamics of bicycle parking, figure 3.2. It illustrates the parties involved in the development and operation of a cycle park and how they work together. As shown in the diagram, NS Stations are responsible for the operation of the facilities. They oversee the operation of the various parking facilities, formulate policy and employ staff. The municipality is responsible for enforcing the removal of orphaned bikes (bikes parked for 28 days or more) within the facilities and finances their construction together with ProRail. It is primarily ProRail's responsibility to ensure that the facilities have sufficient capacity, and it therefore owns the racks. ProRail receives financial support from the Ministry of Infrastructure and Water Management to fund the construction and maintenance of the facilities.

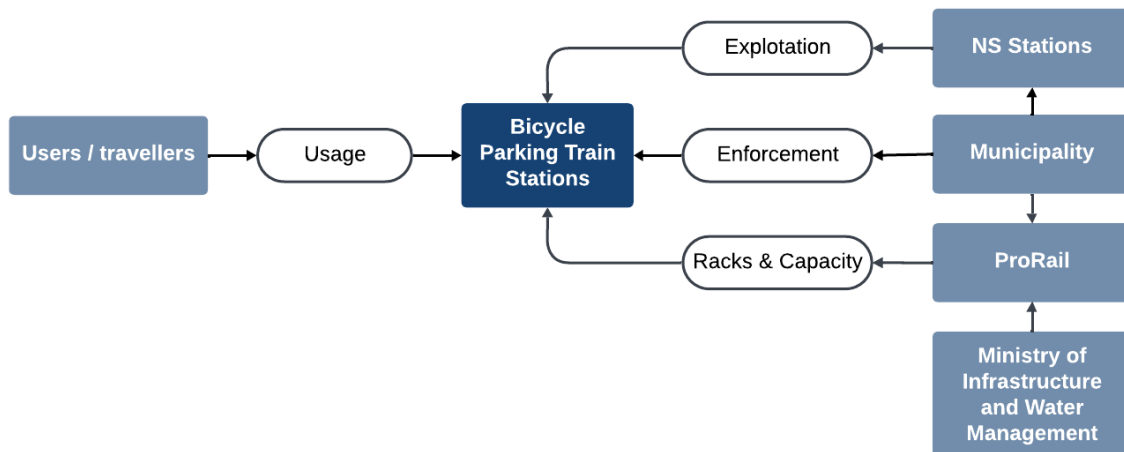


Figure 3.2: Stakeholder diagram of operational dynamics bicycle parking facilities

The interviews with the different stakeholders revealed a variety of perspectives on the cooperation required between the parties to maintain the efficiency of the bicycle parking facilities. Each stakeholder is responsible for specific operational aspects, underlining the critical need for smooth cooperation. For example, successfully enforcing the removal of orphaned bikes requires a well-coordinated effort: ProRail needs to ensure the reliability of the occupancy sensors in the facilities; NS is responsible for identifying bikes that have exceeded their allotted parking time by tagging them; the municipality is then responsible for transferring these bikes to a depot. Any break in this chain can lead to inefficiencies, such as the prolonged storage of orphaned bikes, contributing to overcrowding and compromising facility operations. Streamlined coordination between these entities is therefore essential to optimise service delivery and maintain the functionality of bicycle parking provisions.

As mentioned, the operational responsibility for these facilities lies with NS Stations. Internal forecasts produced by ProRail suggest that there will be a considerable rise in demand for bicycle parking in the forthcoming years. A straightforward response to this growth would be to expand the capacity of the facilities in question. Nevertheless, this is not always a viable option due to spatial constraints and the high costs involved. The cost of creating a single bicycle parking spot can range from €1000 in existing buildings to €3300 in underground or multi-level facilities according to Rijkswaterstaat (n.d.). As indicated by internal documentation from NS, the construction of certain bicycle parking facilities is currently estimated to incur costs ranging from €10,000 to €20,000. These figures underline the financial pressure associated with expansion, necessitating strategic investment and efficient use of space and financial sources are available.

At railway stations in the Netherlands, bicycle parking facilities are categorised into four primary types (PwC, 2020):

- Ground-level: unguarded, sometimes bicycle lockers
- Indoor storage: Always guarded and usually staffed
- Basement storage: Located underground and also guarded and typically staffed
- Bicycle flats: Outside of station, multi-level structures that are generally unguarded (rare since not preferred by ProRail and NS)

The guarded facilities are operated by NS and are part of this research. For guarded facilities, NS employs varied levels of staffing, integrating technology such as surveillance cameras or self-service mechanisms to optimise resource use across these categories.

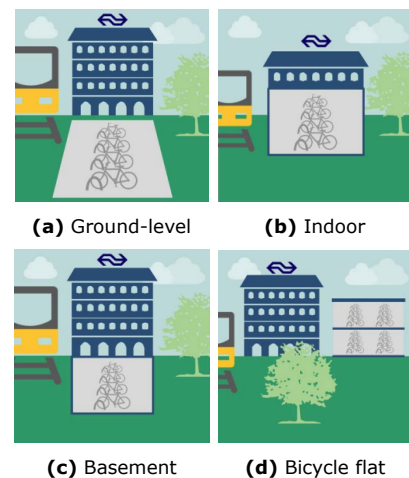


Figure 3.3: Types of bicycle parking facilities at stations (PwC, 2020)

The interviews highlight that self-service bicycle parking facilities, if not clearly signed for way finding and not well-designed, lead to improperly parked bicycles. Without staff presence, users tend to feel less responsible, leading to problems such as improper parking, sometimes even blocking fire extinguishers, or littering. Self-service facilities are also relatively less secure against theft.

Vision Guarded Bicycle Parking

In 2013, NS presented a vision on bicycle parking facilities at its stations (NS, 2013). In general, there was a lack of bicycle parking facilities at large stations in the Netherlands, but also an under-utilisation of the available capacity. At the time, only half of the racks in the 100 or so guarded facilities at stations were being used. At that time, the facilities were always paid for. This led to a new vision to improve customer satisfaction and make better use of the existing capacity in the facilities to make the first 24 hours free.

The aim or vision is to reduce the barrier for users to park their bikes in the facilities and not just leave them in a station square. This is why the concept of 24-hour free parking is introduced. The parking fee after 24 hours is designed to ensure that bicycles do not occupy spaces unnecessarily, thus making the best use of the available capacity.

Pricing Regimes

This introduction of the 24-hour free parking policy at NS guarded bicycle parking facilities represented a big change in user-centred management strategies, aligning with the overarching vision to enhance user experience and optimise existing capacity utilisation.

The literature suggests that people have a willingness to pay and that the willingness to pay is higher closer to the entrances (Molin and Maat, 2015), but that a longer free parking period has a higher utility for users (Hoskam, 2020). This implies that a pricing policy is justified, but that a free period increases user utility. In addition, the findings that switching to a paid scheme does not lead to a significant loss of cyclists and that only a limited number choose to drive to the stations further justifies the use.

Currently, NS Stations employs four pricing and policy frameworks for the bicycle parking facilities they operate, tailored to the level of staffing and services provided (NS, 2022):

- Parking always free of charge (on initiative of municipality)
- First 24 hours free of charge, self-service bicycle parking: after 24 hours €0.55 per 24 hours and year subscription €60,- for all vehicles. (Since January 1st 2025 respectively €0.60 and €65,-)
- First 24 hours free, bicycle parking with staff: after 24 hours €1.35 per 24 hours and year subscription €80,- for bicycles and €2.70 per 24 hours and year subscription €160,- for mopeds, scooters, cargo bikes, tandems, recumbents and other small vehicles. (Since January 1st respectively €1.40, €85, €2.80 and €170)
- Paid bicycle parking with staff: €1.35 per 24 hours and year subscription €110,- for bicycles and €2.70 per 24 hours and year subscription €245,- for mopeds, scooters, cargo bikes, tandems, recumbents and other small vehicles. (Since January 1st respectively €1.40, €115, €2.80 and €255) (old regime, not applied to new (equipped) facilities)

Currently, NS applies a largely uniform pricing policy across its bicycle parking facilities, differentiating only between self-service and staffed facilities. However, given the increasing demand for bicycle parking and the spatial and financial constraints at stations, it is crucial to evaluate whether this approach optimally utilises existing infrastructure. The growing demand for bicycle parking, when considered alongside spatial and financial constraints, underscores the necessity for a critical examination of the usage of the existing bicycle parking facilities. A more targeted approach could result in a better utilisation of existing facilities, thereby ensuring a more effective use of resources and mitigating future challenges.

Capacity

As described, ProRail holds primary responsibility for determining the capacity of new facilities, using forecasts informed by periodic bicycle counts within both facilities and their surrounding areas and transportation forecasts drawn from national calculations and anticipated future developments in surrounding areas (ProRail, 2021). These forecasts are essential for accommodating the long-term growth in bicycle usage and ensuring that facilities remain efficient and functional.

On average, a facility is perceived as full when occupancy reaches 80 percent, reflecting user behaviour and preferences (Jorink et al., 2022). Implementing effective detection systems can mitigate this perception, increasing utilisation by accurately guiding users to available spaces—potentially enhancing occupancy rates up to 90 percent. Such technologies are critical for optimizing facility use without physical expansion.

Moreover, it is crucial to address the challenges faced by certain user groups, as identified by (Gavriilidou et al., 2020). For example, limitations in accessing upper racks can create a perception of fullness even when capacity is not fully reached, underscoring the need for inclusive facility designs that consider diverse user needs.

Facilities cater to various types of bicycles, employing systems that accommodate three distinct categories: regular bikes, non-standard bikes within racks (e.g., bikes with crates or child seats), and non-standard bikes outside racks (e.g., cargo bikes) (ProRail, 2021). Design regulations stipulate that facilities provide a minimum of 5% of spots for non-standard bikes, with location-specific adjustments allowed up to 10%. Additionally, 0.5% of the facility's total surface area should accommodate non-standard bikes outside racks. These provisions implement flexibility and inclusivity, ensuring that diverse user needs are met without compromising on capacity or efficiency.

Collaborative efforts among stakeholders, namely NS Stations, ProRail, municipalities, and the Ministry of Infrastructure, are pivotal in adapting capacity to meet future demand. By engaging in proactive planning and continuous evaluation, these parties can manage space and resources effectively, ultimately supporting the broader integration of bicycle and train transport.

Types of Bicycles

Analysis of the ProRail counts provides insights into the composition of bicycle parking at stations. These counts, conducted by ProRail, provide a quantitative basis for the bicycle demand of the parking facilities at one time point. These counts are conducted in September, October, and November 2024 and serve as a basis for forecasting bicycle parking demand at railway stations. The methodology involves counting the number of parked bicycles during peak hours at 394 stations. They help in planning future capacity needs and are validated against data from previous years. The dataset distinguishes between different bicycle types and parking locations.

The bicycle counting system categorises bikes into various groups to better manage parking and accommodate diverse needs (van Boggelen, 2024):

-  **Category F:** Standard (electric) bicycles. This includes all regular and electric bicycles without those with child seats, crates, racks (category XL), bicycles with panniers (category T), and bicycles with significantly different frames (category XXL).
-  **Category T:** Bicycles with panniers, excluding those also equipped with child seats, crates, or racks (category XL). All pannier-equipped bicycles are counted, including those with small panniers that pose no parking issue.
-  **Category XL:** Bicycles with a child seat, crate, rack, or basket. A bike falls into this category if the rack is wider than 20 cm.

-  **Category XXL:** Bicycles with a non-standard frame, such as cargo bikes, fat bikes, recumbent bicycles, tandems, among others. These bikes typically do not fit standard racks.
-  **Category C:** Mopeds, scooters, and motorcycles on two wheels, recognisable by their blue/yellow license plates, excluding Category Z.
-  **Category Z:** Other vehicles, including uniquely different mopeds and scooters (e.g., microcars) and invalid carriages.

Firstly, the dominance of standard bicycles and e-bikes (category F), which account for 64% of the bicycles parked, reflects the continued predominance of standard models. However, the significant presence, 24%, of bicycles with accessories such as panniers or child seats (category T and XL) far exceeds the design standards set by ProRail, which suggest 5% and sometimes 10%, as described in the section above (NS, 2025). The proportion of XXL bicycles is small at 0.6%.

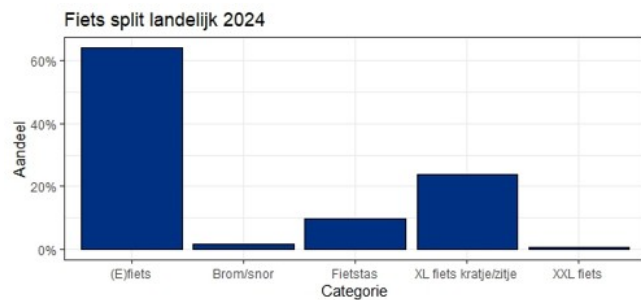


Figure 3.4: National share, respectively category F, C, T, XL, XXL (NS, 2025)

Furthermore, a minimal variance in bicycle types between different types of storage facilities (guarded, unguarded or ground-level) in figure 3.4 suggests that users consistently bring similar bicycles regardless of facility type. These findings highlight the need to review parking design specifications to better reflect the actual distribution of bike types, particularly those with additional accessories. Ensuring sufficient capacity and accessibility for different types of bikes, including non-standard and XXL bikes, through flexible design and possibly technological improvements, will be crucial in addressing these discrepancies.

As highlighted in the interviews, the capacity of facilities can be a bottleneck in the future. Capacity expansions must recognise the ongoing rise in bicycle diversity of bicycles and commuter reliance on bicycle-train systems. Addressing these needs proactively will enable facilities to retain high utility and relevance amidst shifting urban dynamics. The interviews also strongly emphasise the importance of a fitting supply of capacity (for the variety of bikes) according to the growing demand.

Temporal Behaviour

Bicycle parking facilities at railway stations experience distinct temporal patterns that reflect broader commute rhythms and user preferences. Given the predominant use by commuters, certain predictable cycles influence facility usage, aligning closely with the routines of work and travel (Jonkeren et al., 2021). The mainly usage by commuters results in a weekly cycle with also seasonal fluctuations. Holiday periods, school breaks, and extended weekends significantly influence parking facility occupations, often seeing reduced commuter traffic but potentially increased travel for recreational purposes. Weather conditions, such as heavy rain, snow, or excess heat, can alter typical parking behaviour. Research by Cools et al. (2010) supports the assertion that weather variability can act as a deterrent or facilitator of cycling activity, impacting urban transport behaviour.

Interviews highlighted that peak usage typically mirrors the working week, with heightened activity during weekdays, particularly around rush hours. Tuesdays and Thursdays are notably the busiest days, driven by commuter flows. Fridays and weekends might exhibit varied patterns due to leisure travel or reduced commuting.

Summary Facilities

- Bicycle parking facilities at railway stations are governed by various stakeholders including NS Stations, ProRail, municipalities, and the Ministry of Infrastructure and Water Management. Efficient cooperation is vital to operational success.
 - The demand for bicycle parking is projected to increase, highlighting spatial and financial limitations. ProRail forecasts suggest a rise, urging strategic investments.
 - The growing variety of bicycles, particularly those equipped with panniers, child seats and crates, surpasses current design expectations and underscores the necessity of adapting parking facilities to accommodate larger and non-standard bicycles.
 - Temporal behaviours related to commuting and external factors like weather and occasional events affect facility usage patterns.
-

Usage Efficiency

This chapter focuses on understanding and improving the use efficiency of bicycle parking facilities in urban environments. By integrating findings from the literature, a theoretical framework is used to explore the interaction between structural characteristics of parking facilities and individual user behaviour. Using the Coleman Diagram, this chapter outlines how macro-level conditions shape micro-level actions and perceptions that collectively influence system-level outcomes. The analysis aims to provide targeted strategies that not only optimise occupancy, turnover and parking pressure rates, but also address broader societal benefits, ultimately aiming to create user-centred, efficient bicycle parking solutions that support sustainable urban mobility.

4.1. Interaction Users and Facilities

In order to assess the efficiency of the use of bicycle parking facilities, it is essential to understand the interaction between facility characteristics (macro level) and individual user behaviour (micro level). This section presents a theoretical framework to explain these interactions using the Coleman diagram (also known as the Coleman boat), illustrated in figure 4.1.

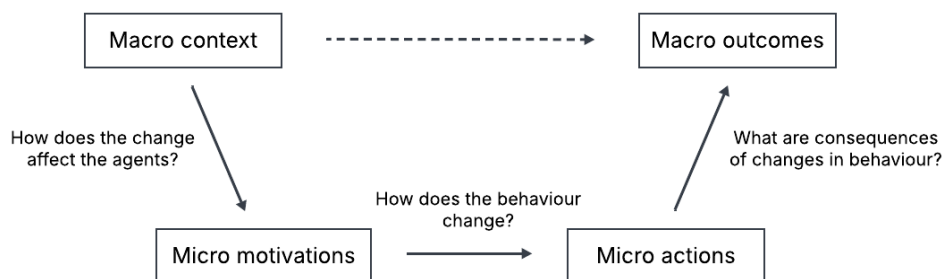


Figure 4.1: Coleman diagram (Ylikoski, 2021)

The Coleman diagram is a sociological model that explains how macro-level conditions influence micro-level actions, which in turn generate new macro-level outcomes. It has four elements:

1. Macro context: Structural or environmental conditions.
2. Micro motivations: How individuals perceive and respond to these structures.
3. Micro actions: Actual behaviour based on these perceptions.
4. Macro outcomes: Aggregated individual behaviour that shapes system-level performance.

This research uses the diagram to link the physical and institutional characteristics of bicycle parking facilities with user perceptions and behaviour, and to assess how these micro-level responses affect the efficiency and performance of the facilities. And finally,

to help inform how these dynamics can inform strategies for the main research question of improving the operational effectiveness of bicycle parking systems.

The macro conditions refer to the structural characteristics of the bicycle parking system, including the facility design and the operational context. The micro motivations refer to the users that form attitudes and expectations formed by these macro conditions, such as perceived convenience, safety, personal preferences, needs and habits (e.g. proximity, safety, purpose of trip). The micro actions are the consequence of the motivations of the users, the parking choice when and where to park and usage indicators as duration, arrival times, types of bicycles used. This results in macro outcomes, the individual parking behaviour aggregated into system-level performance measures.

Analysing the interaction between macro and micro factors through the Coleman Diagram provides a robust framework for developing strategies to improve bicycle parking efficiency and helps to form the conceptual diagram of bicycle parking.

4.2. Indicators Usage Efficiency

As defined in the introduction, this research considers usage efficiency as:

Providing as many travellers as possible with a bicycle parking spot while minimizing resource usage—specifically, the required parking space and the total number of parking spots needed.

This means the facilities should serve as much travellers as possible based on their capacity. There are some indicators that denote this usage.

The usage of the facilities is determined by the aggregate behaviour of all users combined. Different indicators can be determined to describe this aggregate behaviour, the usage. The indicators depend on the demand related to the supply, where the supply is the capacity of the bicycle parking facility. The demand of bicycle parking is determined by the users and their parking actions, the arrival and departure time together with the duration of the parking action determines the demand that is needed.

In literature, not a lot of research has been done on the usage patterns of bicycle parking. A study of Honey-Rosés et al. (2023) researched the usage of parking spots within the city of Barcelona identifying occupation and turnover as important indicators. According to the research of Movares (2021), in bicycle parking three important indicators illustrate the usage demand related to the supply of which two are similar to the research of Honey-Rosés et al. (2023), occupancy and turnover.

Occupancy

The occupancy describes the ratio between the occupied parking spots or the number of bicycles in the facility and at a certain time point (accumulation) and the capacity of the facility (Honey-Rosés et al., 2023). Expressed in a formula:

$$\text{Occupancy} = \frac{\text{Accumulation}}{\text{Capacity}} \quad [\text{ratio occupied racks at time point}]$$

Turnover

Turnover describes the number of bicycles that pass through a location in a certain time period. It reflects the rate at which parking spots are vacated and reoccupied, in other words, how many users or bicycles are served by a single parking spot during that time (Honey-Rosés et al., 2023). This is the ratio between the number of unique instances (volume) and the capacity:

$$\text{Turnover} = \frac{\text{Volume}}{\text{Capacity}} \quad [\text{ratio capacity served in time period}]$$

This is an important indicator since it indicates the level of service provided. Locations that have a high occupancy, while low turnover provide less parking service to users. Locations with a similar turnover but lower occupancy are more likely to offer free spots to users. Therefore, those together can say something about efficiency (Honey-Rosés et al., 2023).

Parking Pressure Rate

The last indicator described by Movares (2021) is the parking pressure rate. It depends on the parking durations in the facility, it represents the total usage time that bicycles occupy parking spaces, reflecting the intensity of use, and the available parking time in the facilities. This is the ratio between the parking durations of all the parking actions in the facility and the available parking time in a certain time period:

$$\text{Parking pressure rate} = \frac{\text{Parking durations}}{\text{Available parking time}} \quad [\text{ratio utilisation in time period}]$$

It provides insight into the strain placed on a facility by comparing the actual utilisation against the available parking capacity during a specific time period. This indicator can be interpreted as the proportion of time all parking racks are occupied within a specified time window. A value of 1 implies that every parking spot is occupied continuously during the entire time period, whereas lower values suggest under-utilisation.

In practice, the efficient use of capacity then translates to:

- High maximum occupancy: ensuring that supply and demand are well aligned, the travellers with the parking spots.
- High turnover: allowing multiple users to use the same spot in a given time frame.
- Relative high parking pressure rate: achieving a time-efficient usage of available the space.

These three capacity-related indicators, occupancy, turnover and parking pressure rate, reflect the balance between available infrastructure and actual user demand. In practice, these indicators are correlated. Facilities with consistently high occupancy tend to have high turnover and parking pressure, indicating efficient use: many travellers are served in a limited space over time. However, if a facility has high parking pressure but low turnover, this indicates inefficiency: bicycles remain parked for long periods, but not a lot of changing users. If all three indicators are low, the facility is likely to be under-utilised. This could be due to a number of factors: the facility may be oversized in relation to current demand, designed for anticipated future growth, nearing the end of its functional life, or poorly sited so that it does not match user preferences or visibility. Understanding these dynamics is essential to developing strategies that optimise capacity utilisation and better align supply with actual demand.

4.3. Conceptual Model of Usage Efficiency

Based on the insights from literature and the previous analysis, a conceptual diagram is developed to illustrate how macro-level structural characteristics and micro-level user behaviour interact to determine parking efficiency. This is presented in figure 4.2.

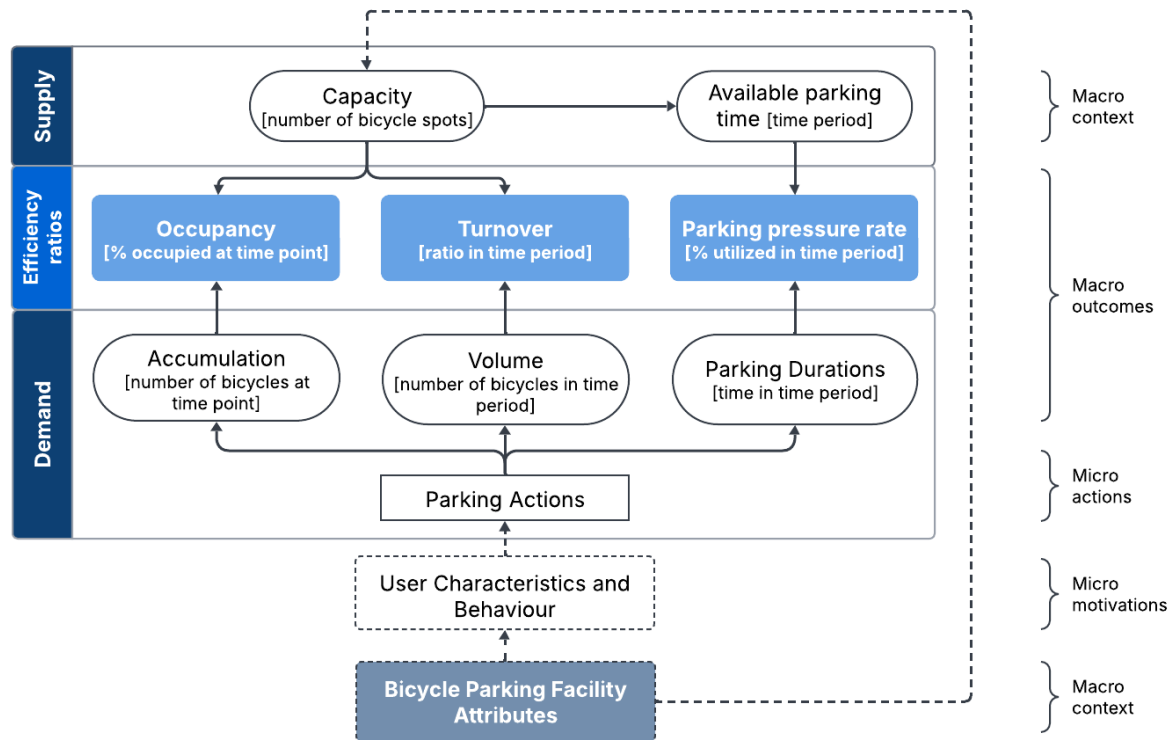


Figure 4.2: Conceptual diagram of usage efficiency

The model connects the macro context, micro actions and micro motivation to the macro outcomes, inspired by the logic of the Coleman diagram, presented in section 4.1. The model outlines the following structure:

- **Macro context:** This includes structural elements such as total capacity, physical attributes of the facility, and total available parking time. These factors shape the environment in which users make decisions.
- **Micro motivations and characteristics:** User-specific factors like travel purpose, parking preferences, and perceived accessibility inform parking choices. These are influenced by the macro environment but reflect personal needs and values.
- **Micro actions:** These are the parking behaviours that follow—where, when, and for how long users park their bicycles.
- **Macro outcomes:** Aggregated user behaviour results in measurable indicators, the occupancy rate, turnover, and parking pressure rate.

Together, these determine the overall usage efficiency of the parking facility. This structure emphasises that usage efficiency is not solely a product of supply or design, it emerges from the interaction between the built environment and user behaviour. Therefore, improving efficiency requires interventions both in infrastructure and user engagement.

The broader context of the surrounding urban environment of the facility must also be considered as part of the macro context. A facility with low occupancy might initially seem inefficient size wise. However, if the surrounding area is cluttered with randomly parked bicycles, this suggests that the facility is either underutilised due to poor accessibility, a lack of enforcement, or user preferences that discourage its use. As discussed in subsection 3.2.2, structural enforcement in the vicinity of bicycle parking facilities can help regulate usage and prevent informal parking, which contributes to urban disorder. Measures such as clear signage, designated no-parking zones, and active enforcement strategies can ensure that parking facilities are used to their full potential, thereby en-

hancing overall efficiency. In addition, the facility should be attractive and accessible to users so that it can be used to its full potential.

The conceptual model provides a theoretical lens through which the research analyses will be conducted. It shows the focus of the research, the efficiency of use of bicycle parking facilities, corresponding to the macro outcomes in the diagram, and links it to how the structural and behavioural factors interact to shape the efficiency outcomes. This will support the development of targeted strategies that address both infrastructure design and user experience, contributing to more effective and user-centred bicycle parking systems. While the aim of this research is to maximise efficiency, the societal benefits of station bicycle parking must not be forgotten; the aim is to serve as many travellers as possible, not just to optimise these three indicators. For example, users' perception of availability plays a role. Research shows that a facility can be perceived as "full" at 80% occupancy. With appropriate way finding tools and real-time availability information, this threshold can be raised to around 90%, improving efficiency without increasing physical capacity. This should be taken into account when assessing indicators.

The interviews reveal that the parking information systems (HBF) often does not function as intended in practice. It frequently misidentifies abandoned bikes or misses them entirely, requiring manual checks by staff. This increases workload and leads to inconsistent enforcement. In some cases, municipalities fail to follow up, leaving labelled bikes standing too long and reducing usable capacity. As a result, the system does not reliably support efficient use of parking facilities.

Summary Usage Efficiency

This chapter answers the first research question by defining usage efficiency through three key operational indicators: occupancy, turnover, and parking pressure rate. It introduces a theoretical framework based on the Coleman diagram to analyse how structural characteristics of facilities (macro context) interact with user perceptions and behaviours (micro level), which together determine system performance (macro outcomes). By combining conceptual insights with practical dynamics, the chapter provides a foundation for evaluating and improving the efficient use of bicycle parking facilities, while also recognising the importance of user experience and broader urban context.

Data Processing

This chapter outlines the data processing steps employed to analyse the usage of bicycle parking facilities. First, it provides an overview of the input data and the preprocessing methods applied to ensure consistency across 97 locations. It then explains how the data is transformed into a structured time series format, and how this supports the analysis of weekly usage patterns. Next, the chapter outlines how the key efficiency indicators of occupancy, turnover and parking pressure are calculated in order to assess the overall performance of the system. Finally, it also details the comparison of three time series similarity methods to identify the most appropriate approach for clustering facility usage behaviour.

5.1. Data Preprocessing

5.1.1. Data Description

As described in more detail in chapter 2 the dataset for this study includes check-in and check-out (CiCo) transactions from bicycle parking facilities managed by NS. For consistency and to mitigate COVID-19 related bias, the analysis focuses on records from 2023 and 2024, with supplemental data from December 2022 to capture activity leading into the new year, considering the maximum parking period allowed. The dataset consists of two primary tables: one detailing individual parking actions and another outlining facility attributes, linked via location names. Key attributes captured include parking prices, timestamps for start and end of parking, duration, staffing, facility addresses, bicycle and service availability, and relevant capacity metrics.

5.1.2. Data Filtering

To ensure the dataset is suitable for analysis, several preprocessing steps are applied to improve data quality and relevance. The dataset initially contained $N = 34,953,521$ records, representing parking actions across 106 locations. However, not all records are relevant or reliable for this study. The preprocessing involved cleaning inconsistencies, filtering out incomplete data, and ensuring that only active and significant facilities are included. This section details the key preprocessing steps undertaken.

- *Timestamp transformation*: The start and end times and dates are converted into timestamps, and parking duration is added in a standardised time format.
- *Removal of check-ins without check-outs*: Parking actions without a recorded check-out are removed, as they lacked parking duration information, which is essential for efficiency analysis. These missing check-outs, accounting for $N = 255,649$ (0.731%) of the dataset, could be attributed to forgotten check-outs or technical issues.
- *Exclusion of records with end dates before 2023*: Parking actions with an end date before January 1st, 2023, are removed, resulting in the remaining of $N = 33,676,518$ records. Among these, 33,658,815 records had a start date in 2023 or 2024, indicating that 17,703 bicycles are already parked at the beginning of 2023. This adjustment ensures that only relevant parking actions within the study period are considered, while also accounting for bicycles that remained in the facilities during the transition from 2022 to 2023.

- *Correction of incorrect time sequences:* Some records contained start times occurring after their respective end times probably due to data storage errors. These errors are only observed in parking actions where both the start and end times are recorded on the same date. A total of $N = 440,996$ records (1.310% of the dataset) exhibited this issue. Further analysis of these records revealed a stable distribution over the year, with higher occurrences on weekdays and lower frequencies during weekends.

To better understand the impact of this error, the distribution of start and end times is examined. Figure 5.1 illustrates the distribution of start times after correcting the sequencing issue, showing a normal peak during the morning rush hour. Similarly, Figure 5.2 presents the distribution of end times, which exhibits a peak in the afternoon rush hour but also an unexpected peak in the morning rush hour.

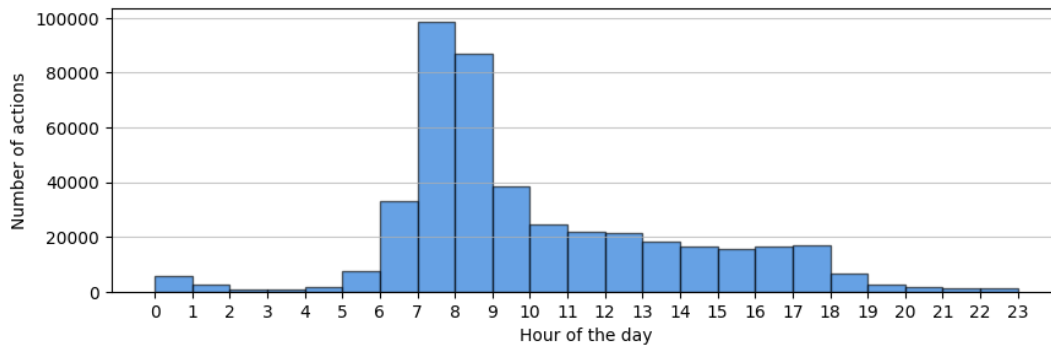


Figure 5.1: Distribution of (rearranged) start hours of number of parking actions

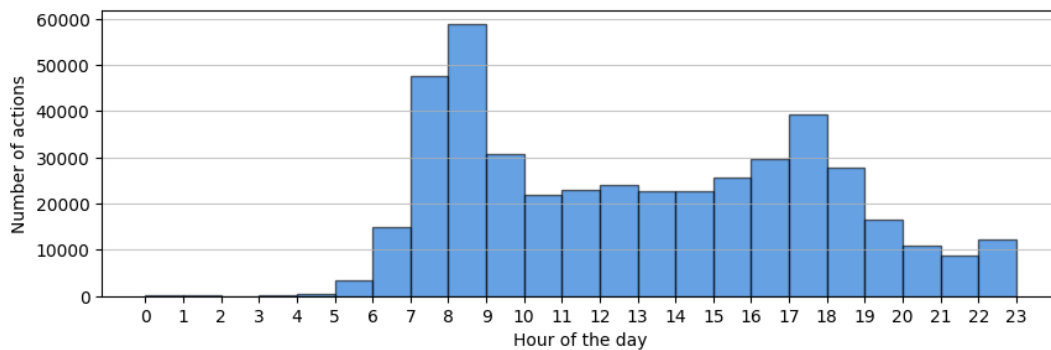


Figure 5.2: Distribution of (rearranged) end hours of number of parking actions

This pattern can be further explained by analysing the parking duration distribution parking actions, a significant number of records had very short parking durations, a factor that is examined in greater detail in the next section.

Since the morning peak appears in the rearranged start times and the afternoon peak in the rearranged end times, this provides strong evidence that the start and end times are mistakenly swapped in the original dataset. This correction ensures that the data accurately represents real parking behaviour and maintains its reliability for further analysis.

The next step involved filtering the facilities in the dataset. To ensure the dataset remained relevant and accurately reflected the study's objectives, several facilities are either removed or adjusted.

- *Exclusion of permanently closed facilities:* Facilities that are replaced by new facilities and thus permanently closed during the study period (2023–2024) are excluded from the dataset to maintain relevance. This included the locations Ede-Wageningen Zuidzijde and Amsterdam Centraal West.
- *Changed name during the period 2023-2024:* In June 2023, Amersfoort Noordzijde is renamed Amersfoort Mondriaanplein in the dataset. To maintain consistency, all

references to the former name are updated accordingly.

- *Removal of underutilised and non-relevant locations:* Facilities with extremely low usage or those not relevant to the study are removed, as their data is insufficient for meaningful analysis. Five facilities are found to have recorded less than 100 uses, in comparison with the next least used facility recorded 16,665 uses. Additionally, Maastricht Perron Brommerstalling, which is dedicated to the parking of mopeds instead of bicycles, is also removed from the dataset.

After applying these filtering and preprocessing steps, the final dataset consists of 33,585,412 records across 97 distinct locations.

Parking Durations

The parking durations have an direct impact on the parking pressure, as well as on the occupancy and the turnover via the number of bikes in the facility. That is why they analysed in more depth.

When analysing the distribution of parking durations across all parking actions, an unusually high number of very short parking actions stands out, as previously mentioned in the preprocessing steps. This pattern becomes evident in the first 24 hours of parking duration, as shown in figure 5.3. The graph reveals a sharp initial peak, followed by a more expected distribution. The highest peak occurs at around 10 hours, aligning with a typical workday combined with travel time, as the majority of users are commuters (chapter 3). Additionally, a smaller peak around 15 hours may be attributed to users storing a 'second bicycle' at their activity station.

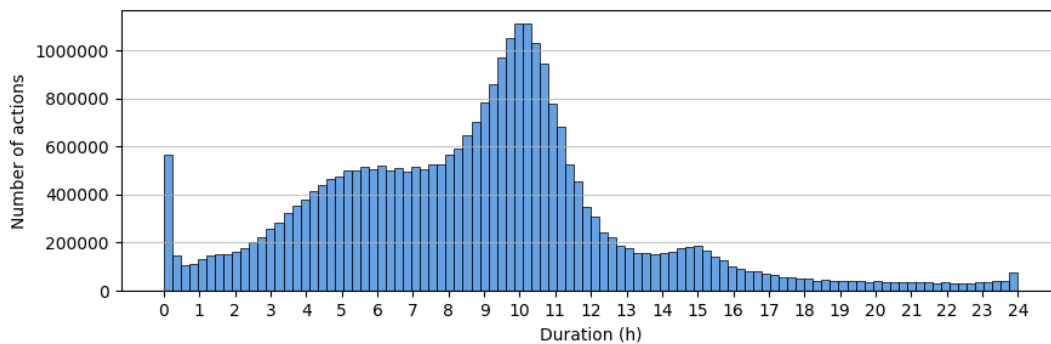


Figure 5.3: Distribution of parking actions first 24 hour

A closer look at the first hour of parking durations in figure 5.4 further highlights this unusual distribution. The first minute exhibits a sharp peak, followed by a rapid decline in the number of parking actions over the next few minutes. After the five-minute mark, the decline slows, and the distribution stabilises. Notably, the lowest point within the first hour occurs at 38 minutes, after which the number of entries begins to rise again.

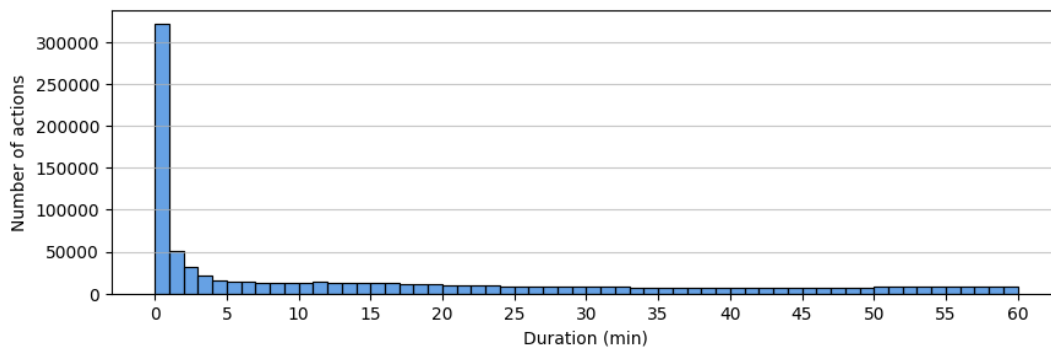


Figure 5.4: Distribution of parking actions first hour

The occurrence of very short parking actions is further analysed to understand its patterns across different facilities. On average, short parking actions, shorter than 5 minutes,

accounted for approximately 1.31% of all parking actions at a given facility. However, the distribution varied significantly by location. In table 5.1 the locations with a percentage of short parking actions higher than 3 percent are displayed. Notably, the five facilities with the highest percentage of short parking actions are all in Amsterdam, with Sloterdijk and Amsterdam Zuid Zuidplein showing particularly elevated rates. It is also noteworthy that all facilities exhibiting high incidences of short parking actions are staffed facilities. This observation suggests that the systems employed in self-service facilities may be more effective in preventing such behaviour or data errors.

Table 5.1: Number and percentage of short actions (<5 min) by location

Location	Number	Percentage [%]
Amsterdam Sloterdijk	8,273	13.91
Amsterdam Zuid Zuidplein	42,019	9.82
Amsterdam Centraal Stationsplein Oost	13,995	4.94
Amsterdam Zuid Mahlerplein	18,692	3.56
Amsterdam RAI	7,204	3.50
Nijmegen	14,719	3.22
Utrecht Vaartsche Rijn Oosterkade	4,106	3.12
Average	4,508	1.31

Identifying the causes behind these patterns is needed to refining the dataset and ensuring an accurate representation of parking behaviour. As a next step, these short parking actions will be further analysed to determine their impact and assess whether they should be retained or excluded from the final dataset.

Figure 5.5 and figure 5.6 illustrate the distribution of parking actions shorter than five minutes over the years 2023 and 2024, as well as their distribution throughout the day.

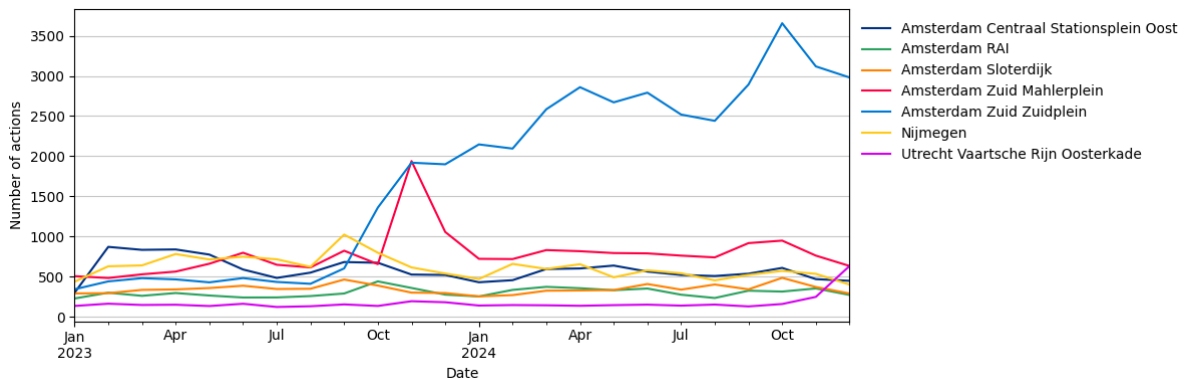


Figure 5.5: Distribution short parking actions over 2023 and 2024

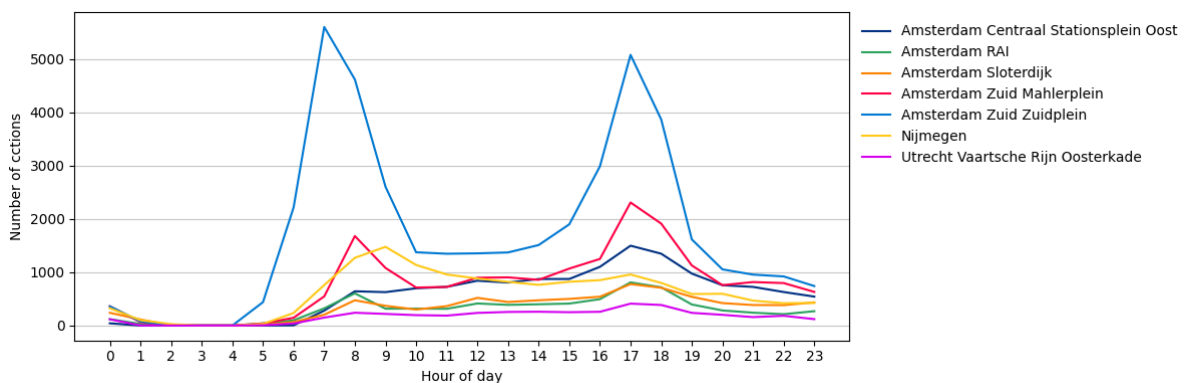


Figure 5.6: Distribution short parking actions over the day

The first graph shows that, for most locations, the number of short parking actions remains relatively stable over the two years. However, Amsterdam Zuid Zuidplein sees a

significant increase in short parking actions starting in October 2023, which remains elevated thereafter. Amsterdam Zuid Mahlerplein also experiences an increase in November 2023, but this trend reverses, returning to a steady level. Notable is that these facilities are both at railway station Amsterdam Zuid and the trend goes up in the same period, no clear indication for this change in usage is found.

The second graph reveals that short parking actions peak during the morning and afternoon rush hours, aligning with the times when most users enter or exit the facility. While these peaks could suggest overcrowding, other factors, such as users attempting to avoid payment, may also contribute. Further research is needed to determine the exact causes.

While the causes of extremely short parking actions require further investigation, several plausible explanations have emerged. Some users may leave the facility almost immediately upon arrival, either because they cannot find an available space or because of changes in their travel plans, such as trains not departing, which could explain the concentration of short durations during the morning peak. In other cases, users may check in a second time before leaving the facility, resulting in an additional short duration entry, which may be more common in the evening for returning commuters or in the morning for those using a second bike. Another possibility is that system problems or data storage errors distort the recorded duration. These anomalies may indicate operational problems at certain facilities, such as overcrowding or inefficient layouts that prevent users from finding a suitable parking space efficiently.

Insights from the interviews and confirmation from a systems expert at NS reveal that when a user checks in a second time before checking out, the system overwrites the initial check-in. As a result, only the second check-in is recorded, and the parking duration is calculated from this second check-in to the final check-out. This can lead to inaccurately short parking durations being registered in the dataset, even if the bicycle was parked for a longer period.

To avoid biasing the analysis, parking actions shorter than five minutes are removed from the dataset, as this threshold coincides with a significant drop in short duration events (figure 5.4). This removes 441,470 records (1.31%). Given the uncertainty around the true reasons for these short actions and their potential to misrepresent actual parking behaviour, especially in metrics such as turnover, removing them helps maintain the reliability and accuracy of the analysis.

The refined dataset serves as the foundation for subsequent analyses, providing a more accurate representation of usage patterns and facility efficiency.

5.2. Usage of Bicycle Parking Facilities

This section analyses the weekly and seasonal usage patterns of 97 bicycle parking facilities at railway stations in order to find a representative usage pattern to effectively analyse the usage of all 97 bicycle parking facilities, based on accumulation data as a direct measure of demand. Understanding these temporal dynamics is important for assessing how effectively facilities are meeting user needs.

The aggregated facility data for 2023 and 2024 show clear temporal trends, as already briefly mentioned in subsection 3.3.1 and confirmed in figure 5.7. This figure shows all parking actions for all 97 facilities of the years 2023 and 2024. Usage follows a consistent weekly rhythm, with notable peaks on Tuesdays and Thursdays, typical commuter days, and significantly lower usage at weekends. There are also seasonal variations, with lower usage during holiday periods such as early January, May, the summer months and the end of December. The trends for 2023 and 2024 are quite similar, but in 2024 there is an unexpected dip at the end of November, which is likely to be a system or data storage problem resulting in a dip for all parking operations. Overall, usage in 2024 is slightly higher than in 2023.

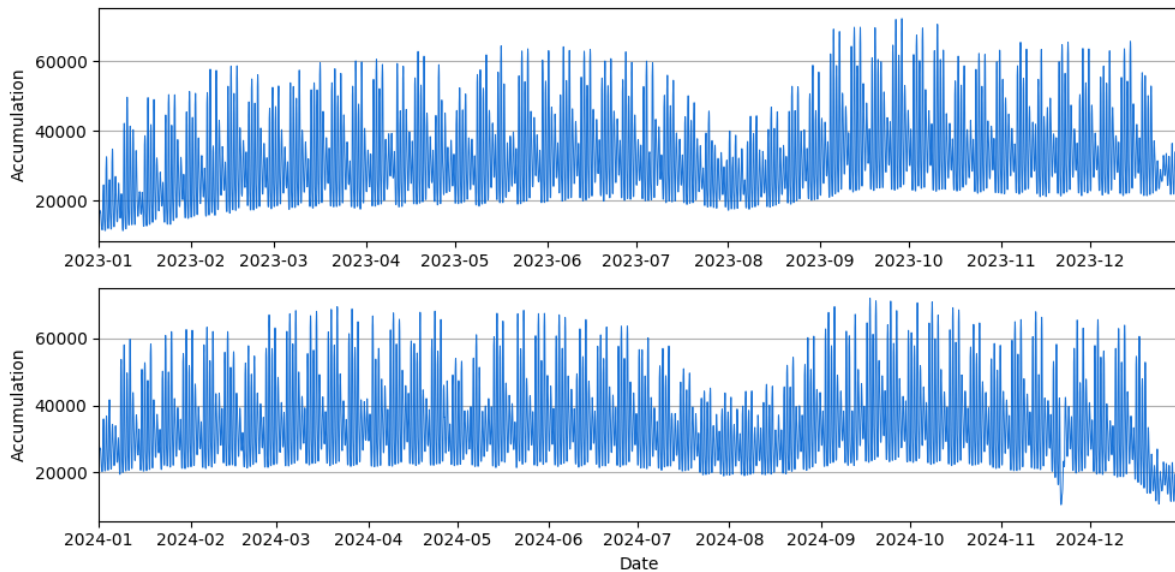


Figure 5.7: Total accumulation in facilities 2023 and 2024

To capture typical demand patterns while excluding irregular periods caused by for example holidays, the analysis focuses on an average week starting in the second week of September, the month when most facilities reach their peak occupancy (figure 5.8). This ensures that the analysis reflects a period of stable, representative demand across the network. Data from either 2023 or 2024 is used, depending on which year had the higher occupancy at each site. The month where the maximum is reached is particularly important as it illustrates the maximum demand that facilities have to accommodate, reflecting increased commuter activity and the capacity challenges that need to be addressed. A full overview of the weeks selected per site is provided in Appendix C. The patterns observed during this illustrative period have been verified against annual trends, confirming they do not significantly deviate from usage behaviours exhibited throughout the year.

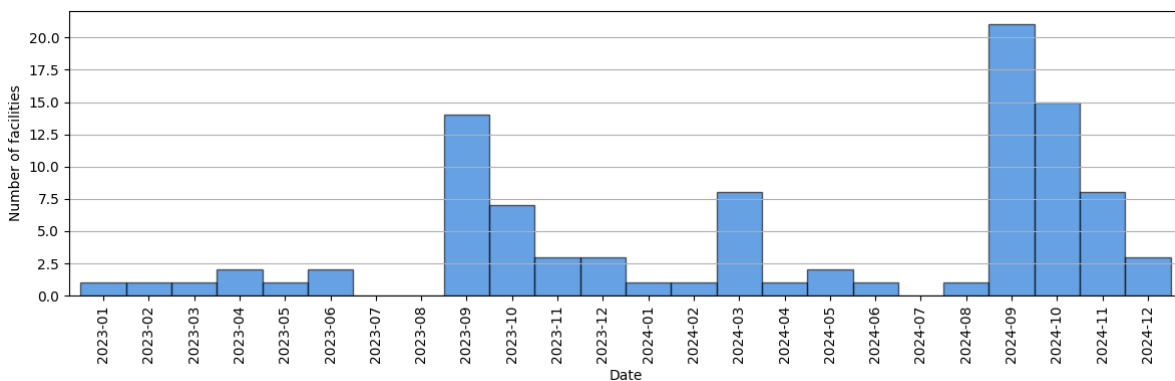


Figure 5.8: Number of facilities with maximum occupancy per month

The average week is determined by usage over a four week period. This average further reduces short-term fluctuations due to weather or occasional events and ensures that the data reflects typical usage. Choosing this stable window in mid-September improves the reliability and comparability of results between facilities.

In order to analyse usage patterns across facilities, this research uses accumulation, the number of bicycles present at any given time, as a direct representation of demand. Unlike occupancy, which is influenced by factors such as enforcement levels, subscription use or the age of the facility, accumulation provides a more comparable picture of actual use. This is particularly important because facilities are designed to meet future demand over their entire lifetime, not just the first few years. Even if a facility is not yet at full capacity, its current use should reflect growing or fluctuating demand over time. To allow a meaningful

comparison, accumulation data is normalised to the weekly maximum of the average week per facility. This highlights relative changes in usage over time, independent of absolute capacity, and is therefore suitable for clustering analysis. In Appendix C, in addition to the year and period of the average week, the maximum value of that period is shown, as well as the day and time it occurred. For most facilities, this is expected to be a Tuesday or a Thursday. How this accumulation is calculated over the week is explained in the next section.

5.3. Macro Context and Outcome

5.3.1. Context variables

This section outlines the macroscopic factors that influence bicycle parking facility usage and performance. These broader contextual variables, such as capacity, exploitation date, type of facility, and pricing regime, are essential for interpreting differences in usage patterns across locations. By defining and structuring these attributes, the analysis accounts for external conditions that shape how and to what extent each facility is used, ensuring that comparisons and clustering results reflect underlying structural differences.

Capacity

As indicated in the conceptual diagram, both occupancy and turnover calculations require the knowledge of the facility's capacity. The capacity of a parking facility can fluctuate over time due to changes such as the removal or addition of racks, adjustments to accommodate non-standard bikes or cargo bikes, or renovations that either increase or decrease the available space. To ensure consistency in the analysis, this study uses the capacity values recorded for 2024, which reflect the most current rack configurations provided by ProRail. In cases where a parking area is available within the facility, the capacity is calculated based on the length of the parking area, with the assumption that each parking space accommodates a bike every 0.75 meters.

Since the capacity of the facilities is based on forecasts for future bicycle parking demand, a simple regression analysis is conducted to test the hypothesis that facilities exploited earlier at train stations might exhibit higher occupancy and parking pressure rates. This hypothesis is rooted in the belief that these facilities are built based on prior forecasts predicting increasing demand for bicycle parking, as supported by NS check-in data which indicates usage trends. Ideally, it is expected that a facility's usage would increase progressively until it reaches saturation or the point where its lifecycle nears completion, ensuring optimal utilisation throughout its years of operation.

Linear regression is often used to describe the relationship between an outcome variable and one or more exposure variables (Laake and Fagerland, 2015). The linear regression model is defined as follows:

$$y = \beta_0 + \beta_1 x + \varepsilon$$

where:

- y is the maximum occupancy rate (dependent variable),
- x is the numerical representation of the exploitation start date (independent variable),
- β_0 is the intercept,
- β_1 is the slope, indicating the strength and direction of the relationship,
- ε is the error term.

The model estimates β_0 and β_1 by minimizing the sum of squared residuals, the error term, between the observed and predicted values of y .

Type of Facility

For comparison purposes, facilities are classified as either guarded or self-service (un-guarded) based on their access and management setup as described in chapter 3. In

addition, facilities may use either a bike lane or hand scanner check-in system. These classifications are included in the dataset to allow analysis of how different usage patterns vary. The level of service is also known, if a facility includes a bike and services point.

Types of Bicycles

Next to that, for each facility, the proportions of each type of bicycle, standard, non-standard in racks and non-standard without racks, are obtained from on-site counts, as the check-in/check-out data do not distinguish between bicycle types, but rack dimensions and space requirements vary considerably between them. These counts are used to calculate the proportion of each bicycle category at each location.

Pricing Regimes

As indicated in chapter 3, parking facilities operate under four pricing regimes. For the purpose of this analysis, only three are included—subscription, first 24 hours free, and paid, since free facilities lack check-in data and cannot be quantitatively assessed. Each location is classified according to its pricing regime to enable comparison across the usage patterns.

Station Typologies and Contextual Information

To get a broader picture of the context, the data is enriched with, contextual information about the attraction and production level of each station the facilities are located. These numbers are from NS's travel behaviour research, based on 89,000 door-to-door train journeys weighted to be representative of train journeys in the Netherlands. This data allows for a classification of stations into production and attraction stations, providing an understanding of whether stations are primarily origin or destination stations. This distinction is important for interpreting usage dynamics and demand at different locations, and for identifying potential mismatches between parking supply and user needs.

The study also includes detailed modal split information for both the access (to the station from home) and the egress (from the station to activity) legs of the journey. These modal shares show how travellers arrive and depart stations, by bicycle, car, walking or public transport, which directly influences the demand for bicycle parking facilities.

Incorporating this contextual information helps to answer the second research question: *"What are the patterns of use of bicycle parking facilities at stations, and how do these patterns vary by time and place?"* Understanding not only how facilities are used, but also where and under what conditions, provides a more complete picture of spatial and temporal usage patterns.

5.3.2. Outcome variables

This section explains how the efficiency indicators are estimated from the data to evaluate the efficiency of bicycle parking facilities. These macro outcomes are calculated using the temporal usage patterns over the selected representative average weeks.

Accumulation and Occupancy

To analyse bicycle parking occupancy over time, an algorithm is developed to determine the number of bicycles checked into a facility at each time step, the accumulation. The dataset D consists of check-in and check-out records, including the facility location and corresponding start and end timestamps of each parking action. Given that the dataset contains over 33 million records over a two-year period, a 15-minute time interval is chosen to balance computational efficiency and temporal resolution. In addition, a 15-minute interval matches typical commuter behaviour and public transport schedules well, capturing fluctuations in usage patterns with sufficient granularity to reflect peak and off-peak transitions. For each location, data is filtered to the selected average week (as described in section 5.2), after which the algorithm calculates accumulation per 15-minute interval. This results in a detailed time series of accumulations and also occupancy per facility.

1. *Define locations and time range*: Let L be the set of all unique bicycle parking facility locations, such that:

$$L = \{l_1, l_2, \dots, l_n\}$$

Define a time range T spanning from the earliest recorded parking start time to the latest recorded end time, with time intervals of Δt (15 minutes):

$$T = \{t_1, t_2, \dots, t_m\}, \quad t_{j+1} = t_j + \Delta t$$

2. *Sort data by location*: For each location $l \in L$, extract the subset of parking records D_L where the parking action occurred at location l .
3. *Count checked in bicycles (accumulation)*: For each time step $t \in T$, the number of bicycles currently parked at location l is calculated as:

$$A_l(t) = \sum_{i=1}^{N_l} \begin{cases} 1, & \text{if } S_i \leq t < E_i \\ 0, & \text{otherwise} \end{cases}$$

where:

- N_l is the total number of parking records for location l ,
- S_i and E_i are the start and end timestamps of parking action i ,

4. *Store the results*: The final result is a set of time series $A_l(t)$ for all locations:

$$\{A_{l_1}(t), A_{l_2}(t), \dots, A_{l_n}(t)\}, \quad \forall t \in T$$

These accumulation time series provide a detailed view of bicycle parking usage dynamics across all facilities.

The *occupancy* at any given time step t for a specific facility l is calculated by dividing the accumulated number of parked bicycles $A_l(t)$ by the maximum capacity C_l of that parking facility:

$$O_l(t) = \frac{A_l(t)}{C_l}$$

where:

- $O_l(t)$ is the occupancy of location l at time t ,
- $A_l(t)$ is the number of bicycles parked at location l at time t (calculated as in the previous steps),
- C_l is the maximum capacity of the parking facility at location l .

By comparing the accumulation over time, the usage of each facility's parking space can be assessed. For each facility, both the maximum occupancy within the selected week and the average occupancy across all 15-minute intervals are calculated. Since occupancy is a time-point-specific indicator, assessing both metrics allows for a nuanced understanding of short-term peak demand and overall usage across the week, enabling consistent comparisons between facilities regardless of size or operating context.

Volume and Turnover

Turnover is estimated by counting the number of bicycles arriving within each time interval. Over longer time periods, the number of arrivals is expected to closely match the number of departures, making it a reliable proxy for how intensively a facility is used. To calculate the volume, a consistent time interval of 15 minutes is used, aligning with the accumulation calculation. The volume is defined as the number of new bicycles arriving during each 15-minute period. These 15-minute intervals are aggregated to provide turnover statistics per day and per week, enabling comparisons across different temporal scales and helping identify usage patterns or trends over time.

1. *Define locations and time range*: Let L be the set of all unique bicycle parking facility locations, such that:

$$L = \{l_1, l_2, \dots, l_n\}$$

Define a time range T spanning from the earliest recorded parking start time to the latest recorded end time, with time intervals of Δt (e.g., 15 minutes):

$$T = \{t_1, t_2, \dots, t_m\}, \quad t_{i+1} = t_i + \Delta t$$

2. *Sort data by location*: For each location $l \in L$, extract the subset of parking records D_L where the parking action occurred at location l .
3. *Count check-ins per time step*: For each time step $t \in T$, the number of bicycles checking in at location l is calculated as:

$$V_l(t) = \sum_{i=1}^{N_l} \begin{cases} 1, & \text{if } S_i \in [t, t + \Delta t) \\ 0, & \text{otherwise} \end{cases}$$

where:

- N_l is the total number of parking records for location l ,
- S_i is the start timestamp of parking action i .

4. *Store the results*: The final result is a set of time series $N_l(t)$ for all locations:

$$\{V_{l_1}(t), V_{l_2}(t), \dots, V_{l_n}(t)\}, \quad \forall t \in T$$

These volume time series serve as the basis for calculating the turnover of bicycle parking facilities, and with these time series, the turnover for different time periods can be calculated. Turnover is computed by counting the number of bicycles that enter the facility within a given time period, such as 15 minutes. The turnover for each location l during time step Δt can be calculated as:

$$T_l(t) = \frac{V_l(t)}{C_l \Delta t}$$

where:

- T_l is the turnover of location l [number of bicycles per time period],
- $V_l(t)$ is the number of bicycles entering at location l in time period Δt (calculated as in the previous steps),
- Δt is the duration of the time step (e.g., 15 minutes).
- C_l is the maximum capacity of the parking facility at location l .

By comparing the turnover rate, which represents the number of bicycles departing per time period, insights can be gained into the flow of bicycles through a facility. A higher turnover rate generally indicates greater efficiency in utilizing available parking spaces, as bicycles are being checked out and replaced more frequently. This suggests that the facility is serving more individuals within a given time frame, contributing to better operational efficiency and capacity utilisation. To provide a comprehensive view of usage patterns, both the weekly turnover over seven days and the weekend turnover (Saturday and Sunday) are assessed, as usage can vary significantly between weekdays and weekends. This differentiation helps to understand how the facility operates under different demand conditions across the week.

Parking Duration and Parking Pressure

Parking pressure depend on the parking actions and especially their durations, which are directly available from the dataset. The following calculation steps are taking for parking pressure rate:

1. *Define locations and time range*: Let L be the set of unique facility locations, such that:

$$L = \{l_1, l_2, \dots, l_n\}$$

Define a time window $T = [t_{\text{start}}, t_{\text{end}}]$ for which pressure will be calculated.

2. *Sort data by location*: For each location $l \in L$, extract the subset of parking records D_l corresponding to location l .
3. *Check durations within time range*: For each parking action $i \in D_l$, include only the portion of the duration that overlaps with T . If needed, truncate start and/or end times to fit within T .

4. *Calculate parking pressure*: For each location l , compute:

$$P_l = \frac{\sum_{i=1}^{N_l} (E_i - S_i)}{C_l \cdot (t_{\text{end}} - t_{\text{start}})}$$

where:

- N_l is the number of parking actions at location l that fall within the time range,
- S_i and E_i are the start and end timestamps of parking action i ,
- C_l is the maximum capacity of the facility at location l ,
- t_{start} and t_{end} define the time range for analysis.

This indicator enables comparisons across different facilities or time periods, offering insights into how intensively the available parking infrastructure is being used. High parking pressure suggests long dwell times or continuous occupation, which may indicate inefficiencies in serving more users, especially when turnover is low.

The section B.1 contains the coding steps estimating the outcome variables for the data as well as the average week.

5.4. Model Fit for Time Series Clustering

After explaining the macro context and outcome variables, this section evaluates the performance of various time series comparison methods used to cluster bicycle parking facilities based on their temporal usage patterns. As outlined in chapter 2, three distance measures were considered: Euclidean distance, dynamic time warping (DTW) and soft dynamic time warping (soft DTW). Each of these measures has distinct capabilities for capturing temporal similarity in usage profiles. Silhouette scores are computed across various numbers of clusters to assess which method provides the most meaningful and internally coherent clusters. This model fit analysis supports the selection of the optimal clustering method and configuration, forming the basis for identifying generalised usage typologies in the next chapter.

As illustrated in figure 5.9, the silhouette scores for the three different clustering methods presented in the methodology are displayed. The silhouette score is a measure of how similar an object is to its own cluster compared to other clusters, with higher scores indicating better clustering (Rousseeuw, 1987). The measure, which ranges from -1 to 1, with 1 indicating a perfect fit and -1 indicating a poor fit between the data points and their corresponding cluster. The threshold for the silhouette score is usually set at 0.5. Scores greater than 0.5 indicate high quality clusters, while scores less than 0.5 indicate low quality clusters (Islam, 2023).

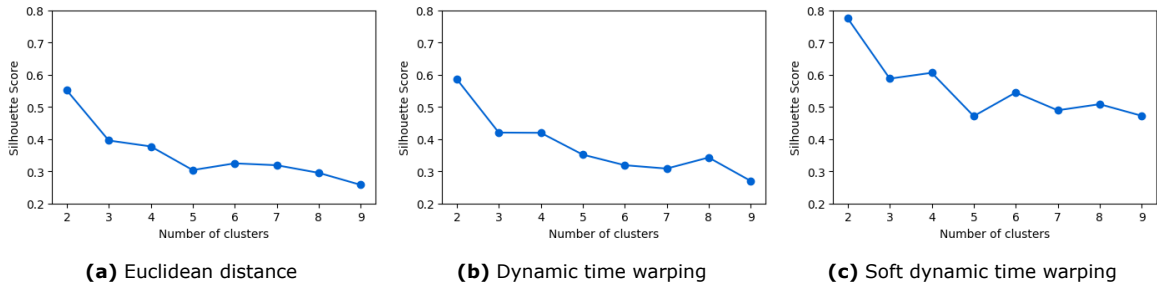


Figure 5.9: Silhouette scores for different methods

Among the methods explored, soft dynamic time warping (soft DTW) showed the highest silhouette score, as shown in sub-figure (c). This suggests that soft DTW provides the

most cohesive grouping of time series data, effectively capturing the temporal dynamics of facility usage. Notably, the silhouette score for soft DTW remains relatively high across a wider range of cluster numbers, indicating its robustness in differentiating usage patterns.

Although the highest silhouette score occurs in two clusters for all methods, particularly for soft DTW, this configuration is not chosen. The aim of clustering is not only to maximise the silhouette score, but also to uncover meaningful variations in usage patterns that may reflect differences in operational efficiency. A two cluster solution would only provide a basic binary categorisation of facilities that is too coarse to reflect the observed diversity in temporal behaviour. Such a limited structure would hinder deeper analysis of how usage patterns relate to efficiency or user dynamics. Therefore, a slightly lower silhouette score is accepted in favour of a clustering solution that provides more granular insights.

In sub-figure (c), two distinct peaks in the silhouette score appear at four and six clusters, indicating that both are potentially good configurations. Although both options are considered, the six-cluster configuration is ultimately chosen. The relative increase in silhouette score from five to six clusters is greater than from three to four, suggesting improved cohesion between groups. In addition, the selection of only four clusters resulted in the loss of several distinct weekly patterns of use, particularly those reflecting weekend-specific behaviour. These weekend variations represent an important aspect of temporal diversity in facility use and provide valuable insights into user needs and efficiency on different days. The Silhouette score of six clusters is 0.55, still indicating relatively good clustering.

By choosing six clusters, the model preserves the diversity, allowing for a more comprehensive and interpretable classification of usage dynamics. This in turn strengthens the study's ability to identify operational patterns and potential mismatches between parking capacity and demand, thereby providing more actionable insights for improving bicycle parking policy.

6

Results

This chapter presents the results of the clustering analysis applied to the weekly usage patterns identified in the previous chapter. It begins by outlining and interpreting the distinct usage patterns that emerged from the clustering process, thereby addressing research question 2. The subsequent section evaluates the efficiency of these patterns using the indicators previously defined, presenting both macro-level outcomes and contextual factors. The chapter concludes by interpreting the results in light of the conceptual model introduced in chapter 4, thereby addressing research question 3. The final section synthesises the findings into a set of strategic recommendations, providing an overall interpretation that contributes to answering the main research question.

6.1. Usage Patterns

This section presents clustering results of bicycle parking usage patterns to address research question 2: “*What are the usage patterns of bicycle parking facilities at railway stations, and how do these patterns vary by time and location?*”. Part of this question is already explored in section 5.2, where seasonal trends across all facilities revealed a distinct commuter-driven usage pattern, with reduced demand during holidays. In this results section, the focus shifts to variation in usage patterns across different facility locations.

Figure 6.1 illustrates the average weekly usage profiles for each cluster, based on Soft-DTW k-means clustering. The dashed coloured lines represent the cluster centroids, capturing the typical usage behaviour within each group. The solid lines show the average usage of all facilities assigned to the respective cluster. The goal of the clustering is to identify generalised temporal usage patterns across facilities. This provides a more structured understanding of operational differences and guides targeted efficiency strategies for groups of facilities, rather than for each facility individually.

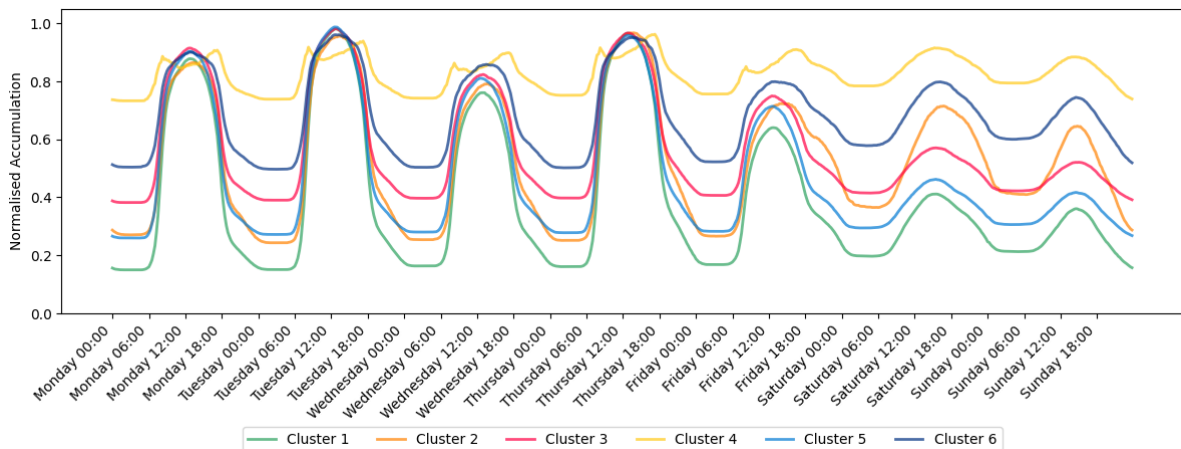


Figure 6.1: Average usage patterns per cluster of the representative weeks

Figure 6.2 provides a more detailed view of individual facilities by displaying the complete time series for each facility, grouped by cluster. In these plots, the coloured lines again

indicate the centroids, while the grey lines represent the usage patterns of the individual facilities within each cluster. This allows for a clearer comparison of patterns between locations and reveals the internal variation within clusters. Notably, Tuesdays and Thursdays show consistently higher and more stable demand between all facilities in clusters 1, 2, 3, 5 and 6, probably reflecting commuting behaviour on typical office days. Cluster 4 shows a more unexpected pattern, which will be discussed further in the following section where the individual results for the clusters are discussed. The specific locations of the facilities associated with each cluster are listed in the appendix D.

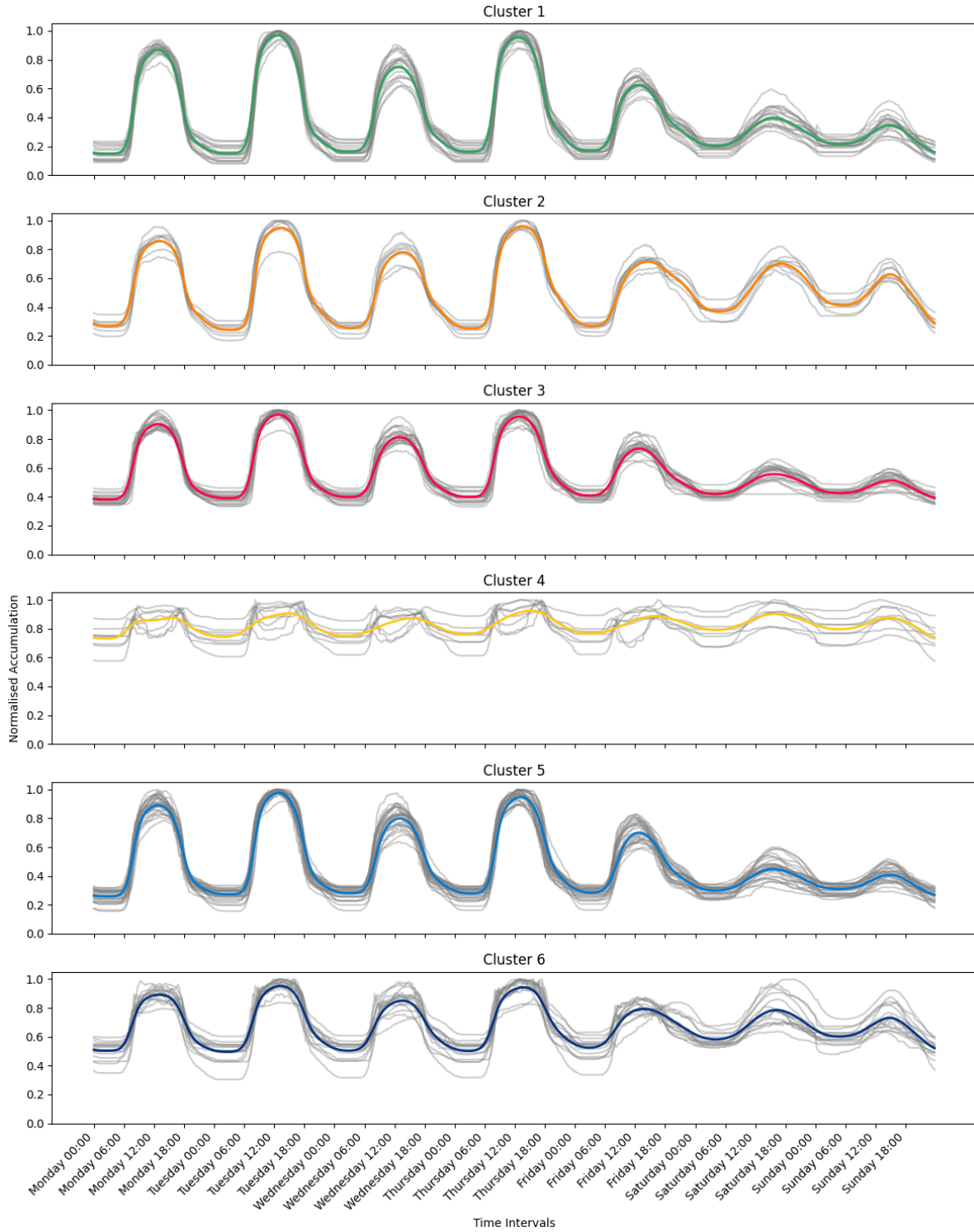


Figure 6.2: Temporal patterns clusters identified using Soft-DTW on time series data.

Cluster 1

The first cluster consists of 19 locations. The graphs demonstrate the usage patterns with pronounced peaks of variation in the morning and afternoon hours and periods of emptiness at night, indicating significant home-end commuter traffic during standard working hours. This dynamic reflects the role of the facilities in serving regular commuters who park their bicycles, take the train to their work in another area, and return in the evening. The intensity of these peaks, marked by the relatively largest differences between day and night usage, suggests robust daily usage tied to routine commuting activities. Illustrative examples from this cluster, such as Alkmaar, Barendrecht, Driebergen-Zeist, Gouda, and Maarssen, demonstrate the commuter-centric trend seen in the graph, highlighting these locations as hubs for facilitating pedal to platform transitions.

Cluster 2

The second cluster is smaller with only 8 facilities. Cluster 2 shows a weekly usage pattern similar to cluster 5 (shown in figure 6.1), but during the week with less pronounced fluctuations between peak and off-peak times compared to cluster 1. This suggests a commuter dynamic where bicycles are not retrieved as often and thus with relatively higher occupancy during the night. Notably, cluster 2 shows increased use at weekends, with facilities remaining relatively full during the night and peaks reaching similar levels on Friday and Saturday. This suggests that bicycles are often left for longer periods over the weekend. The locations of the facilities grouped in this cluster, Eindhoven, Leeuwarden, Rotterdam, Tilburg and Utrecht, are all relatively large cities with significant student populations, which is likely to contribute to the extended weekend usage patterns.

Cluster 3

Cluster 3 consists of 20 parking facilities and shows a consistent weekly cycle, with distinct peaks during commuter hours. The relatively shallow troughs between these peaks, compared to clusters 1, 2 and 5, result in a relatively high occupancy outside peak hours, including at night and at weekends. This pattern suggests prolonged parking durations, which may indicate the presence of second or abandoned bicycles, rather than exclusively home-end commuters. Facilities in this cluster include stations such as Almelo, Culemborg and Zaandam, but also larger cities such as Amsterdam Zuid Strawinskylaan, Eindhoven Noordzijde, Utrecht Overvecht.

Cluster 4

Cluster 4 contains 8 locations and is characterised by a usage pattern less variable than compared to the previous clusters. Fluctuations between peak and off-peak times are less pronounced, indicating a relatively steady flow of users throughout the day. Several facilities within this cluster show a double peak pattern (shown in figure 6.2), one during the morning rush hour and another in the evening, suggesting not only a high influx of users in the morning but also a significant outflow, which could indicate high usage of second bicycles and abandoned bicycles. Stations in this cluster include two facilities at Amsterdam Centraal, Amsterdam Muiderpoort, Amsterdam Zuid, Den Helder, Dordrecht, Goes and Zwolle. As the clustered usage patterns are normalised, this pattern may reflect two different types of facility within the cluster. Some, such as those at major stations, have high volumes of passengers boarding and alighting throughout the day. Others show less variation in activity, probably due to lower daytime usage or more consistent patterns of long-term parking.

Cluster 5

Cluster 5 contains 27 facilities. It shows a usage pattern typical of commuter-oriented facilities, with distinct peaks during weekday rush hours. Compared to cluster 1, the peaks are slightly less pronounced and the facilities tend to empty more overnight, indicating a strong daily commuter cycle. Weekend usage is noticeably low, reinforcing the weekday nature of these locations. Examples of stations in this cluster are Amsterdam RAI, Arnhem Centrumzijde, Amersfoort Schothorst, Lelystad Centrum and Oss.

Cluster 6

The final cluster consists of 15 facilities. Cluster 6 shows peak usage patterns of commuter-oriented facilities, but with more activity during the weekdays. It also has broader and more varied weekend activity and fuller nights during the weekend, similar to clusters 2 and 4. Example locations in this cluster include Amsterdam Amstel, Den Haag Holland Spoor, Enschede, Maastricht and Utrecht Vaartsche Rijn.

In summary, the clustering of bicycle parking facilities based on temporal usage patterns vividly illustrates the different ways they are used across different locations. From strictly home-end commuter-oriented hubs to varied facilities influenced by an educational function or second bicycles, these insights provide a valuable framework for optimising management strategies at railway stations.

6.2. Macro Context and Outcome

In this section the results corresponding with the macro context and macro outcome, as introduced in section 4.3, are presented. This section in combination with the interpretation of the results in section 6.5, where the quantitative results are interpreted in combination with the findings of the qualitative results for usage efficiency, provides an answer to research question 3: *“What operational dynamics of bicycle parking facilities, both efficient and inefficient, can be observed and how can they be related to the usage patterns?”*.

6.2.1. Overall Results

The general analysis of bicycle parking facilities across the Netherlands offers insights into usage patterns of all facilities to compare the clusters to. The exact numbers can be found in table 6.1 in the results chapter in chapter 6.

Context Variables

The average capacity of all facilities is approximately 1,500 parking spaces, including both standard and non-standard bicycles. This relatively high number reflects the integration of bicycle infrastructure at railway stations in the Netherlands, underlining their role as important hubs in the mobility network.

Of the 97 facilities, approximately 40% are guarded by staff, while 60% are unguarded. The decision between guarded and unguarded is determined by the number of people using a station. And so, overall, a relatively large proportion of 40% is a large mobility hub, maintaining a safe, user-friendly environment in locations with high demand or long-term parking needs.

In terms of access systems, 59% of all facilities use a self-service lane for entry, which corresponds with the dominance of unguarded setups. Of the guarded facilities, 13% have a dedicated bikelane and 28% use a handscanner system. The bikelanes are the new system that automatically scans users as they pass, thus also measuring the number of subscribers in the facility.

The distribution of bicycle types in the facilities during the counting at the facilities shows that 75% are standard bicycles. Non-standard bicycles that fit into special racks account for 23.5%, while only 1.5% are non-standard bicycles that cannot be parked in the racks.

In terms of pricing, over 90% of facilities offer the first 24 hours free of charge, with prices varying depending on whether the facility is staffed or self-service. This policy encourages short-term use, particularly for daily commuters, and is in line with the trends in parking duration seen in the outcome variables. Only about 10% of facilities charge users from the first hour.

Approximately 30% of facilities include bicycle service points, such as repair or maintenance areas. Notably, these are present in 75% of all guarded facilities.

Finally, the production-attraction index has an average of 0.55, indicating a slight skew towards production-oriented locations, typically residential areas where commuters start their journey. This context reinforces the observed weekday peaks and longer parking durations, as these facilities mainly serve users who leave their bicycles in the morning and retrieve them after work.

Outcome Variables

The average parking duration across all facilities is 36.60 hours, indicating that some bicycles are parked for extended periods. However, the median parking duration is 9.93 hours, which is more in line with typical commuter behaviour, a working day length with in train travel time. This discrepancy indicates a right-skewed distribution, with a small number of long-term parked bicycles influencing the mean. This could be due to the presence of orphaned bicycles in the facilities that are not collected or are collected after a long period of time, or it could be due to second bicycles at the end of the journey that are not used every day, resulting in longer parking periods.

The weekly turnover rate of 2.91 indicates that, on average, each parking space is used almost three times per week. Weekend turnover is significantly lower at 0.34 compared to a weekday average of 0.42 per day and a weekend average of 0.17 per day. This indicates a lower level of activity over the weekend, possibly reflecting periods when the infrastructure may not be fully utilised.

The average maximum occupancy rate of 0.588 indicates that facilities are at around 59% of capacity at peak times. The weekly parking pressure, defined as the ratio of occupied time to total available parking time, is 0.44. This measure highlights the intensity of usage of the week, and showing that on average 44% of the total available parking time is used.

The average effective parking price of €0.30, a result of the duration of parking and the pricing regime of a facility, supports the earlier finding that most users park for less than 24 hours, taking advantage of the free parking window.

6.2.2. Results per Cluster

An overview of the quantitative results of the macro context and macro outcome is provided in table 6.1. The table includes the results of the context variables and outcome per cluster as well as for all locations combined. The table starts with the cluster sizes followed by the context variables. These context variables come in two forms, numerical variables such as capacity and station typology, as well as categorical variables such as facility type. Numerical variables are summarised by their means, with ANOVA-derived F-statistics and associated p-values indicating between-cluster variation (see subsection 2.1.6). The categorical variables are shown as a the proportion per category within the clusters, with the observed and expected counts of these variables for the chi-squared statistic are provided in Appendix E. These categorical variables are evaluated using chi-squared tests, with corresponding p-values. The outcome variables are all numeric and are presented with their mean, F-statistic and p-value.

The following section presents and compares the results for each of the six clusters, focusing on both context and outcome variables. The overview table 6.1, shows the mean values for each variable across clusters, together with the overall sample mean, test statistics and p-values. If the p-value indicates significant differences between the facilities ($p < 0.05$), it is in bold. In addition, the box plots and bar charts in figures 6.3 and 6.4 show the full distribution or frequencies of each variable within the clusters. These visualisations allow for a more nuanced understanding of how facilities differ, not only on average, as well as their spread and variability.

Table 6.1: Results macro context and outcome clusters

	Cluster	1	2	3	4	5	6		Statistic	p-value
	size	19	8	20	8	27	15	97		
	size(%)	0.196	0.08	0.206	0.082	0.278%	0.155%	1		
<i>Context Variables</i>										
Capacity	mean	1707.1	3750.9	1258.9	1235.0	1033.6	1400.8	1509.5	3.322	0.008
Type of facility									19.440	0.002
Guarded	share	0.579	1.000	0.200	0.500	0.333	0.185	0.412		
Unguarded	share	0.421	0.000	0.800	0.500	0.667	0.370	0.588		
Validation system									26.401	0.003
Self-service	share	0.421	0.000	0.800	0.500	0.704	0.667	0.588		
Bikelane	share	0.053	0.375	0.150	0.250	0.037	0.200	0.134		
Handscanner	share	0.526	0.625	0.050	0.250	0.259	0.133	0.278		
Type of bicycle										
Standard bicycles	mean	0.707	0.775	0.768	0.734	0.745	0.779	0.750	3.285	0.009
Non-standard (in racks)	mean	0.273	0.215	0.215	0.245	0.241	0.210	0.235	2.619	0.029
Non-standard	mean	0.021	0.010	0.016	0.021	0.014	0.011	0.015	0.692	0.631
Pricing regime									8.378	0.137
First 24 h free	share	0.789	0.750	0.950	1.000	0.926	1.000	0.907		
Paid	share	0.211	0.250	0.050	0.000	0.074	0.000	0.093		
Bicycle and services									17.103	0.004
Yes	share	0.421	0.750	0.100	0.500	0.185	0.200	0.289		
No	share	0.579	0.250	0.900	0.500	0.815	0.800	0.711		
Station typology									5.839	0.000
Production	mean	0.608	0.427	0.580	0.444	0.609	0.447	0.549		
Attraction	mean	0.392	0.573	0.420	0.556	0.391	0.553	0.451		
<i>Outcome Variables</i>										
Mean duration [h]	mean	22.96	19.76	42.09	66.16	32.58	47.02	36.60	14.532	0.000
Median duration [h]	mean	9.28	9.31	9.74	13.59	9.54	10.09	9.93	15.145	0.000
Week turnover	mean	2.785	3.028	2.816	2.807	3.188	2.705	2.913	0.369	0.868
Weekend turnover	mean	0.310	0.541	0.289	0.339	0.311	0.393	0.340	2.896	0.018
Occupancy (max)	mean	0.539	0.487	0.590	0.669	0.647	0.555	0.588	0.774	0.571
Parking pressure	mean	0.282	0.286	0.526	0.520	0.454	0.542	0.440	2.891	0.018
Parking price [€]	mean	0.395	0.589	0.201	0.278	0.236	0.249	0.295	1.229	0.302

Context Variables

The results show statistically significant differences between clusters for all context variables except pricing regime and non-standard bicycles that do not fit in racks. This suggests that clustering usage patterns not only captures behavioural patterns, but also corresponds to different infrastructural and operational profiles, as will be explained in the following sections.

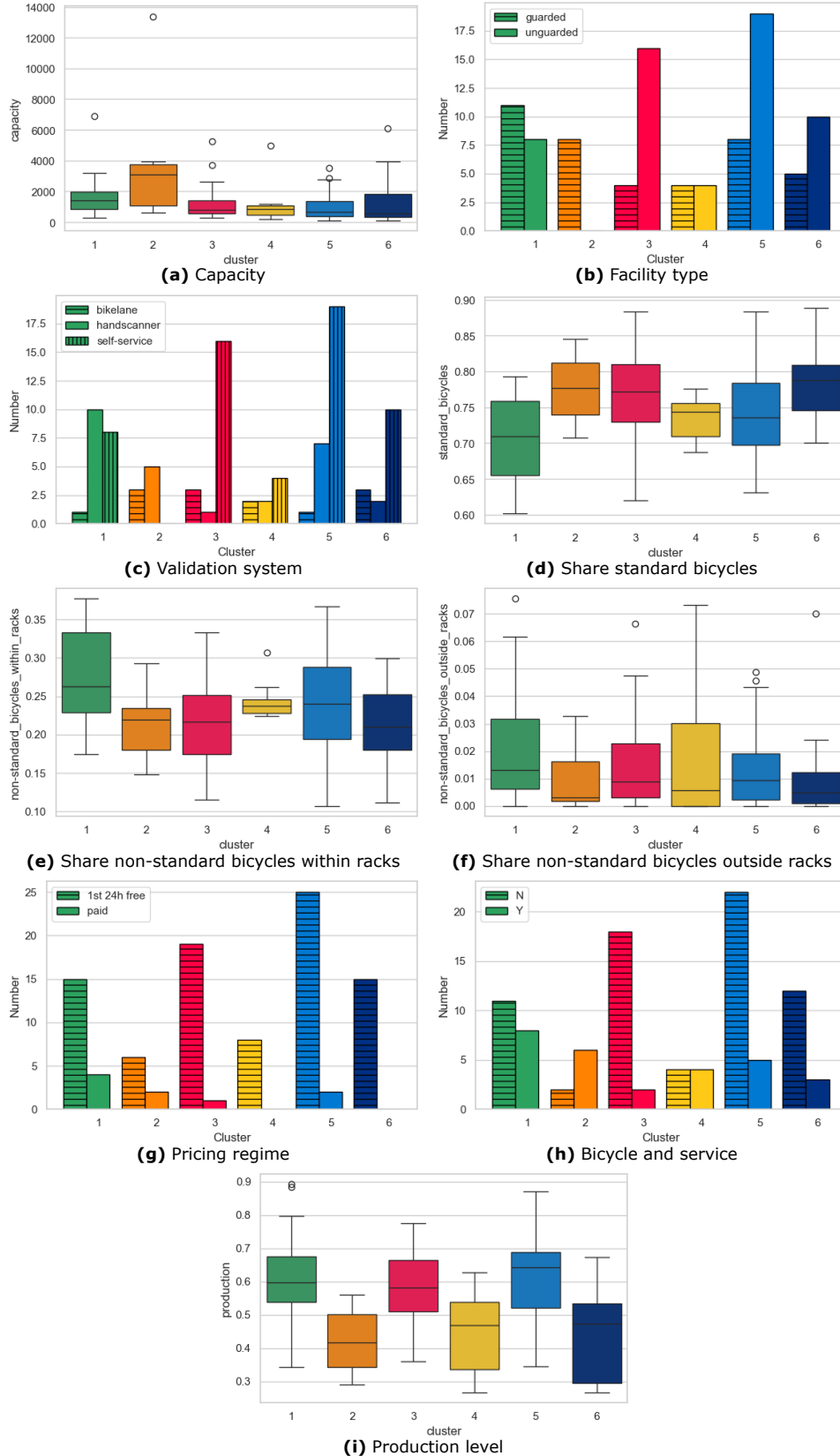


Figure 6.3: Distribution of context variables bicycle parking facilities per cluster

In figure 6.3 and table 6.2 cluster 2 stands out with the largest average capacity (3750.9), significantly higher than other clusters ($p = 0.008$), while clusters 4 and 5 have lower capacities (around 1235 and 1034 respectively). This suggests that facilities in cluster 2 tend to be larger, possibly reflecting their role as major transport hubs. One of the facilities in cluster 1 is for Utrecht Centraal Stationsplein with a capacity of over 13,000 bicycle parking spaces, and can be seen as an outlier in figure 6.3. The ANOVA test confirms a statistically significant difference between clusters ($p = 0.008$).

Table 6.2: Average capacity per cluster

Capacity	1	2	3	4	5	6	Total
Mean [number of racks]	1707.1	3750.9	1258.9	1235.0	1033.6	1400.8	1509.5

Statistic: 3.322 p -value: **0.008**

In terms of facility type, as shown in table 6.3, cluster 2 consists entirely of guarded facilities, whereas clusters 3, 5 and 6 have a significantly higher proportion of unguarded facilities compared to the overall distribution. This variation reflects differences in the level of security and staff presence, which in turn may influence user behaviour and perceived comfort. This distribution also correlates with capacity, as larger stations, typically located at major transport hubs, are more likely to offer guarded facilities with staff presence due to operational decisions on when to use a guarded or unguarded facility. The pattern observed is statistically significant ($p = 0.002$).

Table 6.3: Share of type of facilities per cluster

Type of facility	1	2	3	4	5	6	Total
Guarded	0.579	1.000	0.200	0.500	0.333	0.185	0.412
Unguarded	0.421	0.000	0.800	0.500	0.667	0.815	0.588

Statistic: 19.440 p -value: **0.002**

As all unguarded facilities operate through a self-service lane, the proportion of self-service systems is relatively consistent across clusters. However, a clearer distinction emerges when examining the use of handscanners versus bikelane validation systems. These differences provide an indirect insight into the inclusion of subscription users who typically use the self-service or bikelane options. As shown in figure 6.3, the most pronounced variation is observed between self-service systems and the other two types, mirroring the pattern already discussed under facility type. In particular, clusters 3 and 6 have a relatively high proportion of bikelane validation systems compared to the average, while clusters 1, 2 and 5 rely more heavily on handscanners. Cluster 4, on the other hand, shows an even distribution between handscanners and bikelane systems. The overall distribution of validation systems differs significantly between the clusters ($p = 0.003$), although this variation is again closely related to the type of facility and therefore to capacity. Furthermore, it is important to note that bikelane and self-service validation systems typically include subscription users in their data, whereas handscanner validations do not. This discrepancy may partly explain the observed differences in distribution and should be considered when interpreting the results.

Table 6.4: Share of validation system types per cluster

Validation system	1	2	3	4	5	6	Total
Self-service	0.421	0.000	0.800	0.500	0.704	0.667	0.588
Handscanner	0.526	0.625	0.050	0.250	0.259	0.133	0.278
Bikelane	0.053	0.375	0.150	0.250	0.037	0.200	0.134

Statistic: 26.401 p -value: **0.003**

Table 6.5 reveals that standard bicycles make up the majority across all clusters, with cluster 2 having the highest share at 77.5%, which corresponds to the image of everyday student commuters using standard models. The share of non-standard bicycles in racks is statistically significant across clusters ($p = 0.009$ and 0.029 respectively), with cluster 1 having a higher proportion of non-standard bicycles.

Table 6.5: Average share of bicycle types per cluster

Bicycle Type	1	2	3	4	5	6	Total
Standard	0.707	0.775	0.768	0.734	0.745	0.779	0.750
Non-standard (in racks)	0.273	0.215	0.215	0.245	0.241	0.210	0.235
Non-standard (outside racks)	0.021	0.010	0.016	0.021	0.014	0.011	0.015

Standard – Statistic: 3.285 *p*-value: **0.009**

Non-standard (in racks) – Statistic: 2.619 *p*-value: **0.029**

Non-standard (outside racks) – Statistic: 0.692 *p*-value: 0.631

As can be seen in table 6.6 and figure 6.3, the pricing regime appears to be broadly consistent across clusters, with the majority offering the first 24 hours free. Only a small proportion in clusters 1 and 2 provide paid parking options. This limited variation is reflected in the statistical test, which does not indicate a significant difference ($p = 0.137$). While pricing has been noted in the literature as an important factor influencing facility perception, in this case, it does not emerge as a key differentiator between the identified clusters.

Table 6.6: Share of pricing regime types per cluster

Pricing regime	1	2	3	4	5	6	Total
First 24h free	0.789	0.750	0.950	1.000	0.926	1.000	0.907
Paid	0.211	0.250	0.050	0.000	0.074	0.000	0.093

Statistic: 8.378 *p*-value: 0.137

The availability of additional bicycle-related services also varies between clusters. As shown in table 6.7, cluster 2 has the highest proportion of facilities offering such services (75%), the biggest facilities, while clusters 3, 5 and 6 have significantly lower proportions. These clusters are also those with the highest proportions of unattended facilities, suggesting a relationship between the availability of services and the type of facility. This difference is statistically significant ($p = 0.004$) and is likely due to the correlation with facility capacity and staffing.

Table 6.7: Share of stations with bicycle services per cluster

Bicycle and services	1	2	3	4	5	6	Total
Yes	0.421	0.750	0.100	0.500	0.185	0.200	0.289
No	0.579	0.250	0.900	0.500	0.815	0.800	0.711

Statistic: 17.103 *p*-value: **0.004**

The typology of stations, distinguishing whether a station primarily serves as a production (origin) or an attraction (destination) point, varies across clusters. As can be seen in table 6.8, clusters 1, 3 and 5 are more production-oriented, with a higher level of stations serving as origin points. With 5 having the highest production level, followed by 1 and then 3. In contrast, clusters 2, 4 and 6 show a stronger tendency to serve as destination points, with attraction-oriented stations, with 2 having the highest, followed by 4 and 6. This shift between production design and policy to usage context and attraction roles is statistically significant ($p=0.000$), suggesting that the clusters may serve different urban functions. Production-oriented clusters are likely to be associated with more commuting purposes at the home end of the trip, while attraction-oriented clusters are more likely to be associated with commuters at the activity (work) end of the trip. In addition, attraction may be associated with areas that attract visitors, such as entertainment or cultural centres, which also has implications for bicycle parking facilities. This difference highlights the different roles these stations play in the urban transport network, potentially influencing both the type of services provided and the demand for bicycle parking.

Table 6.8: Station typology (production vs attraction) per cluster

Typology	1	2	3	4	5	6	Total
Production	0.608	0.427	0.580	0.444	0.609	0.447	0.549
Attraction	0.392	0.573	0.420	0.556	0.391	0.553	0.451

Statistic: 5.839 *p*-value: **0.000**

Outcome Variables

This section discusses the variation in outcome variables across the six clusters identified. Figure 6.4 shows the distribution of the outcome variables across the clusters. These are the mean and the median parking duration, week and weekend turnover, the maximum occupancy and the parking pressure. In addition, the average paid parking price that is paid is also considered as outcome variable. The section discusses whether the variables have statistically significant difference and how the clusters differ from each other.

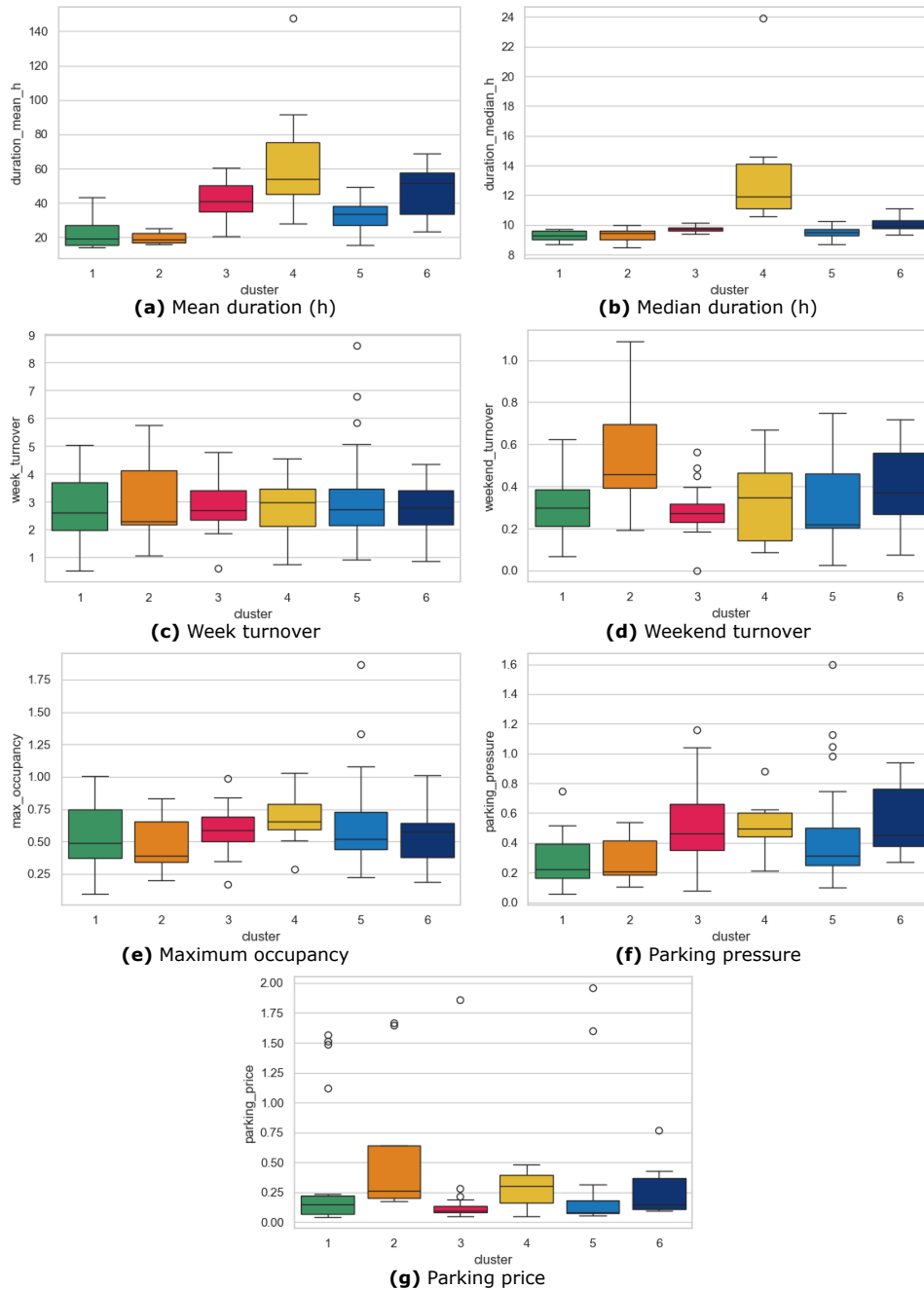


Figure 6.4: Distribution of outcome variables for bicycle parking facilities per cluster

As shown in table 6.9, the mean and median parking duration differs significantly between the clusters ($p = 0.000$). Across all facilities, the average (mean) parking duration is 36.60 hours, while the median is only 9.93 hours, highlighting a right-skewed distribution. This suggests that while most users park their bikes for typical commuting times, roughly the length of a working day including travel, there is a smaller group parking long-term who

significantly inflate the mean. These long durations may be due to orphaned bikes or second bikes left at stations and used only occasionally. Cluster 4 has the longest average duration (66.16 hours), which is consistent with its relatively stable usage pattern and suggests longer storage times. In contrast, Cluster 2 has the shortest average duration (19.76 hours), indicating high turnover, possibly linked to students making short, recurring trips. Clusters 3 and 6 fall in between (42.09 and 47.02 hours respectively), in line with their more mixed usage profiles. The large gaps between mean and median in several clusters reinforce the presence of a small number of bicycles parked for disproportionately long periods, with implications for facility efficiency and management.

Table 6.9: Average mean and median parking duration per cluster (in hours)

Duration	1	2	3	4	5	6	Total
Mean duration	22.96	19.76	42.09	66.16	32.58	47.02	36.60
Median duration	9.28	9.31	9.74	13.59	9.54	10.09	9.93

Mean duration – Statistic: 14.532 *p*-value: **0.000**
Median duration – Statistic: 15.145 *p*-value: **0.000**

Weekly turnover does not vary significantly between clusters ($p = 0.868$), as shown in table 6.10, indicating that a baseline level of activity is common to all station types. However, weekend turnover is significantly different ($p = 0.018$), with cluster 2 again standing out. Its high weekend turnover reflects a more continuous use throughout the week, probably due to its locations in vibrant urban centres with active weekend users such as students or recreational cyclists. In contrast, Clusters 1 and 5, which are more strictly home-end commuter-oriented, have lower weekend occupancy, in line with their pronounced weekday peaks and night-time emptiness.

Table 6.10: Average weekly and weekend turnover per cluster

Turnover	1	2	3	4	5	6	Total
Week turnover	2.785	3.028	2.816	2.807	3.188	2.705	2.913
Weekend turnover	0.310	0.541	0.289	0.339	0.311	0.393	0.340

Week turnover – Statistic: 0.369 *p*-value: 0.868
Weekend turnover – Statistic: 2.896 *p*-value: **0.018**

Despite some differences in average maximum occupancy (seen in table 6.11), these are not statistically significant ($p = 0.571$). Nevertheless, the higher peak occupancy in cluster 4 supports the interpretation that it is a destination for long-term or less predictable parking needs, possibly driven by its central urban location and large facilities.

Table 6.11: Maximum occupancy per cluster

	1	2	3	4	5	6	Total
Occupancy (max)	0.539	0.487	0.590	0.669	0.647	0.555	0.588

Statistic: 0.774 *p*-value: 0.571

As illustrated in table 6.12, parking pressure varies significantly between clusters ($p = 0.018$). Cluster 6, has the highest pressure (0.542), suggesting that these stations may be in locations with limited space or more intensive usage, requiring better management of capacity to avoid overcrowding. The hybrid commuter and weekend profile of this cluster is likely to contribute to this intensity. In contrast, cluster 1, which serves mainly commuters, has the lowest pressure (0.282) due to distinct peak times with longer periods of underutilisation at night.

Table 6.12: Parking pressure per cluster

	1	2	3	4	5	6	Total
Parking pressure	0.282	0.286	0.526	0.520	0.454	0.542	0.440

Statistic: 2.891 *p*-value: **0.018**

No significant differences in effective parking prices are observed between the clusters ($p = 0.302$, table 6.13). However, cluster 2 again has the highest average price (€0.589), while the parking duration is not the longest, while cluster 4 has the longest parking duration but not the highest price, suggesting orphaned bikes that are not picked up, or a lot of subscriptions in facilities with a bike lane or self-service. And the overall similarity in prices supports the idea that cost is not the main determinant of user behaviour and that usage patterns are more influenced by context and station type.

Table 6.13: Effective parking price per parking action per cluster

	1	2	3	4	5	6	Total
Parking price [€]	0.395	0.589	0.201	0.278	0.236	0.249	0.295

Statistic: 1.229

p -value: 0.302

6.3. Qualitative Results Efficiency

The interviews highlighted several operational aspects that influence the efficiency of bicycle parking facilities, ranging from technological infrastructure to human behaviour, stakeholder collaboration and enforcement regimes. While some practices promote efficient operations, others create friction, inefficiency or misuse.

Staffing and Facility Type

An important distinction has emerged between guarded and unguarded (self-service) facilities. Staffed facilities benefit from greater oversight, user assistance, and real-time monitoring of facility conditions. The interviewees noted that user behaviour is generally more disciplined in staffed environments, bikes are parked more neatly, vandalism is lower. In contrast, self-service facilities, while more cost-effective due to reduced staffing, present more challenges. Users tend to feel less responsible, leading to behaviours such as blocking emergency exits, parking in front of fire extinguishers or leaving litter. This highlights the importance of design elements in self-service facilities. Clear signage, logical layouts and intuitive routing are repeatedly cited as crucial to encouraging responsible use. Facilities lacking these features often experienced chaotic parking behaviour and higher maintenance needs.

Subscriptions and Long-Term Parking

Subscription users often park for longer periods, despite the official policy of a maximum stay of 28 days. The interviews indicated that enforcement of this rule is inconsistent. The presence of subscription users can seriously distort occupancy figures, when a validation system with handscanner is in use, creating the illusion of low usage when in fact many racks are full. Some facility managers described difficulties in determining whether bikes are abandoned or simply long parked, complicating operational decisions about tagging and removal.

Enforcement

Enforcement of bicycles that overstay varies considerably between facilities. Some facilities have strict routines for tagging and removal, often in conjunction with local enforcement by the municipality. Others have infrequent procedures, resulting in a build-up of unused or abandoned bikes and lower turnover. This variability leads to different occupancy dynamics, particularly in high-demand locations. In contrast, facilities with clearly defined agreements between NS, ProRail and the local authority appeared to be better able to manage these processes effectively.

Size of bicycles

Several interviewees noted that standard rack designs often fail to accommodate non-standard bicycles such as cargo bikes, electric bikes, bicycles with wide handlebars, child seats, or panniers and this group of users is growing. These bikes either don't fit in the

designated racks or take up more than one space, effectively reducing the usable capacity of the facility. Users of such bicycles are often forced to park outside formal racks or even outside the facility, which can obstruct walkways and lead to negative perceptions of overcrowding.

Layout

The interviews pointed out that the layout of a facility influences user behaviour, which can lead to operational inefficiencies. In some facilities the internal routing is not intuitive, with ramps, or unclear wayfinding. These physical barriers can make it difficult for users to navigate the space efficiently, particularly for those with heavy, electric, or non-standard bicycles. Moreover, users tend to park in the first available space they encounter, regardless of whether it is designed for their type of bicycle. This is particularly problematic in facilities where special spaces for oversized or non-standard bicycles are not clearly marked or are positioned too close to the entrance. As a result, standard bicycles occupy these larger spaces, making it difficult for those who need them to find a suitable place to park.

Examples of Efficient Usage

An example of efficient usage is the bicycle parking facility at Utrecht Centraal Station-splein, where some areas serve dual purpose by accommodating both PT-bikes during the night, but during the day, when the OV-bikes are rented out, regular users can park their non-standard bicycle there. In Barendrecht, the neighbouring bicycle repair shop increases the attractiveness of the facility by offering additional services, and more importantly improving the perception of security.

6.4. Summary Results

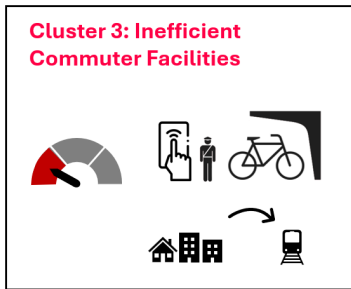
This section summarises the results of the clustering analysis. It also provides name for each cluster alongside an icon representing some of the main factors. It indicates their relative efficiency and shows the number of self-service versus staffed facilities in the cluster. At the bottom, it illustrates how most users use the facility, so from home to train or from train to activity. For production stations, this is primarily at the home-end of the journey, whereas at attraction stations, people use it at both the home-end as the activity-end.



This cluster includes facilities that tend to be medium sized (average capacity of 1707) with a mix of guarded and un-guarded access, a moderate presence of services, and high use of handscanners. The bicycle parking facilities tend to be located at stations with a production-oriented profile. The usage patterns exhibit clear weekday commuting peaks with relatively short mean and median parking durations (22.96h, 9.28h), consistent with daily use. Weekend activity is low (turnover: 0.310), and parking pressure is the lowest among clusters (0.282). This results in a relatively efficient usage pattern for bicycle parking facilities at production stations.



This cluster contains the largest facilities (average capacity of 3750), this fully guarded cluster has strong attraction-oriented characteristics with extensive services and dominant use of handscanners. Despite high overall usage, it surprisingly has the shortest mean parking duration (19.76h), indicating rapid turnover possibly linked to students or short-stay urban travellers. It also has the highest weekend turnover (0.541), reinforcing its continuous, multi-day or intermodal usage profile. This results in a relatively efficient usage of these facilities at stations that have a more attraction character.



therefore more flexible usage patterns. This results in relative less efficient usage of these facilities.



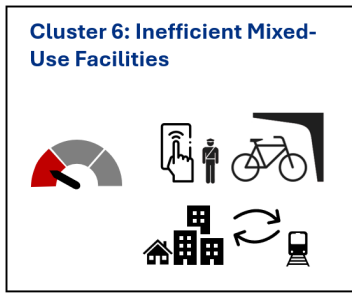
Smaller, unguarded facilities with a clear production-leaning context, cluster 3 relies heavily on self-service validation with minimal service availability. Usage is low, but the mean parking duration is relatively long (42.09h), while the median parking duration is relatively lower (9.74) and the maximum occupancy is high (0.590), suggesting that a small number of users park for longer periods, including during off-peak hours or weekends. Parking pressure is moderate but above average (0.526), possibly reflecting less strict enforcement and therefore more flexible usage patterns. This results in relative less efficient usage of these facilities.

This cluster has a relatively low capacity (average 1235), with a mix of relatively small facilities in Amsterdam and four other facilities in much smaller towns (Goes, Zwolle, Den Helder, Dordrecht). The cluster with a balance between guarded and unguarded access, mixed validation systems and average service levels has a more attraction-oriented profile, mainly due to the location in Amsterdam and Zwolle as an attraction at its location. It shows less variations in usage, evenly distributed throughout the week, and the longest mean and median parking duration (66.16h, 10.09h), possibly due to long-term or orphaned bicycle parking. Maximum occupancy (0.669) and parking pressure (0.520) are both high, indicating intensive use of the facility. Pricing is relatively low (€0.278), which may encourage long-term parking through subscriptions or reduced enforcement, and thus orphaned bikes.

This cluster consists of only eight institutions and shows a usage pattern that is relatively inefficient compared to the other groups. Its particular characteristics make it particularly valuable for comparison, and so a closer look at individual locations is warranted. The macro-level performance of these facilities is detailed in Appendix F. For example, Amsterdam Zuid Zuidplein has a high turnover rate of 4.6, but also a high parking pressure of 0.63, indicating significant congestion. This location, located in a dense business district, is likely to attract users with second bicycles and therefore where bicycles are left overnight. Whilst overnight use may appear efficient, it contributes to congestion at peak times, as travellers at the home end of their journey tend to park earlier than those arriving at the activity end. This congestion reduces overall efficiency. Amsterdam Muiderpoort has an even higher parking pressure of 0.88 and a lower turnover of 3.8. This also indicates a congested facility with limited user circulation and long average parking times. Similar patterns are observed at Amsterdam Centraal IJzijde West and Stationsplein Oost. Other locations in this cluster, including Den Helder, Dordrecht and Goes, also have long parking times, contributing to high pressure but limited turnover. In addition, Zwolle Stationsplein also has a high turnover with a relatively short parking duration compared to the others in this cluster, possibly also due to the presence of second bicycles.



This cluster consists of small, mostly unguarded facilities (average capacity of 1034) with dominant use of self-service validation. The peaks and troughs and relatively short stays point to intensive commuter usage, reflected in a moderate median parking duration (9.54h) and low weekend turnover (0.311). The mean parking duration is quite high compared to the median (32.58h), indicating possible long stays due to subscriptions or orphaned bikes. Parking pressure is moderate (0.454). As these facilities tend to be located at production stations, they fit the profile of predictable, weekday-oriented flows, resulting in a moderately efficient usage of these facilities.



With medium sized capacity, largely unguarded facilities, and limited services, cluster 6 leans towards attraction-oriented usage. It shows mixed usage patterns with higher weekend turnover (0.393), long mean parking duration (47.02h), and the highest parking pressure (0.542), indicating facilities under strain from varied user demands. This aligns with a dual user base of commuters and more recreational use at the attraction stations. This dual use leads to a usage pattern that is relatively less efficient than the other clusters.

The qualitative findings shed light on how operational, design and behavioural factors influence the patterns observed in the six cluster types. Guarded facilities (clusters 1, 2 and 4) benefit from the presence of staff, which generally leads to better user discipline, cleaner environments and perceptions of security. In the case of clusters 1 and 2, this resulted in higher turnover and more reliable occupancy patterns. In contrast, unattended self-service facilities (clusters 3, 5 and 6) face greater challenges in terms of user behaviour and enforcement. Inconsistent enforcement of subscription policies may have an impact on clusters 4 and 6, where long-term parking and high pressure suggest difficulties in identifying and removing overstaying or abandoned bicycles. Facilities using handscanners are particularly vulnerable to distorted usage data due to subscriptions, which helps to explain why actual occupancy may appear lower despite high pressure on racks. Design issues such as poor layout, unclear signage and inadequate routing emerged as critical operational weaknesses in self-service facilities. These issues contribute to chaotic parking behaviour, reduced effective capacity and user frustration. Such inefficiencies are reflected in longer parking times and lower turnover rates in these clusters.

The increasing prevalence of non-standard bicycles puts further strain on poorly designed facilities. All clusters have relatively high proportions of non-standard bicycles compared to design requirements. This mismatch between infrastructure and bicycle types often results in users parking outside of formal racks, contributing to perceived overcrowding and reduced operational efficiency.

6.5. Interpretation

6.5.1. Occupancy and Facility Age

The figure 6.5 illustrates a substantial uncertainty surrounding the relationship between the start date of facility exploitation and occupancy rates and parking pressure across various locations. The wide confidence interval (95%) surrounding the regression line suggests significant variability in occupancy rates as well as parking pressures, which cannot be explained solely by exploitation dates.

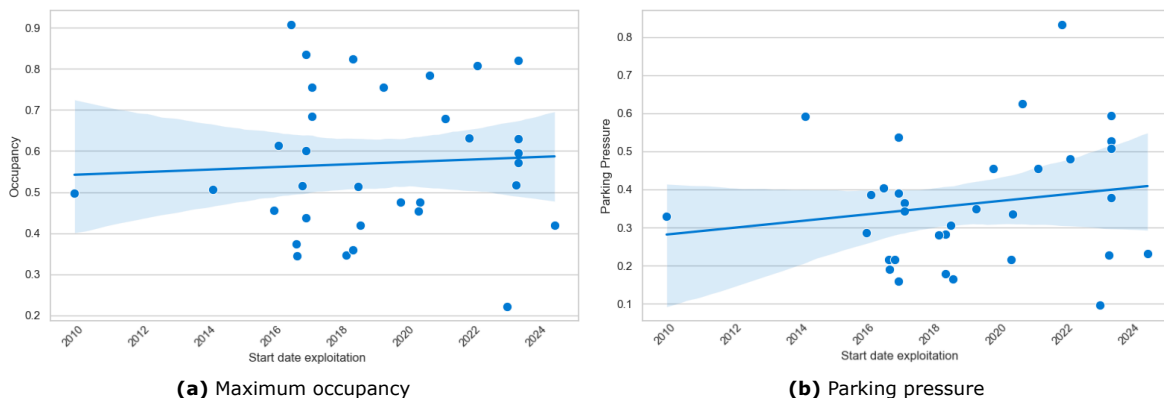


Figure 6.5: Comparison of maximum occupancy rate and parking pressure with exploitation date

This lack of a discernible trend implies that the original hypothesis, that early facility development correlates positively with higher occupancy or higher parking pressure, is not supported by the current dataset. Parking pressure even shows an opposite trend, but with a wide confidence interval, making it highly uncertain. Upon further examination, several factors may contribute to this disconnect. One potential factor is the enforcement regime at various facilities, which can directly impact their perceived fullness and real occupancy rates by affecting the turnover and clearance of bicycles. If enforcement of orphaned bicycles is inconsistent or too little, it may lead to longer parking durations and reduced turnover, skewing actual occupancy figures.

The interviews reveal considerable variation in enforcement practices between municipalities and NS employees, influenced by local agreements, staffing levels, and available resources. While NS staff are responsible for labelling bicycles that overstay their parking time, the frequency of this labelling varies significantly between locations. Additionally, the removal of these bicycles depends on municipal follow-up, which is often irregular or delayed due to capacity issues. This fragmented enforcement process contributes to the prolonged presence of abandoned bicycles, reducing available space.

Moreover, the presence of subscription users, who often park for extended periods without precise check-in/check-out records, might obscure true occupancy dynamics. This results in facilities appearing less utilised than they are, given the propensity of some users not to release occupied spaces regularly.

Interview findings indicate that, although NS enforces a maximum parking duration of 28 days for both normal and subscription users (NS, 2021), this rule is often applied flexibly for subscription users. These users frequently leave their bicycles parked for extended periods, sometimes even months, especially when using the facility for second bikes or during prolonged absences. This practice contributes to an underestimation of occupancy in some facilities and may hinder optimal use of capacity in high-demand periods.

An important consideration in interpreting the results of this research is thus that the analysis reveals no clear relationship between the date of exploitation of bicycle parking facilities and their current occupancy rates. This finding challenges the initial assumption that facilities developed earlier would have higher occupancy rates. Instead, the variability in occupancy appears to be driven more by operational factors such as inconsistent enforcement of parking rules and the behaviour of subscription users. These factors can mask true demand and reduce the effective capacity of facilities. Consequently, improving occupancy accuracy and space efficiency may require more consistent enforcement practices and better monitoring of long-term parking behaviour, rather than focusing solely on the future demand of facilities.

6.5.2. Efficiency Clusters

In figure 6.6, the week turnover and the parking pressure of the average week for all locations are plotted against each other. In the figure, clusters are distinguished by different colours, with each cluster represented as a polygon connecting the locations of the corresponding facilities. This creates a visual 'efficiency plane' for each cluster.

As can be seen, parking pressure and turnover are positively correlated, with the data points generally following a diagonal trend from the bottom left to the top right of the figure. This suggests that facilities with higher turnover tend to have higher parking pressure. Clusters positioned higher on the graph reflect a relatively higher turnover in relation to their parking pressure, suggesting more efficient usage. Conversely, clusters lower on the graph represent facilities with relatively low turnover compared to their parking pressure, indicating less efficient usage. This regression trend starting from zero has been plotted in figure 6.6, resulting in a distinction of efficiency in clusters that indicates which facilities are more efficient compared to the other facilities. This is a context-dependent measure of efficiency, in this case dependent on the parking policies at railway stations in the Netherlands.

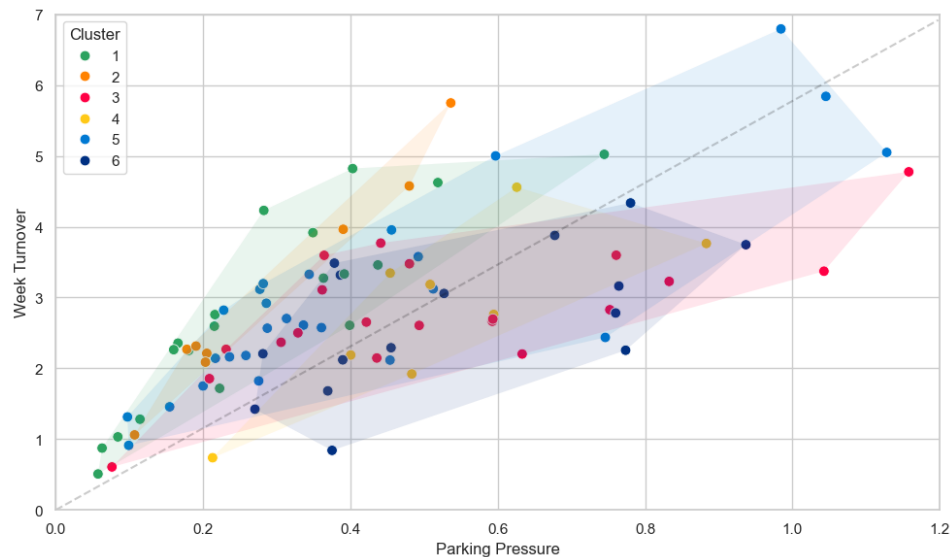


Figure 6.6: Usage efficiency clusters through turnover and parking pressure

In an ideal scenario, a facility progresses over its lifespan from the lower-left corner to the upper-right corner of the figure, ideally remaining in the upper half of the diagonal. This trajectory would indicate that as the intensity of use (parking pressure) increases over time, the facility continues to serve a high number of travellers (turnover) relative to that pressure, signifying efficient and effective utilisation of capacity.

When examining the individual clusters, clusters 1 and 2 appear higher in the graph, indicating that the facilities in these groups achieve relatively high turnover rates relative to their parking pressure, suggesting more efficient use. In contrast, clusters 4 and 6 appear lower on the graph, reflecting lower turnover relative to their parking pressure, which may indicate inefficiency or underperformance in space management. Clusters 3 and 5 occupy intermediate positions with large scatter plots, indicating moderate levels of efficiency and less cluster specificity.

Comparing clusters 1 and 2, cluster 2 has a smaller area while cluster 1 has a relatively more spread out area, which can be explained by the cluster sizes of 1 and 2, which are 19 and 8 respectively. Cluster 1 and 2 both have high peaks and low troughs in their usage patterns, 1 has the lowest troughs but 2 has higher peaks at the weekend. Looking at the macro context, 2 stands out for its capacity, and therefore for having only guarded facilities. Cluster 1 is located at the production stations, while cluster 2 is located at the attraction station, highlighting the different users of these facilities.

Cluster 5 covers almost the entire middle area, with 27 facilities, this is also the largest cluster, showing an intermediate commuting pattern corresponding to the users of the production station to which these facilities relatively belong. Most of the facilities are less efficient than cluster 1, which is also located in production stations. Cluster 3 has a similar coverage to 5, but the right part of the figure shows lower turnover, this cluster consists of 20 facilities with a station with a relatively higher production level.

Clusters 4 and 6 have fewer points above the diagonal of the graph, indicating lower efficiency. These clusters are located at attraction stations with long parking times, indicating orphaned or second bicycles.

6.5.3. Operational Strategies

The preceding analysis of usage patterns and efficiency across clusters reveals significant differences in the performance of bicycle parking facilities in relation to demand and context. These insights provide a basis for identifying targeted interventions to improve operational efficiency. Based on the observed differences between clusters, this section

proposes strategic measures tailored to the specific dynamics of each group. These strategies aim to enhance the overall effectiveness of bicycle parking systems, support sustainable mobility, and answer the main research question: what strategies can enhance the usage efficiency of bicycle parking facilities at railway stations in the Netherlands based on their operational dynamics? The proposed strategies closely align with the conceptual model introduced in chapter 4, linking macro-level outcomes to micro-level interventions relating to behaviour, enforcement and design. First, overarching, system-level strategies are outlined, followed by cluster-specific recommendations based on the identified typologies.

Monitor efficiency throughout facility's lifespan

High occupancy alone does not equate to operational efficiency. As a facility matures over its lifespan, transitioning from lower to higher occupancy to meet growing demand, its efficiency remains a dynamic parameter. An important indicator of performance at any point in time is the turnover relative to parking pressure. Facilities that maintain high turnover relative to pressure serve a greater number of users, thus using capacity more effectively. This relation between turnover and parking pressure provides a powerful benchmark for identifying when and where intervention is required. By systematically monitoring this metric, operators can identify inefficiencies in usage and implement targeted strategies, such as parking time restrictions, improved monitoring or pricing adjustments, to restore or improve utilisation efficiency, as further discussed in these strategies.

Strengthen enforcement

Extended parking durations are associated with bicycle clutter in facilities and reduced operational efficiency. Municipalities and operators must intensify enforcement through consistent monitoring, improved digital detection systems, and adequate staffing in case of the guarded facilities. Current systems often fail to reliably identify long-term or abandoned bicycles, undermining turnover and increasing parking pressure. Addressing this requires both upgrading detection technologies and rethinking how enforcement responsibilities are coordinated among NS Stations, municipalities, and ProRail. Currently, ProRail is responsible for the technical infrastructure, including detection systems and rack management; NS Stations oversees enforcement within the facility, such as monitoring and checks; while municipalities are responsible for the actual removal of orphaned bicycles. These three stakeholders are operationally interdependent. The enforcement of removals remains particularly reliant on municipal action. However, differences in urgency, financial resources, and local policy priorities result in highly variable enforcement performance across municipalities. This fragmented structure often leads to enforcement delays and reduced turnover. Clearer coordination agreements and a more integrated enforcement framework, supported by shared digital systems and streamlined protocols, could enable a more consistent and efficient approach to managing long-term parked and abandoned bicycles.

From a systems perspective, stricter enforcement affects both macro and micro dynamics: at the macro level, it improves capacity availability by removing underutilised bicycles; at the micro level, it influences user behaviour. As supported by literature, when users are aware that long-term parking is actively monitored and enforced, they are more likely to comply with regulations. This behavioural shift, brought about by changes in the operational context, enhances user motivation to adhere to time limits and ultimately promotes more efficient usage of the facility.

Match design and policy to usage context

Facility design and policy must be closely aligned with the specific operational context and user behaviour. At high-demand urban stations, this includes features such as guarded services, intuitive layouts, and integration with shared bicycle systems. In contrast, smaller stations may benefit more from compact, self-service layouts, visible entrances, and clear signage. Crucially, design and regulation should reflect actual usage patterns.

Where data shows extended parking durations, the underlying causes must be examined, such as subscription structures, the use of second bicycles or insufficient enforcement. In such cases, potential interventions include reducing the maximum permitted parking time (e.g. from 28 to 14 days) in combination with strict enforcement to ensure compliance (van der Spek & Scheltema, 2015), introducing a new or dynamic pricing to discourage long-term parking or encourage weekend use.

Introducing a new pricing model, for example, where parking remains free or low-cost for short stays but increases beyond a certain duration, can help regulate demand without deterring everyday use. Studies such as Hoskam (2020) and Molin and Maat (2015) support the effectiveness of pricing in influencing user behaviour. The first price increase has a greater behavioural impact on the number of users than subsequent increases, so the number of users will probably not decrease significantly while a bigger incentive to collect the bicycle is in place. However, it should be noted that users now pay upon leaving the facility, so there is no direct incentive to pick up their bicycles if they do not value them.

To encourage off-peak and weekend use, policies could include offering free or discounted weekend parking, but only at certain times, so as not to compromise the Monday morning peak. This would encourage leisure and occasional use, while preserving capacity for the high turnover of commuters at the start of the week. Another operational challenge arises when public spaces near stations become saturated with parked bicycles while nearby facilities remain underused, as observed at Utrecht Vaartsche Rijn station. In such cases, targeted policies could include better wayfinding, shorter walking distances to platforms or local enforcement of informal parking to encourage use of the facility.

From an organisational standpoint, coordination between stakeholders is essential. NS Stations has operational experience, while ProRail is responsible for rack design and total capacity. In order to ensure that design choices truly reflect observed usage patterns and operational needs, the two organisations must collaborate more closely, with NS providing active input to inform ProRail's long-term planning and infrastructure decisions. Closer collaboration would enable facilities to be better tailored to macro context user behaviour and more adaptable to future demand.

As outlined in the conceptual model, targeted micro-level interventions in areas such as pricing, design and enforcement can reshape user motivations and actions, ultimately influencing system outcome at a macro level.

Accommodate diverse bicycle types

Qualitative findings combined with design regulations and the bicycle census indicated a lack of suitable infrastructure for non-standard bicycles with crates or children's seats, but also for larger bicycles such as cargo bikes, fat bikes and scooters. These bicycles are often parked outside of designated racks, where they are more likely to be removed and relocated by staff. Users tend to park in the most convenient and visible locations, typically near the facility entrance or on the walking route to the station. If this is where the non-standard cycle spaces are located, this behaviour further reduces the availability of space for non-standard users. Moreover, existing facilities often do not have appropriate racks for these larger bikes and ask people to park in the top racks, which are unsuitable for some bikes due to their weight and dimensions. To address this, facilities should invest in innovative, space-efficient racks tailored to non-standard bicycles. The type and quantity of infrastructure may vary from place to place, based on observed user demand and spatial constraints. Adaptable, context-sensitive facility design allows for use that better meets the demand of specific bicycle types, reduces informal parking, and improves overall system efficiency. This strategy supports the conceptual model's call to match supply and demand not only in terms of volume, as the model implies, but also by bicycle type.

Improve user experience of self-service facilities

In self-service facilities, particularly at smaller, production-oriented stations, security, both perceived and actual, plays a key role in user satisfaction and usage. Although outdoor

parking is often available, users tend to prefer indoor options for the added sense of security they provide. However, theft is more common in unstaffed facilities, which can reduce trust and discourage regular use. Improving security through measures such as better lighting or nearby commercial services, as seen at Barendrecht, can boost user perception and, according to the conceptual model and the advice of Barneveld (2022) to focus on the dissatisfiers, increase turnover.

Clear signage and intuitive layouts are also essential. Without on-site staff to assist them, users must navigate independently. Unclear wayfinding can lead to operational inefficiencies, such as standard bikes occupying spaces intended for non-standard types. This reduces functional capacity and increases perceived crowding, thereby lowering overall efficiency. Standardising layouts and improving visual communication can guide users to the appropriate zones and support smoother operation of the facility.

Self-service models can be particularly effective at production stations with a high proportion of regular users. They can also be effective at smaller facilities at attraction stations with mostly regular users because the location is less intuitive, such as Utrecht Centraal Knoop. This familiarity enables efficient use without the need for constant staffing, making self-service a cost-effective solution when supported by clear information and adequate security.

These overall strategies will be applied in a more targeted manner to individual clusters, based on their usage patterns and the results of the macro context and outcomes.

Cluster 1: Efficient Weekday Commuter Facilities

Facilities in this group are generally efficient, characterised by high turnover relative to their parking pressure and a parking duration that matches commuter peaks. However, off-peak periods, particularly weekends, remain underutilised. This reflects the possibility of serving more travellers during these off-peak periods. To increase efficiency over the whole weekly cycle, policies such as free or discounted access at weekends could be considered to encourage leisure travellers or occasional users. These strategies are consistent with the principle of maximising turnover rather than static occupancy by encouraging continuous circulation beyond peak hours.

Cluster 2: Efficient Urban Hub Facilities

Facilities in this group support both commuter flows and relatively more overnight parking, while maintaining high turnover relative to parking pressure, indicating efficient use. Given their large size and increasing demand for shared bicycles such as public transport bicycles (PT-bikes), efficiency can be further improved by allowing flexibility for dual use. Capacity should be dynamically allocated over time; for example, these PT-bikes take up a lot of valuable space in the facility while they are often rented out during the day, by allowing short-term parking in this space, this capacity can be utilised. Supporting infrastructure such as real-time availability displays, improved signage and user guidance should help guide users to the right parking behaviour and help maintain high turnover as demand increases.

Cluster 3: Inefficient Commuter Facilities

Facilities in this cluster are characterised by high occupancy combined with low turnover, signalling inefficiency due to long parking times and a high likelihood of abandoned bicycles. These facilities are often unstaffed, self-service types located at production stations where, despite apparent pressure, user turnover is relatively lower. To improve efficiency, targeted enforcement can be useful. Strengthening both manual checks and digital monitoring systems can help identify long-term parkers and reduce overstaying. Clear and strategically placed signage is equally important to guide users intuitively to the appropriate racks and discourage inappropriate use, particularly in facilities where the layout is not self-explanatory. Behavioural nudges, such as warning signs and timed removal reminders, can increase awareness of time limits and reinforce compliance. From the systemic perspective of the conceptual diagram, these interventions improve macro-efficiency

by reshaping micro-level user actions through adjusted motivations and clearer expectations.

Cluster 4: Congested Mixed-use Facilities

Cluster 4 contains two different types of institutions. Some, such as Den Helder, Goes and Amsterdam Muiderpoort, have long parking periods and low turnover relative to parking pressure. Others, such as Amsterdam Zuid Zuidplein, are heavily used with high turnover, but show signs of extensive use of second bicycles. In both cases, efficiency is compromised by long-term storage, which reduces turnover and space availability.

Improving efficiency in this cluster requires a clear understanding of the underlying causes at each facility. Where long-term parking dominates, enforcement should be strengthened and maximum parking time policies reviewed. Clearer communication with user and stricter monitoring can encourage better compliance with the policies in the facilities. In cases where second bicycle use is prevalent, especially in space-constrained locations such as Amsterdam Zuid Zuidplein, subscription policies should be evaluated. Qualitative findings suggest that users who park a second bicycle often have a subscription. Adjusting the price or limiting the availability of subscriptions can help reduce unnecessary long-term storage and free up space for active users.

To ensure the right strategies are applied, further qualitative research is recommended, particularly through interviews with facility staff. This can clarify how space is used in practice and help align management approaches with actual user behaviour. Matching operational responses to demand characteristics at the facility level is essential to improve turnover and overall efficiency in this cluster.

Cluster 5: Intermediate Efficiency Commuter Facilities

These commuter-oriented facilities operate with moderate efficiency. Targeted improvements such as improved security and clearer wayfinding can increase their attractiveness to off-peak users without disrupting core commuter flows. Collaboration with nearby businesses, events or public transport services, as suggested for cluster 1, can help to further attract occasional or recreational cyclists. Compared to cluster 1, parking times are relatively longer here, suggesting a possible lack of enforcement. Increased monitoring and compliance could help to improve turnover. It remains important to prioritise commuter demand, while also exploiting unused potential during weekends to increase overall weekly efficiency.

Cluster 6: Inefficient Mixed-Use Facilities

This cluster is characterised by the attraction nature of the locations resulting in a diverse user base, including daily commuters at home- and activity-end, and consistently low turnover compared to its turnover. Facilities tend to be medium-sized, mostly unguarded. Despite the varied demand and particularly higher turnover at weekend, the combination of high parking pressure, long average parking times suggests that facilities are under operational pressure and result in inefficiencies. The extended parking times suggest that enforcement could be improved. There are similarities with cluster 4, but the inefficiencies are less severe. As with cluster 4, the causes of congestion need to be further investigated in order to identify appropriate strategies. The introduction of measures similar to those for cluster 4, such as improved enforcement, subscription review, could improve efficiency.

Improving usage efficiency is not about maximising capacity, but about managing it better. Facilities must balance demand and turnover by matching design and policy with observed use and the corresponding micro motivations. By strengthening enforcement, designing for context, and encouraging dynamic use, railway station facilities in the Netherlands can serve more users within existing infrastructure and promote sustainable mobility more effectively.

Conclusion, Discussion and Recommendations

This chapter answers the research questions, discusses the implications and generalisability of this research, and concludes with recommendations for practice and future research.

7.1. Conclusions

How can usage efficiency be expressed in operational dynamics of bicycle parking facilities?

Usage efficiency in bicycle parking facilities can be measured through three operational indicators: occupancy, turnover, and parking pressure rate. These indicators quantify how effectively the available capacity serves users over time, capturing both spatial and temporal aspects of demand. Occupancy reflects the proportion of parking spaces filled at a given moment, indicating how well supply aligns with real-time demand. Turnover measures how many different users occupy a single space within a defined period, showing how dynamically the facility is used. Parking pressure rate represents the ratio of total time bicycles occupy the spaces versus the total available parking time, the capacity multiplied by the time period under observation. It offers insight into overall intensity of use. These indicators are linked to each other, meaning that higher occupancy tends to be associated with higher turnover or parking pressure.

To understand and interpret these metrics meaningfully, the research introduces a conceptual framework (figure 7.1), which maps the interaction between structural characteristics of the facility and individual user behaviour. The diagram shows how macro-level conditions such as capacity, pricing, signage and enforcement shape user perceptions. These perceptions influence individual behaviours of when, where and for how long users park, which when aggregated produce measurable outcomes.

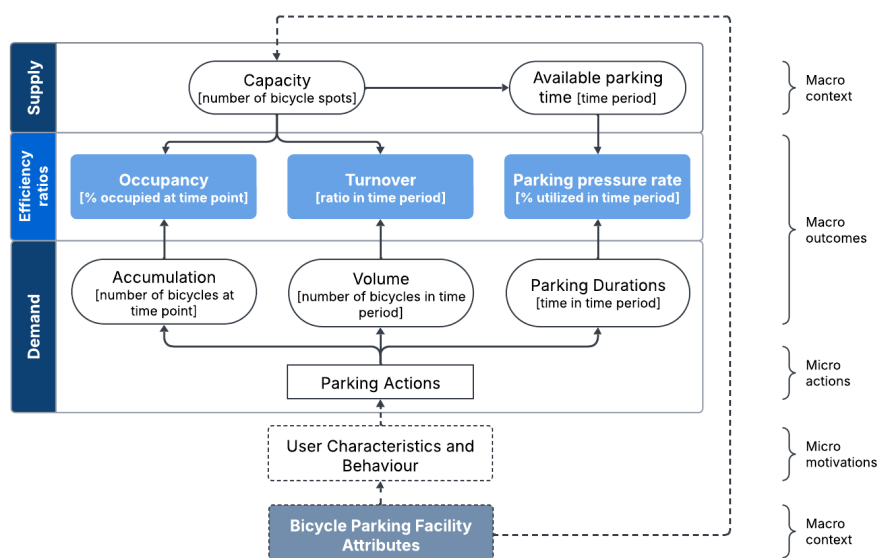


Figure 7.1: Conceptual diagram of usage efficiency

This framework shows that usage efficiency depends not only on infrastructure supply but also on the interaction between facility design, user behaviour, and preferences. A large facility may still be used inefficiently if it is hard to access or poorly organised, leading to underuse or informal parking nearby. External factors such as informal parking in the surrounding of facilities, transit connections, and facility visibility also influence how efficient it is used and should be considered part of the broader context.

What are the usage patterns of bicycle parking facilities at railway stations, and how do these patterns vary by time and location?

Bicycle parking at railway stations follows a strongly commuter-driven pattern, with clear weekday peaks, particularly on Tuesdays and Thursdays, and significantly lower activity at weekends and during holiday periods. Seasonal and weekly rhythms reflect standard commuting habits, with some variation by location and user demographic.

The application of the clustering model revealed that the average weekly usage patterns obtained using Soft Dynamic Time Wrapping (Soft-DTW) varied significantly across the six clusters identified:

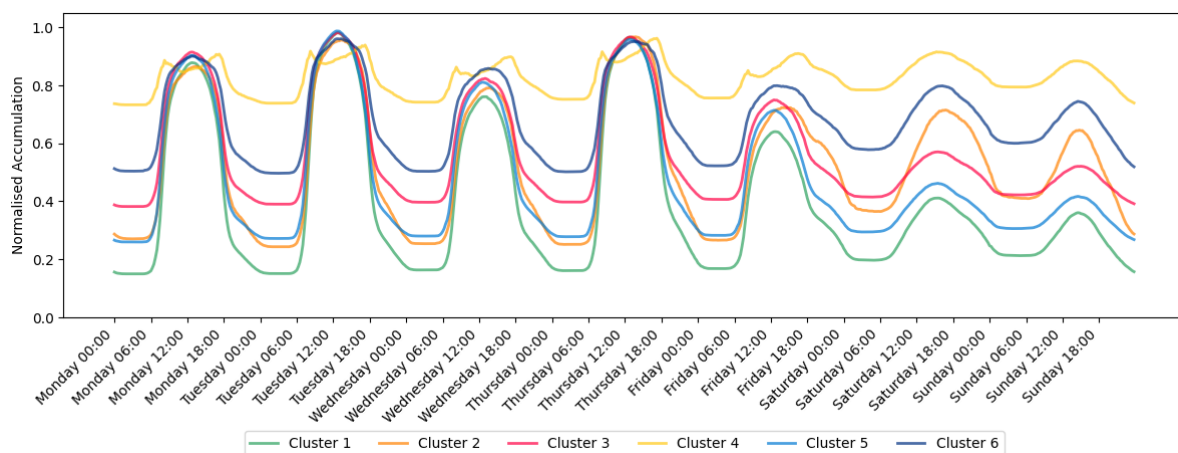


Figure 7.2: Average usage patterns per cluster of the representative weeks

- **Cluster 1 Efficient Weekday Commuter Facilities:** shows strong morning and evening usage peaks and low overnight and weekend use, typical of high-frequency commuter stations.
- **Cluster 2 Efficient Urban Hub Facilities:** combines commuter activity with extended overnight and weekend use, probably driven by students and urban travellers in larger cities.
- **Cluster 3 Inefficient Commuter Facilities:** shows both commuter and non-commuter use, with high occupancy throughout the week and into the weekend.
- **Cluster 4 Congested Mixed-use Facilities:** shows relatively stable occupancy with moderate day/night fluctuations, reflecting bi-directional flows and second bike use in urban centres.
- **Cluster 5 Intermediate Efficient Commuter Facilities:** corresponds to traditional commuter cycles, with strong weekday peaks and low weekend activity, with facilities often empty at night.
- **Cluster 6 Inefficient Mixed-Use Facilities:** shows a mix of weekday commuting and significant weekend use, suggesting a dual role in serving both daily commuters and leisure travellers.

Taken together, these clusters reveal a spectrum of usage types influenced by station location, urban context and user demographics, providing important insights for tailoring management and design strategies to answer the main research question.

What operational dynamics of bicycle parking facilities, both efficient and inefficient, can be observed and how can they be related to the usage patterns?

The operational efficiency of bicycle parking facilities is determined by a combination of infrastructure design, access type, enforcement and user behaviour. Efficient usage patterns, characterised by short parking durations, high turnover and moderate parking pressure, are typically found in medium to large guarded facilities, such as those in clusters 1 and 2. These facilities tend to offer a good level of service and include staff presence, which supports commuter-driven use. In the efficiency plot (figure 7.3), these clusters appear in the upper region, indicating a relatively high turnover relative to their parking pressure and reflecting efficient use of available capacity.

In contrast, inefficient usage patterns are more likely to be observed in smaller or unattended self-service facilities, particularly those in clusters 3, 4 and 6. These facilities tend to have longer parking times, low turnover and high parking pressure, which are signs of poor efficiency. Their lower position in the efficiency plot highlights this imbalance, suggesting that capacity is occupied for long periods without corresponding user throughput. This inefficiency may be related to limited subscription-based access models that allow long-term or even abandoned bicycle parking. Qualitative findings confirm that the absence of staff, poor signage and the prevalence of non-standard bicycles further reduce operational efficiency by undermining capacity and order.

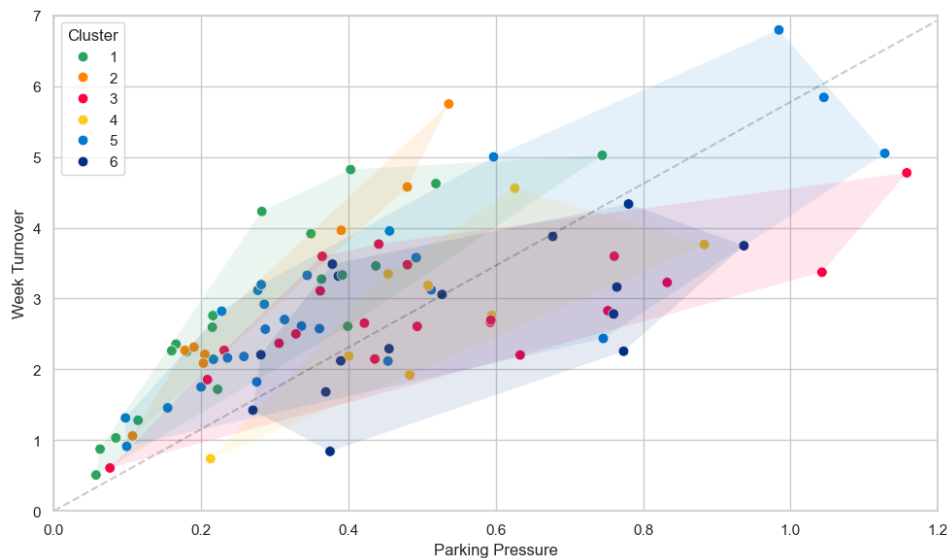


Figure 7.3: Usage efficiency clusters through turnover and parking pressure

The analysis of efficiency reveals a important operational insight: the effectiveness of a bicycle parking facility is not solely determined by its intensity of use, but by its ability to translate demand into dynamic, high-frequency usage. Facilities that maintain a high turnover relative to their parking pressure demonstrate more efficient use of space, serving a greater number of users within a given capacity. Conversely, facilities with prolonged parking durations, despite high occupancy, are less efficient, as they accommodate fewer unique users over time. As such, operational success depends not only on infrastructure size or usage volume, but on encourage active circulation and mitigating long-term or abandoned bicycle storage.

What strategies can enhance the usage efficiency of bicycle parking facilities at railway stations in the Netherlands based on their operational dynamics?

The bicycle parking facilities at Dutch railway stations are shaped by predictable commuter flows and varying spatial contexts. Usage patterns are influenced by both macro-level conditions, such as design, enforcement and pricing, and micro-level motivations, such as perceived convenience, safety and effort. Despite differences in facility size, location and

management models, shared operational dynamics emerge across clusters, offering an opportunity for system-wide improvements. Increasing efficiency requires more than just increasing capacity; it also involves improving the use of existing capacity, ensuring high turnover, adapting to demand patterns and reducing inefficiencies caused by long-term storage or abandoned bicycles.

The conceptual model in figure 7.1 guiding this research emphasises the importance of aligning facility-level interventions with user motivations in order to influence behaviour and ultimately improve macro-level outcomes. This results in five overarching strategies that can be applied to all facilities, alongside more targeted, cluster-specific recommendations.

Monitor efficiency throughout facility's lifespan: Efficiency is not static, it evolves as the facility transitions through different occupancy levels and changes in user behaviour over time. Regularly tracking turnover relative to parking pressure provides a robust operational benchmark. Facilities with reduced turnover under high pressure may require targeted interventions, such as shorter parking time limits, pricing incentives or improved signage, to influence behaviour. Ongoing monitoring enables inefficiencies to be identified early and informed decisions to be made on where and how to intervene.

Strengthen enforcement: Extended parking durations and abandoned bicycles reduce available capacity and create clutter, particularly in self-service or unstaffed facilities. Co-ordinated enforcement across NS Stations, municipalities, and ProRail is crucial. Upgraded digital detection systems, clearer stakeholder roles and shared data protocols can significantly improve the identification and removal of long-term parkers, restore circulation and influence behaviour by raising awareness of time limits.

Match design and policy to usage context: The design of a facility and its regulatory framework must be tailored to its location, user group and observed parking patterns. In high-demand stations, this may involve guarded services, shared bicycle integration, and intuitive layouts. In smaller or lower-pressure stations, self-service models with visible entrances and simple signage may suffice. Where long-term parking or second bike use is prevalent, interventions such as reducing maximum parking durations, introducing dynamic pricing or adjusting subscription policies can mitigate inefficiencies. Effective coordination between NS Stations and ProRail is essential to ensure the infrastructure reflects operational requirements.

Accommodate diverse bicycle types: Many facilities lack adequate infrastructure for cargo bikes, scooters or bicycles with child seats or crates. These often end up being parked informally, which reduces available space and increases the likelihood of them being removed. Investing in adaptable, space-efficient racks for non-standard bicycles, particularly near facility entrances, can reduce these issues and improve the experience for a broader range of users.

Improve user experience of self-service facilities: Self-service models can work well in locations with regular users, such as production stations, but only when supported by sufficient perceived security, intuitive wayfinding and infrastructure that reduces misuse. Measures such as better lighting, CCTV and visual cues to guide correct parking can reduce theft and informal use and improve trust in the facility overall. This also supports efficient turnover, particularly at smaller or unattended locations.

These approaches are further refined by cluster-specific strategies:

- **Cluster 1 Efficient Weekday Commuter Facilities:** Encourage weekend and off-peak use by offering free or discounted parking, thereby increasing efficiency throughout the full weekly cycle.
- **Cluster 2 Efficient Urban Hub Facilities:** Facilitate dual-use functionality by real-locating capacity for short-term parking when shared bicycles are not in use. This should be supported by real-time availability displays and user guidance.

- **Cluster 3 Inefficient Commuter Facilities:** Focus on improving enforcement to address long-term parking, enhance layout clarity and encourage appropriate behaviour through signage.
- **Cluster 4 Congested Mixed-use Facilities:** Address inefficiencies by strengthening enforcement, reviewing subscription policies to discourage the storage of second bikes, and tailoring interventions to the specific causes of long-term occupancy at each facility.
- **Cluster 5 Intermediate Efficient Commuter Facilities:** Improve signage, lighting and perceived security to attract more off-peak users while reinforcing compliance during peak commuter periods.
- **Cluster 6 Inefficient Mixed-Use Facilities:** Similar to Cluster 4, with investigating the underlying causes of inefficiency and applying targeted interventions, such as enforcement and subscription adjustments.

Improving the usage efficiency of bicycle parking facilities requires smarter management, not solely more infrastructure. This includes dynamically monitoring performance, designing for diverse users and contexts, enforcing policies to encourage circulation and improving the user experience, especially in self-service environments. By applying general and cluster-specific strategies, operators can better match supply with demand, promoting more efficient, equitable and sustainable mobility at railway stations across the Netherlands.

7.2. Discussion

7.2.1. Implications

This study contributes to the understanding of station bicycle parking by offering a comprehensive operational perspective, rather than focusing solely on user preferences as seen in previous research (Arbis et al., 2016; Gavriilidou et al., 2020; Hoskam, 2020). While earlier work has emphasised factors like accessibility, safety, and user satisfaction, this research shifts the focus to the efficiency of entire parking facilities, integrating quantitative time series data with qualitative insights into operational dynamics. The clustering of usage patterns allows for a more targeted view of how different facilities operate over time, providing a clearer understanding of the factors influencing cycling infrastructure efficiency.

In light of growing rail use in the Netherlands, this operational view is becoming increasingly important. As urban populations grow and sustainability targets become more pressing, public transport systems are under pressure to serve more passengers efficiently. Cycling plays a crucial role in this context, with approximately half of all train passengers currently accessing stations by bike (ProRail, 2024). As mentioned in the introduction, integrating cycling and train travel improves accessibility, reduces environmental impact and promotes transport equity (Zuo et al., 2020). As demand for rail travel increases, so does the importance of efficient and scalable bicycle parking infrastructure at stations. This research provides valuable insights that could inform the development of more effective strategies to address this growth.

One contribution of this research is to identify inefficiencies that are not always apparent from user satisfaction alone. For example, facilities with high parking pressure but low turnover may indicate the presence of long-term or abandoned bikes. These inefficiencies place unnecessary strain on facility capacity and result in sub-optimal use. However, the impact of such inefficiencies is not universal. At smaller stations, where space constraints are less severe and demand is lower, inefficiencies may have less impact. In these cases, the balance between service level and cost effectiveness becomes more important. Simple facilities such as outside bicycle racks or lockers may be sufficient to meet demand and provide a financially viable solution. In contrast, stations in dense urban contexts face space constraints that require more sophisticated management strategies, as discussed

by Ton and van den Heuvel (2023). This distinction is crucial for policy makers, who need to ensure that interventions are proportionate to the spatial and operational realities of each station.

This spatial view also helps in interpreting findings related to the impact of improved infrastructure. The work of Martens (2007) and Heinen and Buehler (2019) has shown that better quality facilities lead to more cycling to stations and therefore more parked bicycles. Combined with the findings from van Mil et al. (2021) that users are willing to cycle longer distances to avoid additional transfers, it is clear that high quality, strategically located facilities can change travel behaviour. These changes also reflect aspects of station choice, where users may bypass closer but less equipped stations in favour of those offering better infrastructure and convenience. These behavioural shifts put additional pressure on urban centres where space is most limited. However, the results of this study show that large stations such as Utrecht Centraal, both Stationsplein and Jaarbeursplein, belong to cluster 2, the most efficient group identified. This shows that even under high spatial and operational pressure, facilities can work efficiently if there is good corporation between all operational stakeholders, they are well adapted to user demand and station function. It also reinforces the idea that thoughtful design and active management can overcome the limitations of dense urban environments. It should be noted that both Utrecht Centraal locations use a validation system involving handheld scanners, excludes subscription users from the data. This distinction may partly explain the higher efficiency compared to the Amsterdam facilities in Cluster 4, which rely largely on open-access bike lanes and exhibit more inefficiencies. While this observation suggests that subscription-based access may be associated with lower efficiency, this relationship was not investigated in detail within the scope of this study. Future research could explore how different access models impact user behaviour, turnover and overall facility performance.

The user profiles described in the literature by Jonkeren et al. (2021), mainly younger, commuting employees, are consistent with both the qualitative findings from the interviews and the temporal usage patterns revealed in this study. These results underline the strong commuter-driven nature of facility use and reinforce the need to prioritise this user group when designing and managing bicycle parking facilities. Given their predictable time patterns and daily presence, facilities tailored to the needs of commuters are likely to yield high operational returns.

A further implication emerges when considering the findings of Paix Puello and Geurs (2014), which highlight the increased sensitivity of users to the quality of bicycle parking during the egress leg (activity-end). The quality of bicycle parking at the activity end can significantly influence mode choice, more so than at the home end of the journey. The results of this study suggest that facilities serving both access and egress functions tend to be less efficient, possibly due to conflicting user demands and time patterns. This finding raises important questions about how these dual functions can be better integrated without compromising operational performance. While such facilities may be more difficult to manage, they contribute to wider levels of accessibility by rail. Improving the quality of these facilities, particularly in facilitating the 'last mile', remains an essential to increase the attractiveness of the bicycle rail combination and shared mobility, which is a space-efficient option for facilitating the last mile (Zimmermann & Palgan, 2024), could offer interesting solutions. However, this solution is significantly more expensive (nearly €5 per day), compared to a subscription for private bicycle parking, which can cost up to €85 per year depending on the type of facility. In order to reduce the use of second bicycles, the options should be comparable for users. It would therefore be advisable to make shared bicycles more affordable when used in combination with train, or alternatively to increase the price of subscriptions in order to promote the use of shared bicycles, given that they are more space efficient.

7.2.2. Generalisability

The indicators and methodologies developed in this study, occupancy, turnover and parking pressure, are broadly applicable to bicycle parking facilities beyond the Dutch station context. However, their effective use requires careful consideration of local user demographics and the specific operational context of each facility. Just as this research tailored strategies to the unique spatial, managerial and cultural conditions of Dutch stations, practitioners elsewhere must first characterise their user groups (e.g. commuters, students, leisure cyclists) and facility environments before applying these metrics and interventions. Interpreting the indicators in light of both the macro-level context and the micro-level motivations of facility users is essential to derive actionable insights. Importantly, the concept of efficiency itself may need to be reconsidered depending on the intended function of the facility and local mobility objectives. The conceptual diagram developed in this study can serve as a valuable tool to guide this interpretation process and support sustainable cycling integration beyond the station context.

The Netherlands benefits from an extensive infrastructure that allows for a seamless integration of bicycles with public transport systems, which is not universally available in other countries. This integration facilitates multimodal transport with a strong emphasis on the combination of bicycle and rail, a model that is particularly relevant for the Dutch urban environment (Martens, 2007, Jorritsma et al., 2021). In contrast, regions with less developed transport networks or where cycling is not a primary mode of transport may not experience and need the same level of operational efficiency. In addition, the cultural emphasis on cycling in the Netherlands, which contributes significantly to the usage patterns observed in the study, may be different elsewhere, potentially affecting the applicability of the findings in terms of user behaviour and facility use. Therefore, while the findings of this research can serve as inspiration for improving the efficiency of bicycle parking, their implementation in different global contexts will require adaptations that take into account local infrastructure capabilities and cultural practices.

The extent to which the methodologies used in this research can be applied globally is highly dependent on local traffic dynamics. While the occupancy and turnover analysis framework provides a universally applicable approach to measuring the efficiency of bicycle parking facilities, the primary objective of using such metrics may differ in scenarios where cycling is less dominant as a mode of transport. In regions without high levels of cycling or integrated cycling infrastructure, the objective may shift to promoting general awareness and increasing cycling rates, rather than optimising existing facilities for maximum efficiency. Consequently, the international implementation of these strategies requires nuanced adaptations to reflect local geographic and demographic factors, such as urban density and commuting trends.

In conclusion, while the models and strategies developed in this study provide a structured guide for municipalities to improve bicycle parking facilities, their successful application in different contexts requires an understanding of the unique local infrastructure and urban density, travel habits and cultural practices. These insights are essential to ensure that the facilities effectively support global sustainable mobility goals.

7.3. Recommendations

7.3.1. Recommendations for Practice

This research provides operational evidence in support of a more targeted, adaptive and data-driven approach to the management of bicycle parking at Dutch railway stations. While the conclusion discusses specific strategies, this section offers broader, practice-oriented recommendations for design, monitoring and collaboration among stakeholders, particularly given the rising demand and limited space in urban centres.

Use key indicators for proactive monitoring and evaluation

The three indicators developed in this study (occupancy, turnover and parking pressure) are analytical tools and practical metrics for day-to-day operational monitoring. When visualised in platforms such as Power BI or included in regular performance dashboards, they enable dynamic, ongoing assessment of a facility's effectiveness. Rather than focusing solely on occupancy, operators can identify hidden inefficiencies, such as low turnover under high pressure or clusters of long-term parked bicycles. By systematically tracking these indicators over time, stakeholders can intervene early with targeted strategies such as time restrictions, pricing adjustments, layout changes or communication nudges. Facilities falling below the diagonal in the usage efficiency plot (figure 3) require particular attention as they demonstrate high occupancy but low turnover, indicating inefficient usage that necessitates redesign or policy revision.

Apply the five overarching strategies across the system.

The strategies identified in this research are applicable to a wide range of station types and operational contexts.

1. Monitor efficiency throughout facility's lifespan
2. Strengthen enforcement
3. Match design and policy to usage context
4. Accommodate diverse bicycle types
5. Improve user experience of self-service facilities

Ongoing monitoring is essential to support these strategies. The three key performance indicators (occupancy, turnover and parking pressure) offer a practical and scalable way to evaluate facility performance. When visualised using platforms such as Power BI, they provide insight into not only how full a facility is, but also how effectively it is being used over time. For example, facilities that show high occupancy but low turnover may suffer from long-term storage or abandonment.

Operators can use the usage efficiency graph in figure 3 to identify underperforming facilities falling below the diagonal and apply targeted interventions accordingly. This approach ensures that strategies are data-driven and context-responsive.

Targeted, cluster-based interventions can also help prioritise resources where they are most needed, depending on whether a facility is experiencing congestion, inefficiency or underuse.

Strengthen governance and stakeholder collaboration

The current division of roles between ProRail (infrastructure), NS Stations (operations) and municipalities (enforcement and removal) leads to fragmented management, resulting in delayed interventions and blind spots. Strong governance is essential to ensure shared responsibility for performance across organisations and enable a faster response to operational problems, such as abandoned bicycles. It also supports more flexible interventions, such as dynamic pricing or adjusted time limits, based on shared data insights. In order to align operational responses and strategic planning, a common data framework, regular coordination between stakeholders are required. Staff working in guarded facilities can provide invaluable insights into real-time user behaviour, misuse and emerging trends. Their input could be helpful in identifying the underlying causes of changes in usage patterns, for example, and this information could be incorporated into evaluations and plans to help the facilities adapt to these changes.

Design new facilities based on context, not just user volume

Currently, the design framework often determines the type of facility (e.g. capacity and guarded vs. unguarded) based primarily on expected user numbers. While this approach is useful, it can be overly rigid and risk overlooking important contextual factors, such as

spatial constraints, station function (access vs egress), user type (commuter vs leisure) and surrounding informal parking dynamics. For new facilities, a more context-sensitive design approach is recommended to support the efficient use of space, enhance the user experience, and make the facility resilient to growing demand.

7.3.2. Limitations and Recommendations for Future Research

Data limitations

A first limitation concerns the dataset, particularly in relation to subscription users. Incomplete check-in and check-out records for these users may introduce bias into the analysis of usage patterns and facility turnover. Qualitative findings suggest that subscription users tend to park for longer periods. As a result, facilities with a high proportion of these users may even have higher parking pressure relative to turnover. While technical improvements in the integration of bike lanes are being implemented and are expected to improve data quality, the current findings should be interpreted with caution. Future research could investigate the impact of these system improvements through a case study, comparing usage patterns before and after integration to quantitatively assess the behaviour of subscription holders.

A second limitation is the exclusion free, guarded bicycle parking facilities. This study focused exclusively paid facilities, which limits the generalisability of the findings to the wider range of station parking types. Pricing, as shown by Molin and Maat (2015) and Arbis et al. (2016), has a significant impact on user behaviour. Although this study distinguished between fully paid and 'first 24 hours free' facilities, the distinction proved to be statistically insignificant, likely due to the declining prevalence of this pricing model, as it no longer aligns with NS's current vision for bicycle parking at railway stations. Nevertheless, qualitative evidence suggests that users of free facilities may feel less personal responsibility for their bicycles, potentially leading to higher rates of long-term parking or abandoned bikes. These dynamics could pose various operational challenges. With the implementation of a reliable tracking system, such behavioural assumptions could be quantitatively tested in future research, providing a valuable extension to this study.

Quantitative Research

Another limitation concerns the method used to estimate the volume of use based on parking actions. In order to reduce noise, parking events of less than five minutes were excluded from the analysis, as the nature of these actions was not known and it was assumed that they could represent inauthentic or erroneous behaviour. However, this approach runs the risk of filtering out legitimate behaviour, such as overriding check-in data, which the qualitative research suggested may be the case. Conversely, not all implausible actions are filtered out, some five-minute parking actions, for example, may still represent system noise or unrealistic behaviour. These issues complicate the interpretation of turnover rates and overall system efficiency. In addition, informal or unregistered parking, could lead to inaccuracies in the estimation of actual facility use. Further research is needed to better understand the nature of short parking actions, including its frequency, causes and operational implications, in order to develop more accurate filtering criteria and improve the robustness of occupancy estimates.

A degree of subjectivity was introduced in the clustering analysis, as the number of clusters was not selected solely based on the highest silhouette score, which is a common metric for evaluating cluster validity. Instead, a compromise was made between statistical performance and the interpretability of the resulting clusters, prioritising practical relevance and the ability to derive meaningful insights for policy and operations. While this approach enhances the applicability of the findings, it also introduces a model selection bias. The decision to prioritise interpretability over strict statistical optimisation may influence the generalisability and reproducibility of the clustering results. This subjectivity limits the methodological transparency of the study and suggests that alternative clustering solutions could potentially yield different insights. Future research may benefit

from exploring multiple clustering validation techniques to assess the robustness of the identified patterns.

Broader contextual factors, such as enforcement practices within and around the facility and the ease of access to the station from the parking location, could not be systematically included in the analysis. Elements such as the frequency and consistency of enforcement actions are known to have a significant impact on turnover rates and overall facility efficiency. Similarly, the physical and perceived accessibility of a facility can influence user behaviour. The absence of these variables means that the operational context captured in this study remains partial. As a result, the findings may not fully reflect the influence of external conditions that interact with facility performance. Future research should aim to integrate more of these contextual dimensions to provide a more comprehensive understanding of the dynamics of station bicycle parking.

Qualitative Research

On the qualitative side, the interview sample may be subject to selection bias, as participants were facility staff who have a direct stake in the performance and public perception of bicycle parking services. As they are responsible for day-to-day operations, their responses may reflect a more positive or operational perspective. This limits the extent to which the qualitative findings capture the full range of operational (in)efficiencies.

In addition, as discussed in the implications section, the role of shared mobility in bicycle parking facilities at railway stations requires further investigation. In particular, the increasing use of shared bicycles, such as PT-bikes, may reduce the prevalence of 'second' bikes left at destinations, potentially increasing the overall efficiency of the facility. However, this study excluded the use of shared bicycles from the analysis, so the clustering results primarily reflect private bicycle behaviour. Future research should explicitly consider shared mobility patterns to better understand their impact on parking demand, turnover and spatial pressure at stations.

References

- Aghabozorgi, S., Seyed Shirkhorshidi, A., & Ying Wah, T. (2015). Time-series clustering – A decade review. *Information Systems*, 53, 16–38. <https://doi.org/10.1016/j.is.2015.04.007>
- Arbis, D., Rashidi, T. H., Dixit, V. V., & Vandebona, U. (2016). Analysis and planning of bicycle parking for public transport stations. *International Journal of Sustainable Transportation*, 10(6), 495–504. <https://doi.org/10.1080/15568318.2015.1010668>
- Arendsen, K., Faber, R., Francke, J., Haas, M. d., Hamersma, M., Horst, M. v. d., Huang, B., Jonkeren, O., Jorritsma, P., Knoope, M., Kolkowski, L., Krabbeborg, L., Moorman, S., Romijn, G., Visser, J., Wüst, H., & Zijlstra, T. (2023, November). *Kennisinstituut voor Mobiliteitsbeleid | Mobiliteitsbeeld 2023* (tech. rep.). Den Haag.
- Barneveld, A. (2022). *Cyclists Station Choice: Investigating railway station choice for cyclists including perceived social safety and comfort factors* [Doctoral dissertation, Delft University of Technology].
- Blondel Arthur Mensch Jean-Philippe, M. (2021). *Differentiable Divergences Between Time Series* (tech. rep.).
- Broer, K. (2016, June). Buitenmodelfietsen: een flinke groep in de stationsstalling. <https://www.fietsberaad.nl/Kennisbank/Buitenmodelfietsen-een-flinke-groep-in-de-stations>
- Cools, M., Moons, E., Creemers, L., & Wets, G. (2010). Changes in Travel Behavior in Response to Weather Conditions. *Transportation Research Record: Journal of the Transportation Research Board*, 2157(1), 22–28. <https://doi.org/10.3141/2157-03>
- Cuturi, M., & Blondel, M. (2018). Soft-DTW: a Differentiable Loss Function for Time-Series. *Cornell University*.
- Fukuda, D., & Morichi, S. (2007). Incorporating aggregate behavior in an individual's discrete choice: An application to analyzing illegal bicycle parking behavior. *Transportation Research Part A: Policy and Practice*, 41(4), 313–325. <https://doi.org/10.1016/j.tra.2006.09.001>
- Gavriilidou, A., Pardini Susacasa, L., Reddy, N., & Daamen, W. (2020). Bicycle Parking Choice Behaviour at Train Stations. A Case Study in Delft, the Netherlands. https://doi.org/10.1007/978-3-030-55973-1_{ }59
- Gemeente Maastricht. (2020). *Actieplan Fietsparkeren Maastricht 2020-2025* (tech. rep.). <https://www.maastrichtbeleid.nl/beleidsinformatie/Beleidsinformatie/2020/Actieplan%20Fietsparkeren%20in%20Maastricht/Actieplan%20Fietsparkeren%20in%20Maastricht.pdf>
- Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *British Dental Journal*, 204(6), 291–295. <https://doi.org/10.1038/bdj.2008.192>
- Google. (2023, May). Google Maps Streetview Parking Facility Vaartsche Rijn. <https://www.google.com/maps>
- Handy, S., van Wee, B., & Kroesen, M. (2014). Promoting Cycling for Transport: Research Needs and Challenges. *Transport Reviews*, 34(1), 4–24. <https://doi.org/10.1080/01441647.2013.860204>
- Harvey, L. (2024). Efficiency. <http://www.qualityresearchinternational.com/glossary/>

- Heinen, E., & Buehler, R. (2019). Bicycle parking: a systematic review of scientific literature on parking behaviour, parking preferences, and their influence on cycling and travel behaviour. *Transport Reviews*, 39(5), 630–656. <https://doi.org/10.1080/01441647.2019.1590477>
- Honey-Rosés, J., Ortega, V., Dejaegher, S., & Corbera, E. (2023). Bicycle Parking Use Patterns, Occupancy and Rotation Rates in the Streets of Barcelona. *Active Travel Studies*, 3(2). <https://doi.org/10.16997/ats.1392>
- Hoskam, S. J. M. (2020, June). *The willingness to pay of various types of bike parking-users at train stations for different types of facilities and stations* [Doctoral dissertation]. https://repository.tudelft.nl/file/File_469fd6d3-27c9-42c5-89b9-de436c3fd6f5?preview=1
- Islam, Q. (2023, January). Threshold silhouette score for cluster analysis.
- Januzaj, Y., Beqiri, E., & Luma, A. (2023). Determining the Optimal Number of Clusters using Silhouette Score as a Data Mining Technique. *International Journal of Online and Biomedical Engineering (iJOE)*, 19(04), 174–182. <https://doi.org/10.3991/ijoe.v19i04.37059>
- Jonkeren, O., Harms, L., Jorritsma, P., Huibregtse, O., & Bakker, P. (2018, July). *Kennisinstituut voor Mobiliteitsbeleid | Waar zouden we zijn zonder de fiets en de trein?* (Tech. rep.). Ministry of Infrastructure and Water Management.
- Jonkeren, O., & Kager, R. (2021). Bicycle parking at train stations in the Netherlands: Travellers' behaviour and policy options. *Research in Transportation Business & Management*, 40, 100581. <https://doi.org/10.1016/j.rtbm.2020.100581>
- Jonkeren, O., Kager, R., Harms, L., & Brömmelstroet, M. t. (2021). The bicycle-train travellers in the Netherlands: personal profiles and travel choices. *Transportation*, 48(1), 455–476. <https://doi.org/10.1007/s11116-019-10061-3>
- Jorink, S., David, J., & Duijnisveld, M. (2022, December). *Fietsenstalling van de toekomst* (tech. rep.). Movares Nederland B.V.
- Jorritsma, P., Witte, J.-J., Alonso González, M. J., & Hamersma, M. (2021, October). *Kennisinstituut voor Mobiliteitsbeleid | Deelauto- en deelfietsmobiliteit in Nederland* (tech. rep.).
- Kager, R., Bertolini, L., & Te Brömmelstroet, M. (2016). Characterisation of and reflections on the synergy of bicycles and public transport. *Transportation Research Part A: Policy and Practice*, 85, 208–219. <https://doi.org/10.1016/j.tra.2016.01.015>
- Kallio, H., Pietilä, A.-M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, 72(12), 2954–2965. <https://doi.org/10.1111/jan.13031>
- Kate, R. J. (2016). Using dynamic time warping distances as features for improved time series classification. *Data Mining and Knowledge Discovery*, 30(2), 283–312. <https://doi.org/10.1007/s10618-015-0418-x>
- Kobylin, O., & Lyashenko, V. (2020). Time Series Clustering Based on the K-Means Algorithm. *Journal La Multiapp*, 1(3), 1–7. <https://doi.org/10.37899/journallamultiapp.v1i3.191>
- Laake, P., & Fagerland, M. W. (2015). Statistical Inference. In *Research in medical and biological sciences* (pp. 379–430). Elsevier. <https://doi.org/10.1016/B978-0-12-799943-2.00011-2>
- Lamkey, K. (2023). Quantitative Methods for Plant Breeding. In W. Suza (Ed.), *Chapter 8: The analysis of variance (anova)*. Iowa State University Digital Press. <https://doi.org/10.31274/isudp.2023.145>
- Martens, K. (2007). Promoting bike-and-ride: The Dutch experience. *Transportation Research Part A: Policy and Practice*, 41(4), 326–338. <https://doi.org/10.1016/j.tra.2006.09.010>

- Ministry of Infrastructure and Water Management. (2025). *Concessie voor het Hoofdrailnet* (tech. rep.). <https://open.overheid.nl/documenten/dpc-365c3ea388f96beeff9723733902db8c526d3a81/pdf>
- Molin, E., & Maat, K. (2015). Bicycle parking demand at railway stations: Capturing price-walking trade offs. *Research in Transportation Economics*, 53, 3–12. <https://doi.org/10.1016/j.retrec.2015.10.014>
- Movares. (2021, December). *Inzicht in fietsparkeren Casus Stationsplein Utrecht* (tech. rep.).
- NS. (2013). *De eerst dag voor niets een plek voor je fiets*.
- NS. (2021, August). Algemene voorwaarden jaarabonnement fietsenstalling.
- NS. (2022). Tarieven. https://www.ns.nl/binaries/_ht_1645695595702/content/assets/ns-nl/tarieven/2022/tarieven-2022-ns-fietsenstallingen.pdf
- NS. (2025). *Fietssoorten in de fietsenstalling* (tech. rep.).
- Paix Puello, L. I., & Geurs, K. (2014). Integration of unobserved effects to improve transport impedances of cycling to railway stations. https://www.researchgate.net/publication/273567204_INTEGRATION_OF_UNOBSERVED_EFFECTS_TO_IMPROVE_TRANSPORT_IMPEDANCES_OF_CYCLING_TO_RAILWAY_STATIONS#fullTextFileContent
- ProRail. (2021, June). *Ontwerpvoorschrift: Bouw en ombouw fietsenstallingen bij stations* (tech. rep.).
- ProRail. (2024, February). Fietsparkeren bij stations. <https://www.prorail.nl/reizen/stations/fietsen>
- Pucher, J., & Buehler, R. (2008). Making Cycling Irresistible: Lessons from The Netherlands, Denmark and Germany. *Transport Reviews*, 28(4), 495–528. <https://doi.org/10.1080/01441640701806612>
- PwC. (2020, January). *De kosten van beheer, onderhoud, exploitatie en handhaving van fietsenstallingen bij stations* (tech. rep.). Amsterdam. https://fietsberaad.nl/g etattachment/5a0d36df-4467-4b4f-b4a8-4bfb9516b5c9/ProRail_Rapportage-Fietsparkeren.pdf.aspx?lang=nl-NL&ext=.pdf
- Rahimi, S., & khatooni, M. (2024). Saturation in qualitative research: An evolutionary concept analysis. *International Journal of Nursing Studies Advances*, 6, 100174. <https://doi.org/10.1016/j.ijnsa.2024.100174>
- Rijksoverheid. (n.d.). Duurzaam openbaar vervoer. <https://www.rijksoverheid.nl/onderwerpen/openbaar-vervoer/duurzaam-openbaar-vervoer>
- Rijkswaterstaat. (n.d.). Factsheet: Fietsparkeren. <https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/werkwijzen/werkwijze-in-gww/communicatie-bij-werkzaamheden/werkwijzer-hinderaanpak/toolbox-slim-reizen/factsheet-fietsparkeren>
- Rousseeuw, P. J. (1987). Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, 20, 53–65. [https://doi.org/10.1016/0377-0427\(87\)90125-7](https://doi.org/10.1016/0377-0427(87)90125-7)
- Schakenbos, R., & Ton, D. (2023). Is de fiets-treincombinatie wel de passende oplossing voor de toekomst?
- Shelat, S., Huisman, R., & van Oort, N. (2018). Analysing the trip and user characteristics of the combined bicycle and transit mode. *Research in Transportation Economics*, 69, 68–76. <https://doi.org/10.1016/j.retrec.2018.07.017>
- Tallarida, R. J., & Murray, R. B. (1987). Chi-Square Test. In *Manual of pharmacologic calculations* (pp. 140–142). Springer New York. https://doi.org/10.1007/978-1-4612-4974-0_{ }43
- Ton, D., & van den Heuvel, J. (2023). Trends in access and egress transportation to and from train stations in The Netherlands. *European Transport Conference 202*.

- van Boggelen, O. (2024). *PvE Fietsparkeertellingen ProRail* (tech. rep.).
- van Mil, J. F. P., Leferink, T. S., Annema, J. A., & van Oort, N. (2021). Insights into factors affecting the combined bicycle-transit mode. *Public Transport*, 13(3), 649–673. <https://doi.org/10.1007/s12469-020-00240-2>
- van der Spek, S. C., & Scheltema, N. (2015). The importance of bicycle parking management. *Research in Transportation Business & Management*, 15, 39–49. <https://doi.org/10.1016/j.rtbm.2015.03.001>
- Ylikoski, P. (2021). Understanding the Coleman boat. *Research Handbook on Analytical Sociology, edited*, 49–63.
- Zimmermann, K., & Palgan, Y. V. (2024). Upscaling cargo bike sharing in cities: A comparative case study. *Journal of Cleaner Production*, 477, 143774. <https://doi.org/10.1016/j.jclepro.2024.143774>
- Zuo, T., Wei, H., Chen, N., & Zhang, C. (2020). First-and-last mile solution via bicycling to improving transit accessibility and advancing transportation equity. *Cities*, 99, 102614. <https://doi.org/10.1016/j.cities.2020.102614>



Summaries Interviews

A.1. Thematic Summary of Bicycle Parking Interviews

This section provides an integrated analysis of the interviews, highlighting the most mentioned and common themes related to the management, usage, user behaviour, and future prospects of bicycle parking facilities.

1. Role in Bicycle Parking Facilities

- All respondents emphasize a role in ensuring that the facility functions smoothly on different levels. This includes responsibilities such as opening/closing the facility, performing security checks, and maintaining general upkeep. Staff members and managers interact directly with users by greeting and assisting them, answering questions, and enforcing parking rules (e.g., proper placement and labelling of wrong parked bicycles). Managers are involved in scheduling (rosters and hour tracking), monitoring occupancy, and coordinating with external partners such as municipalities and ProRail, ensuring policy compliance.

2. Facility Usage

(a) Layout of the Facility:

- **Design and Space Allocation:** Most facilities feature a fixed layout. However, the increasing prevalence of non-standard bicycles (e.g., cargo bikes, bikes with child seats, fat bikes) stresses the system. Oversized bikes are expected to be parked in upper racks, but many users find this challenging due to physical limitations.
- **Signage and Clarity:** Several interviews note that clear signage (for example, designated areas for oversized bikes) is essential to guide proper parking but is not always adequate.

(b) Enforcement by the Municipality:

- **Labelling and Removal Procedures:** A common practice is to label bikes that are wrongly parked or have been parked too long (often around 28 days). In some facilities, chalk-marking is used to track long-term parking, while in others a systematic (although sometimes unreliable) tracking (HBF) system is employed.
- **Variability and Coordination:** The degree and method of enforcement vary by location. Some sites experience discrepancies in the removal process, occasionally resulting in wrongful removals due to system inaccuracies.

(c) Procedures for a Full Facility:

- **Redirection:** Many facilities, when nearing capacity (especially in areas designated for non-standard bikes), redirect users to nearby facilities. In some cases, space is reserved for subscription holders or allocated to different levels within the facility.

- **Perceived Clutter:** Even if space is available, the presence of numerous labels and wrongly parked bikes gives an untidy impression, which staff work to mitigate.

(d) **Differences Between Facility Types:**

- **Staffed vs. Self-Service vs. Automated:** Interviewees generally report that staffed facilities (with personal interaction) tend to have better rule compliance, while self-service and bike lane systems (often using scanners) may offer faster throughput but can lead to misuse or technical issues.
- **Paid versus Free Systems:** Some locations differentiate between paid and free parking areas. In several cases, paid facilities are associated with higher compliance and a greater sense of security, whereas free facilities sometimes experience higher rates of abandoned bikes.

(e) **Fluctuating Usage Patterns:**

- **Temporal Variations:** Usage peaks during morning and afternoon rush hours, typically reflecting commuter patterns. Weekdays are dominated by daily commuting while weekends see a different mix of users (e.g., leisure, event-driven traffic).
- **Impact of External Events:** Festivals, public events, and even football matches (e.g., when people travel to stadiums) significantly affect occupancy and user behaviour.

(f) **Different Types of Bicycles:**

- **Increased Variety:** There is a clear trend towards an increasing variety of bicycle models—especially non-standard bikes—which often do not fit the traditional rack design.
- **Limited Adaptability:** Facilities struggle to quickly adapt to these evolving demands, leading to issues such as overcrowded areas designated for oversized bikes.

(g) **Impact of Surrounding Environment:**

- **Context-Specific Usage:** Usage patterns are also influenced by the immediate surroundings, such as proximity to city centres, train stations, or event venues, which can either increase convenience or lead to congestion.

3. Users of Bicycle Parking Facilities

(a) **User Feedback and Needs:**

- **Amenities:** Users across facilities have expressed a need for additional features such as air pumps, restrooms, and alternative check-in methods (e.g., bank card versus OV-chipkaart (corresponding with train tickets)).
- **Facility Preferences:** There is high demand for secure parking, which is reflected in the preference of some users for paid facilities where users feel their bicycle is safer.
- **Non-standard Bikes:** A common request is for more space allocated to non-standard bicycles, including cargo bikes, e-bikes with wide tires, and bikes with child seats.

(b) **Abandoned Bicycles:**

- **Differences Among User Groups:** Abandoned bikes are more common in free parking areas. Subscription holders tend to adhere more closely to facility rules, while casual users are more likely to leave bikes unattended.

(c) **Subscriptions:**

- **Usage Patterns:** Subscription holders often use the facility daily, for multiple-day storage and sometimes for second bicycles.
- **Behaviour:** These users are generally more familiar with and compliant with facility procedures.

4. Future of Bicycle Parking Facilities

- **Technological Integration:** Future developments will likely include increased automation and digital systems (e.g., real-time display of available spots, app-based check-in/out), while retaining a human presence for enhanced user support.
- **Adaptability to Evolving Demands:** Facilities must evolve to accommodate larger and more diverse bicycle models, ensuring that innovations in rack design and layout keep pace with the market.
- **Enhanced User Experience:** Overall, there is an expectation that future systems will be more user-friendly and secure, balancing the need for efficiency with accessibility for all user groups, including those who may require assistance.

A.2. Individual Interviews

A.2.1. District Manager Region Utrecht

Facilities (with regime): *Bilthoven, Maarssen, Woerden, Utrecht Centraal Stationsplein, Utrecht Centraal Jaarbeursplein, Utrecht Centraal Knoop, Utrecht Central Sijpesteijn, Utrecht Overvecht-fietsenstalling, Utrecht Vaartsche Rijn Oosterkade, Utrecht Vaartsche Rijn Westerkade*

1. Role in bicycle parking facilities

- Responsible for all services at railway stations in the Utrecht region, except train operations. Oversees bicycle parking operations but works in collaboration with municipalities (facility owners), ProRail (rack owners), and NS (service providers).

2. Facility usage

The occupancy of the check in check out patterns from different locations align in general terms with real-world observations, but gaps remain, especially in tracking users who do not check in/out, subscriptions.

(a) Layout of the facility

- There are relatively few spots for non-standard bicycles, despite an increase in their use.
- At facilities where the overview for the staff lacks some users do not check in, affecting data accuracy. At Utrecht Stationsplein, a cycle path within the facility reduces visibility of users checking in.

(b) Enforcement by municipality

- The parking duration of bicycles is tracked by HBF if available or labelled manually to track their parking duration. After 28 days, they are classified as abandoned and should be moved to a depot by the municipality.
- In reality in Utrecht a backlog exists in removing abandoned bicycles, and because the removal does not use a first-in, first-out removal system and there are more abandoned bikes added therefore some bicycles are parked way longer than the maximum parking time. This backlog is partly because of depot overcrowding in Utrecht.

(c) Procedures full facility

- The closing of Utrecht Jaarbeurs has big impact on the occupancy of the Stationsplein-facility. If a facility reaches full capacity and safety is compromised, a floor may be closed with for example barrier tape.

(d) Layout of the racks

- Upper racks are less frequently used, making perceived occupancy higher than actual capacity since for some users the upper racks are not accessible.

(e) Differences self-service, scanner or staffed

- Bicycle lanes integrated into parking facilities improve data reliability by leading all users through a check-in point.

(f) Fluctuating usage

- Traveller flow patterns heavily influence parking facility usage, underscoring the need for strategic space allocation. E.g. Sijpesteijn is a crowded facility and Knoop a relatively empty one, although they are at the same station and close together people are not changing their habits.

(g) Different types of bikes

- Non-standard bicycles require dedicated space, which is currently insufficient. Limited space for non-standard bikes in for example a self service facility, this leads to congestion between standard racks (e.g. Bilthoven).
- There are too little spots for cargo bikes (rejecting them happens often) and not in every facility it is possible to park them. Users tend to avoid facilities without designated spots because they know they are rejected, skewing demand assessment.
- A pilot project in Knoop station added spaces for cargo bikes, but demand is lower than it was at Sijpesteijn (closed for maintenance) when that facility was still open.

(h) Impact surrounding of facility

- The facilities (e.g. shops, offices or entertainment) in the surrounding definitely impact the parking facilities. In Utrecht there are agreements with the municipality and contribute to the facility.
- At the facility Utrecht Vaartsche Rijn, the surrounding of the station is full with bikes while the parking facilities are not completely filled (example seen in figure A.1).



Figure A.1: Example of surrounding bicycle parking facility Vaartsche Rijn (Google, 2023)

3. Users

The parking officers probably have a better view on the users they see everyday.

(a) User feedback and needs

- The majority of users are commuters. In Utrecht Centraal, OV rental bikes are in high demand, particularly on Tuesdays and Thursdays, allowing temporary use of these spaces for non-standard bikes until 16:00.

(b) Abandoned bikes

- Many bicycles remain parked beyond 28 days, often without being retrieved even after being moved to a depot. The bikes vary from less expensive, but also expensive are abandoned.

(c) Subscriptions

- Due to the lack of check-in/check-out data of subscription holders, it is difficult to track how many subscription holders actively use their spaces.

4. Future of bicycle parking facilities

- Bicycle parking will play a crucial role in sustainability efforts.
- Capacity planning often lags behind demand, particularly for non-standard bikes. In the future there are improvements possible to better match demand and supply.
- Data-driven solutions could optimize space usage, allowing for better allocation on high-demand days.

A.2.2. District Manager Region Randstad Zuid

Facilities (with regime): *Alphen aan den Rijn, Barendrecht, Den Haag CS Stichthage, Den Haag Holland Spoor, Dordrecht, Gouda, Gouda Zuidzijde, Leiden Centraal LUMC, Rijswijk, Rotterdam Centraal, Schiedam-fietsenstalling, Voorburg, Zwijndrecht*

1. Role in bicycle parking facilities

- District Manager Randstad South, responsible for car parking, luggage lockers, toilets, bicycle parking, OV-bicycles, and bike & service facilities. Oversees teams, safety, KPIs, budgets, and coordination with municipalities and ProRail to ensure bicycle parking functions well.

2. Facility usage

- Together with ProRail and the municipality, the goal is to encourage bike use for station access. Improving the station area's liveability by attracting bikes into the parking facilities through co-financing has proven effective, reducing street clutter and making cycling to the station more appealing. The success of the facilities is that a lot of people want to park their bikes there, it is up to us (NS, ProRail, municipality) to create enough capacity.
- Facilities vary a lot since they have their own surrounding and context.
- The usage of the facilities shows recognizable patterns in general but does not fully capture real-life parking dynamics.

(a) Layout of the facility

- Bicycle parking has some concepts. The bigger facilities are staffed, the smaller ones are self-service, based on the number of passengers entering and leaving that station.
- The parking layout is fixed, but bicycle models evolve quickly, the existing racks incompatible with the many of the non-standard bicycles nowadays.

(b) Enforcement by municipality

- Enforcement by municipality varies by location. E.g. In Delft twice a week, 50-75 bikes are removed, based on chalk marks because the HBF system is outdated in that facility.

(c) Procedures full facility

- Different handling per facility, for example Gouda has single entrance, easy to close and refer to the other facility at the station when full. While Delft has open design with passing bicycle path which prevents closures.

(d) Layout of the racks

- Parking areas for non-standard bikes in crowded facilities often become so overcrowded that bikes are at risk of damage, making them less desirable.

(e) Differences self-service, scanner or staffed

- In staffed facilities, users follow parking rules more closely. In self-service facilities, users often park bikes improperly and also more little, due to a lack of surveillance. self-service facilities have on occasional staff visits to rearrange bikes and remove waste.
- Also differences between regimes. Commuters heavily use the first 24-hour free option, while paid parking sees much lower usage (e.g., Rotterdam and The Hague Central). In free parking areas like Delft, people feel less responsible for their bikes. When payment is required, they feel more accountable. Free racks tend to have more abandoned bikes. Ideally, an in-and-out check system would help.

(f) Fluctuating usage

- Depends on the users of the facility. In student cities you see high demand in September due to new students. Which decreases after a couple of months. And for example Delft is very crowded during the weekends because of the different needs of students there compared to commuters. While for example Gouda has the peak during the week.

(g) Different types of bikes

- The increasing variety of bikes (cargo bikes, e-bikes) does not match the available infrastructure. Non-standard bikes often do not fit, leading for example in a self-service facilities to illegal parking in aisles or near emergency exits.
- Newer racks for larger bikes exist, but they take up more space, reducing total parking spots. In tension with ProRail since the ministry requires them to supply a minimum number of spots, making it difficult to replace standard racks with more non-standard bike spaces.

(h) Impact surrounding of facility

- Differs per location and depends on the context of and facilities in surrounding area. In Rotterdam, a small paid subsection contrasts with a large free municipal area, where most bikes are parked, while pricier ones tend to be in the NS subsection.

3. Users of bicycle parking facilities

(a) User feedback and needs

- Main group is commuters. Other important group students. Municipalities want to keep the parking also attractive for students to avoid street clutter.

(b) Abandoned bikes

- Free facilities see more abandoned bikes because users feel less responsible for their bicycles.

(c) Subscriptions

- Two main types of subscription users, those who want a guaranteed spot and those leaving their bike for multiple days.

4. Future of bicycle parking facilities

- In future capacity there are challenges. The three facilities in Delft are full, and demand continues to rise. Shared bikes could be a solution as many users park a second bike at their destination station. So shared bikes could replace those 'second' bikes.
- Bicycle parking facilities adapt too slowly to changing needs. Need for adjusting facility layouts to match real demand of the moment.

Location specific other findings:

- Dordrecht: Leakage over entry gates caused malfunctions, leading to prolonged open access.
- Alphen aan den Rijn: Increased demand after switching to a first 24h free model.
- Den Haag: KJ parking facility closed due to high-rise construction leading to heavy pressure on Stichthage facility.
- Gouda: Zuidzijde has self-service facilities, first 24h free, while Gouda is staffed facility and paid from the start, leading to low usage. Now considering switching to 24h free to increase use.

A.2.3. Unit Lead, Utrecht**1. Role in bicycle parking facilities**

- Manages multiple facilities, overseeing monitoring, maintenance, and rule enforcement.
- Works with municipalities to ensure smooth coordination.
- Unit lead and location manager for multiple facilities: Vaartsche Rijn Oosterkade, Knoop, Jaarbeursplein, Seipestein, and several self-service (self-service facilities) facilities including Maarssen, Woerden, Bilthoven, Overvecht, and Vaartsche Rijn Westerkade.

2. Facility usage

(a) Layout of the facility

- Racks for non-standard bicycles significantly reduce total parking capacity.
- Several solutions exist for oversized bicycles, such as designated areas at the sides of the facility with proper signage.
- If oversized bicycles are incorrectly parked, they are labelled and relocated, especially if they obstruct emergency equipment such as fire extinguishers.

(b) Enforcement by municipality

- Bicycles are labelled if left for 28 days, monitored, and subsequently removed by the municipality.

(c) Procedures full facility

- Full capacity situations are rare.
- Users are redirected to alternative parking locations.
- If one level of a facility is full, users are directed to another level while ensuring that subscription holders retain their designated spots.

(d) Layout of the racks

- The organisation of racks varies significantly between different facilities.
- The bicycle counting systems (HBF) do not always function correctly, sometimes incorrectly displaying available spots, which frustrates users.

(e) Differences self-service, scanner or staffed

- Facilities with bikelanes allow faster entry and exit.
- Harder to forget the check in. If a user forgets to check in, they are asked whether they parked for more than 24 hours. If longer than 24 hours, they are asked to pay.

(f) Fluctuating usage

- Peak hours align with train travel patterns: 7:30–10:30 AM and 4:30–7:30 PM.
- Thursday, Friday, and Saturday evenings also see high usage due to city visitors and students.

(g) Different types of bikes

- Non-standard bikes struggle to fit into standard racks, leading to improper parking if the non-standards bicycle parking spots are full.

(h) Impact surrounding of facility

- The surrounding environment, including events and proximity to city centers, influences facility usage patterns.

3. Use of the Bicycle Parking Facility

(a) User feedback and needs

- Currently, check-in and check-out are only possible with an OV chip card, but users express the need for bank card check-ins, similar to the train system.
- More designated spaces are needed for bicycles with child seats and crates (non-standard bicycles).
- Demand for electric bike charging stations is growing.

(b) Abandoned bikes

- Long-term parking happens especially during vacations. They are often held a bit longer than the 28 days in the facility, but after that period they are collected by the municipality.

(c) Subscription holders

- Subscription holders do not need to check in, making their parking process faster.
- The facilities want to guarantee spots to subscription holders so leave some empty spots.
- Some users with subscriptions leave their bikes for extended periods, including vacations, sometimes exceeding the 28-day limit, assuming they can park indefinitely.

4. Future of Bicycle Parking Facilities

- Bicycle parking facilities are undergoing increased automation. Despite automation, many users still value the presence of staff and express a need for human interaction.

A.2.4. Staff Member 1, Utrecht

1. Role in bicycle parking facilities

- Responsible for opening the facility, security checks, assisting customers, enforcing parking rules, relocating improperly parked bikes, and general upkeep.
- Ensuring that bicycles are parked correctly and that emergency exits remain unobstructed.
- Handling customer questions and providing guidance on parking procedures.

2. Facility usage

(a) Layout of the facility

- Layout differs per location
- Some customers park at the incorrect location of due to being in a hurry.
- Staff relocate bikes to the correct locations, attaching a label explaining the reason for the move.

(b) Enforcement by municipality

- Bicycles with labels due to parking longer than 28 days are removed by the municipality in collaboration with the unit manager.
- The current tracking system (HBF) system does not function optimally for the removal of abandoned bicycles. Dust and bike tyres are checked and sometimes chalk is used to mark the tyres.

(c) Procedures full facility

- When full, users are redirected to nearby bicycle parking facilities.

(d) Layout of the racks

- The availability of spots for non-standard bikes varies per facility. Non-standard bicycles take up extra space, if dedicated spots are full asked to put in upper racks.

(e) Differences self-service, scanner or staffed

- The bike lane system uses automatic check-in and check-out via a tag resulting in faster check-in and check-out.

(f) Fluctuating usage

- Peak usage corresponds with train schedules, busiest in the morning and late afternoon. Tuesdays and Thursdays are the busiest days.

(g) Different types of bikes

- Increasing amount on non-standard bikes

(h) Impact surrounding of facility

- The facility is used not only by commuters but also by shoppers, city visitors, and travellers going on vacation.

3. Users

(a) User needs and feedback

- Customers request additional services such as air pumps, restrooms, rental bikes with child seats, and child seat rentals.
- Each customer has different needs, and experience helps staff handle these effectively.

(b) Abandoned bikes

- Labelled bicycles are removed after a certain period.

(c) Subscriptions

- Subscribers often do not live in the same city and leave their bicycles parked for multiple days.
- Subscription holders are not required to check in or out.

(d) Forgotten check-in

- According to facility rules, users must pay for forgotten check-ins, but in practice, this is often overlooked.

A.2.5. Staff Member 2, Utrecht

1. Role in bicycle parking facilities

- Manager and host of the bicycle parking facility.
- Assists users with parking-related inquiries, such as explaining the system and helping users fit their bikes into racks.

2. Facility usage

(a) Layout of the facility

- Each facility has a different layout.
- Insufficient space for cargo bikes (kratfietsen) relative to their increasing use.
- When no dedicated cargo bike spots are available, users are asked to park in the upper racks, though this is often not feasible due to the weight of the bicycles.
- Some users refuse to park in the designated facility (e.g., preferring Jaarbeurs over Knoop) and instead leave their bikes outside the racks.
- OV-fiets parking areas are frequently used for short-term parking by individuals visiting the municipal office from Jaarbeurs until rush hour begins.
- Users often choose the first available parking space they see, leading to congestion on lower levels while upper levels remain underutilized.

(b) Enforcement by municipality

- The tracking system (HBF) has a high margin of error.
- Staff assess abandoned bicycles based on HBF data, dust accumulation, and deflated tires before labeling them for removal.
- Abandoned bicycles are removed by the municipality after a waiting period to avoid mistakenly tagging active users.
- Subscription holders are treated with more leniency since they are likely to return, whereas non-paying users' abandoned bikes are removed more quickly.

(c) Procedures full facility

- Users often ignore "FULL" signs, requiring redirection to upper levels or different facilities.
- If only upper racks are available, users often struggle to lift heavier modern bicycles.
- Facility managers must limit lifting due to physical strain.

- 5% of spaces are reserved for subscription holders, leading to conflicts when non-subscribers see available spots and attempt to park.
- At Stationsplein, levels are sometimes subsectioned off to direct traffic to different areas. All users enter the facility at the floor for subscription holders, so users park in the subscription-only zones out of convenience or lack of awareness.

(d) Layout of the racks

- Upper racks are commonly used by cyclists with lightweight bikes or those unable to find a ground-level spot.
- Some bicycles do not fit in lower racks, leading to misuse of upper racks despite physical challenges in lifting.
- Some exploit the system by resetting their last check-in by briefly tapping their card upon entry.

(e) Differences self-service, scanner or staffed

- self-service facilities experience higher instances of theft and loitering, particularly in locations such as Maarssen.
- Poor signage leads to improper parking, such as normal bicycles occupying cargo bike spots.
- In Woerden, upper racks remain empty while bicycles are incorrectly parked near emergency exits.
- Bilthoven suffers from overcrowding, forcing users to park outside designated racks.
- Overvecht experiences significant issues with loitering, including discarded cigarette butts, nitrous oxide canisters, and cut locks.
- In facilities where front-row spaces are designated for oversized bicycles, regular bicycles are often parked there instead due to convenience.

(f) Different types of bikes

- Newer racks for large bikes exist but take up more space.

(g) Fluctuating usage patterns (weekly/daily)

- Tuesdays and Thursdays are the busiest days.
- Mondays are becoming increasingly crowded.

(h) Impact surrounding of facility

- Events at Jaarbeurs attract non-train travellers who often do not carry an OV-chipkaart.
- Temporary loan cards have been used to accommodate these users but are being phased out.
- The highest demand stems from commuting traffic.
- Knoop facility remains underutilized.

(i) Forgotten check-in

- Users sometimes attempt to bypass the check-in system.

3. Users

Most of the users are commuters going to their work.

(a) User feedback and needs

- Users express a need for electric bicycle charging stations, though fire safety concerns exist.
- Current check-in is only possible with an OV-chipkaart, leading to issues when users assume bank card check-ins (as with trains) are also valid.
- Loan cards temporarily address this issue but are sometimes unavailable.
- More cargo bike spaces are needed at Jaarbeurs, but users are reluctant to park at Knoop.

(b) Abandoned bikes

- Not explicitly discussed in this interview.

(c) Subscription

- Some subscribers leave their bikes for long periods.

4. Future of Bicycle Parking Facilities

- There is added value in maintaining staffed bicycle parking facilities rather than transitioning entirely to automated systems.
- Users appreciate staff presence, as it contributes to a sense of social safety, especially in stations.

Additional observations operation

- OV rental bikes are stored efficiently with pedals positioned at 6 and 12 o'clock. Upcoming smart locks in Utrecht may introduce challenges as bicycles will be locked in fixed positions.

A.2.6. Unit Lead, Rotterdam

1. Role in Bicycle Parking Facilities

- Unit leader and location manager responsible for staffing, scheduling, time tracking, and ensuring policy compliance within the facility.

2. Facility Usage

(a) *Layout of the facility*

- The number of non-standard (oversized) bicycles is increasing, and these are expected to be placed in upper racks.
- Due to their weight, users often do not comply. Bicycles that are incorrectly parked are labeled with the reason and date as a reminder or prompt for an explanation.
- User responses to this vary; some change their behavior, others do not.
- The goal is to maintain accessibility for all users, including those who cannot lift their bicycles.
- Usage patterns differ based on staff visibility—areas with more visibility show better compliance.
- Users choose to park in the paid NS facility over the adjacent free municipal facility for security and convenience.

(b) *Enforcement by municipality*

- Agreements exist with the municipality, but currently, there is no system in place for bike removal. A suitable solution is being developed.

(c) *Procedures for full facilities*

- The facility rarely reaches full capacity.
- While labeled bikes give an untidy impression, space remains available, including for regular users and subscription holders.

(d) *Layout of the racks*

- (Not explicitly detailed by the interviewee, but inferred context: Racks present issues for non-standard or heavy bikes, especially when only upper levels are available.)

(e) *Differences in self-service, scanner, or staffed systems*

- Staffed system in place, with hand scanners used for check-in/check-out.
- Also responsible for other self-service facilities in Barendrecht, Zwijndrecht, and Dordrecht.

- Behavioural differences are evident between locations: e.g., Dordrecht sees scooters parked inside (against regulations), Zwijndrecht had theft issues, while in Barendrecht, collaboration with a nearby bike repair shop creates a clean and secure environment.
- Bike lanes enable quicker access but reduce the personal service aspect.

(f) *Fluctuating usage patterns*

- Usage follows a weekly rhythm and is affected by weather, train service interruptions, and public holidays.

(g) *Different types of bicycles*

- Very limited space for cargo bikes (bakfietsen) and fat bikes, which do not fit into regular racks.
- These are redirected to municipal facilities when space permits, but priority is given to subscription holders.

(h) *Impact of surrounding environment*

- Festivals and other city events noticeably increase facility usage.

3. Users

(a) *User feedback and needs*

- The main weekday user group consists of commuters during peak hours.
- Weekend users typically visit for leisure or events.
- A common user request is for more parking space for oversized bicycles, including e-bikes with wide tires.

(b) *Abandoned bicycles*

- Rare for private users; more common among subscription holders, often with prior arrangement for long-term parking.
- Subscription users are generally well informed about facility rules and self-sufficient.
- Casual users are more likely to make mistakes or require assistance.

(c) *Subscriptions*

- A portion of subscription users utilize the facility for storing second bicycles, particularly for multi-modal commuting.

4. Future of Bicycle Parking Facilities

- Technology will play a larger role, including bikelane integration and real-time display of available parking spots.
- The trend of larger and more customized bicycles will continue, particularly in urban environments where they increasingly replace cars.

A.2.7. Staff Member 1, Rotterdam

1. Role in Bicycle Parking Facilities

- Service staff member responsible for observing all users entering and exiting the facility.
- Manages access for both subscription holders (who can walk through directly) and users who must check in/out.
- Handles the rental of OV-fietsen (public rental bicycles).

2. Facility Usage

(a) *Layout of the facility*

- A designated area for oversized bicycles is located at the entrance, but this space is insufficient for the variety and volume of non-standard bicycles.

- Due to time pressure or lack of clarity, users often park between or next to the racks, outside designated areas.

(b) *Enforcement by municipality*

- Rotterdam presents a unique case with an unstaffed municipal facility located next to a staffed NS facility.
- In the municipal facility, bicycles are labeled on day 13 based on the HBF system and removed on day 14.
- Due to inaccuracies in the system, bicycles are sometimes wrongly removed.
- In the NS facility, bicycles may remain for 28 days. Once a month, bikes are marked with chalk; if a bicycle receives two chalk marks, it is moved to the rear and later removed—resulting in actual stay durations often exceeding the official 28 days.

(c) *Procedures for full facilities*

- The facility generally does not reach full capacity, except for the section dedicated to oversized bicycles.
- When this section is full, users are directed to the adjacent public facility if space is available.

(d) *Layout of the racks*

- Many users avoid using the upper racks due to the effort required, especially with electric or cargo bikes that often do not fit in lower racks.
- Encouraging users with lightweight bicycles to use upper racks could improve overall utilization.
- Some users intentionally use upper racks to avoid potential damage to their bicycles.

(e) *Differences in self-service, scanner, or staffed systems*

- The facility uses handheld scanners. Users occasionally forget to check out and are charged accordingly.
- In most cases, conflict is avoided, and users are informed about the charge and reminded for next time.

(f) *Fluctuating usage patterns*

- Weekdays primarily attract daily commuters who interact minimally.
- Weekends bring a different user group with more time and questions, leading to more interaction with staff.

(g) *Different types of bicycles*

- Demand for space in the staffed facility exceeds supply.
- Cargo bikes are frequently parked haphazardly in the public facility.
- Despite higher fees, cargo bike users are willing to pay for secure parking.

(h) *Impact of surrounding environment*

- Events such as festivals and football matches (e.g., Feyenoord games) significantly influence facility usage.
- Users may leave their bikes at the station and continue their journey by tram or train to event locations.

3. Users

(a) *User feedback and needs*

- Users request more spaces for non-standard bikes with wider tires, child seats, and crates.
- There is a demand for charging points for electric bikes, though these come with safety considerations.

- Entry and exit require an OV-chipkaart (business, personal, or anonymous). During events, many users lack such cards.
- Loan cards are available but frequently run out during peak times, causing some users to be denied access.
- The shift toward debit/credit card travel on public transport leads to confusion, as this is not yet supported in the bicycle parking system.

(b) *Abandoned bicycles*

- As noted earlier, bicycles are chalk-marked monthly. Despite the 28-day limit, actual removal occurs much later.

(c) *Subscription holders*

- Bicycles under active yearly subscriptions are not removed, even if parked for extended periods.
- Subscription bikes are often left at the facility during weekends or long absences, with the facility functioning as a storage solution for “second” bikes.
- This trend increases summertime usage, particularly by commuters.

4. Future of Bicycle Parking Facilities

- There is a need for modernization of racks to accommodate wider bicycles and improve usability of upper racks.
- Enhancements should focus on accessibility, allowing broader user groups—including the elderly—to make better use of upper-level parking.

A.2.8. Staff Member 2, Rotterdam

1. Role in Bicycle Parking Facilities

- Responsible for scanning users in and out of the facility and managing OV-fiets (public bike) rentals.
- Labels incorrectly or long-parked bicycles to initiate the removal process or encourage compliance with rules.

2. Facility Usage

(a) *Layout of the facility*

- A small area is designated for oversized bicycles; however, due to frequent overcrowding, users are often turned away.
- Bicycles with crates or child seats are directed to be parked in upper racks.
- The left side of the facility, which is closer to the entrance and within clearer sight of the staff, fills up more quickly.
- Users prefer the secure (paid) NS facility over the adjacent free public parking, especially when seeking convenience and safety.

(b) *Enforcement by municipality*

- Bicycles are labeled when incorrectly parked or left for too long.
- Reactions to enforcement vary: some users adjust their behavior, while others continue to park improperly due to time pressure.
- Common violations include parking against walls or in walkways.

(c) *Procedures for full facilities*

- Full capacity is rare, except in the front section. There is usually still space available in upper racks toward the back.
- In contrast, the adjacent free public facility, which operates with the HBF system and a two-week maximum stay, fills up more frequently.

(d) *Layout of the racks*

- Not all users can lift their bikes into the upper racks, particularly elderly users or those with heavy or non-standard bicycles.
- Staff aim to find a balance between what is feasible for the user and the rules for optimal space use.

(e) *Differences in self-service, scanner, or staffed systems*

- Users are checked in by staff.
- Occasionally, individuals attempt to bypass check-in, assuming the facility is free.
- These cases are usually clarified by staff upon exit, often involving people unfamiliar with the system.

(f) *Fluctuating usage patterns*

- Peak usage occurs between 08:00 and 09:00, largely due to commuters and OV-fiets rentals.
- Different user groups are observed during weekends and nighttime hours, including travelers who rely on bikes due to lack of nighttime public transport.

(g) *Different types of bicycles*

- The number of oversized and non-standard bicycles is growing, and current facilities do not offer sufficient space for them.

(h) *Impact of surrounding environment*

- The facility serves a wide range of users from across the city.
- Early-morning and nighttime travelers use the facility to connect to train services due to limited public transport availability during those hours.

3. Users

(a) *User feedback and needs*

- Users prioritize getting to the train quickly.
- The secure (staffed) parking option is valued for its safety, especially compared to the adjacent public facility, where theft is more common.
- The facility is primarily used by commuters in the early morning and by leisure users from 11:00 onward.
- Many users have yearly subscriptions or use employer-paid accounts, especially for secondary bicycles.

(b) *Abandoned bicycles*

- Bicycles can remain parked for a maximum of 28 days.
- Bikes are chalk-marked and labeled during routine checks and moved to the rear of the facility before eventual removal.

(c) *Subscription holders*

- Yearly subscription holders may exceed the 28-day rule in consultation with staff.
- These users often leave bikes parked for extended periods, especially during holidays or travel, and receive a label with a specified return date.

4. Future of Bicycle Parking Facilities

- Increasing the number of spaces for non-standard and oversized bicycles is seen as a necessary future development.

B

Data Processing and Model Application

This appendix provides an overview of the code and definitions used to estimate the efficiency indicators and usage patterns and to apply the clustering model to the usage patterns.

B.1. Data Processing

```
1
2 # Volume
3 all_locations = list(bicycle_parking_cico['LOCATION_NAME'].unique())
4
5 def list_incoming_volumes_per_quarter(data, locations, end_date):
6     time_range = pd.date_range(start=data['PARKING_START_TIMESTAMP'].min(), end=data['PARKING_END_TIMESTAMP'].max(),
7                                 freq='15min')
8     all_locations_incoming_volumes = []
9
10    for location in locations:
11        loc_data = data[data['LOCATION_NAME'] == location]
12        loc_incoming_volumes = []
13
14        for time_point in time_range:
15            count = (loc_data['PARKING_START_TIMESTAMP'] >= time_point) & \
16                    (loc_data['PARKING_START_TIMESTAMP'] < time_point + pd.Timedelta(minutes=15))
17            loc_incoming_volumes.append(count.sum())
18
19        loc_incoming_volumes_df = pd.DataFrame({'Timestamp': time_range, 'Incoming_Volume': loc_incoming_volumes})
20        loc_incoming_volumes_filtered_df = loc_incoming_volumes_df[loc_incoming_volumes_df['Timestamp'] <= end_date]
21
22        all_locations_incoming_volumes.append(loc_incoming_volumes_filtered_df.set_index('Timestamp')['Incoming_Volume'])
23
24    return all_locations_incoming_volumes
25
26 incoming_volumes_all_locations = list_incoming_volumes_per_quarter(bicycle_parking_cico,
27                             all_locations, end_date='2025-1-1')
28
29 #Accumulation
30 def list_checked_in_users_per_location(data, locations, end_date):
31     time_range = pd.date_range(start=data['PARKING_START_TIMESTAMP'].min(), end=data['PARKING_END_TIMESTAMP'].max(),
32                                 freq='15min')
33     all_locations_checkedin = []
34
35     for location in locations:
36         loc_data = data[data['LOCATION_NAME'] == location]
37         loc_checkedin = []
38         for time_point in time_range:
39             count = ((loc_data['PARKING_START_TIMESTAMP'] <= time_point) &
```

```

40         (loc_data['PARKING_END_TIMESTAMP'] > time_point)).sum()
41         loc_checkedin.append(count)
42
43         loc_checkedin_df = pd.DataFrame({'Timestamp': time_range, 'Checked_In': loc_checkedin
44         })
45         loc_checkedin_filtered_df = loc_checkedin_df[loc_checkedin_df['Timestamp'] <=
46         end_date]
47
48         all_locations_checkedin.append(loc_checkedin_filtered_df.set_index('Timestamp')['
49         Checked_In'])
50
51     return all_locations_checkedin
52
53 lists_occupation_all_locations = list_checked_in_users_per_location(bicycle_parking_cico,
54     all_locations, end_date='2025-1-1')
55
56 # Average week
57 def calculate_average_week_by_timestamp(normalised_df, start_date, end_date):
58     normalised_df.index = pd.to_datetime(normalised_df.index)
59     df_filtered = normalised_df.loc[(normalised_df.index >= start_date) & (normalised_df.
60     index <= end_date)].copy()
61     df_filtered = df_filtered.assign(Weekday=df_filtered.index.day_name(), Time=df_filtered.
62     index.time)
63     average_week = df_filtered.groupby(['Weekday', 'Time']).mean()
64     weekday_order = ['Monday', 'Tuesday', 'Wednesday', 'Thursday', 'Friday', 'Saturday', '
65     Sunday']
66     average_week = average_week.reindex(weekday_order, level='Weekday')
67
68     return average_week
69
70 average_week_sep_2024 = calculate_average_week_by_timestamp(checkins_2023_2024, '2024-09-09',
71     '2024-10-06')
72 average_week_sep_2023 = calculate_average_week_by_timestamp(checkins_2023_2024, '2023-09-11',
73     '2023-10-08')
74
75 def normalise_dataframe(df):
76     max_value_per_week = df.max(axis=0)
77     normalised_df = df.div(max_value_per_week, axis=1)
78     return normalised_df
79
80 normalised_average_week_sep_2024 = normalise_dataframe(average_week_sep_2024)
81 normalised_average_week_sep_2023 = normalise_dataframe(average_week_sep_2023)
82
83 # Visuals average week
84 def plot_average_week(week_df, locations, color = None):
85     plt.figure(figsize=(20, 5))
86
87     for location in locations:
88         location_column = location
89
90         combined_index = [f"{weekday}_{time.strftime('%H:%M')}" for weekday, time in week_df.
91         index]
92         series_values = week_df[location_column].values
93         plt.plot(combined_index, series_values, label=location, color = color )
94
95     plt.xlabel('Time')
96     plt.ylabel('Accumulation')
97     plt.xticks(np.arange(0, len(combined_index), step=12), rotation=20, ha='right')
98     plt.legend(title='Locatie', fontsize='xx-small')
99     plt.grid(True)
100    plt.tight_layout()
101    plt.show()
102
103 def plot_average_week_normalised(week_df, locations, color = None):
104     plt.figure(figsize=(20, 5))
105
106     for location in locations:
107         location_column = location

```



```

101     combined_index = [f"{weekday}_{time.strftime('%H:%M')}" for weekday, time in week_df.
102         index]
103     series_values = week_df[location_column].values
104     plt.plot(combined_index, series_values, label=location, color = color )
105
106     plt.xlabel('Time')
107     plt.ylabel('Accumulation')
108     plt.ylim(0,1)
109     plt.xticks(np.arange(0, len(combined_index), step=12), rotation=20, ha='right')
110     plt.legend(title='Locatie', fontsize='xx-small')
111     plt.grid(True)
112     plt.tight_layout()
113     plt.show()
114
115 # Choose year average week
116 highest_accumulation_sep2324 = pd.DataFrame()
117 for location in locations_with_higher_2024:
118     highest_accumulation_sep2324[f"{location}_{(2024)}"] = average_week_sep_2024[location]
119 for location in locations_with_higher_2023:
120     highest_accumulation_sep2324[f"{location}_{(2023)}"] = average_week_sep_2023[location]

```

B.2. Temporal Usage Pattern Clustering

```

1
2 X_mm_normalised = normalised_highest_accumulation_sep2324
3 X_mm_normalised = X_mm_normalised.T
4
5
6 # experiment 1 DTW
7 silhouette_score_mm = []
8
9 for i in range(2, 10):
10
11     start = time.time()
12
13     km = TimeSeriesKMeans(n_clusters=i, metric="dtw", max_iter=20, max_iter_barycenter=10,
14         random_state=0, metric_params={"sakoe_chiba_radius": 4})
15     y_pred_mm = km.fit_predict(X_mm_normalised)
16     score_mm = silhouette_score(X_mm_normalised, y_pred_mm, metric="dtw", metric_params={"sakoe_chiba_radius": 4})
17     silhouette_score_mm.append(score_mm)
18     stop = time.time()
19     duration = stop - start
20
21     print(f"K={i}. Took {duration:.2f} seconds to calculate.")
22
23 plt.figure(figsize=(5, 3))
24 plt.plot(range(2, 10), silhouette_score_mm, "-o", color = '#0063D3')
25 plt.xlabel('Number of clusters')
26 plt.ylabel('Silhouette Score')
27 plt.ylim(0.2, 0.8)
28
29 # experiment 2 Euclidian Distance
30 silhouette_score_mm_eu = []
31 for i in range(2, 10):
32     start = time.time()
33     km_eu = TimeSeriesKMeans(n_clusters=i, metric="euclidean", max_iter=20, random_state=0)
34     y_pred_mm_eu = km_eu.fit_predict(X_mm_normalised)
35     score_mm_eu = silhouette_score(X_mm_normalised, y_pred_mm_eu, metric="euclidean")
36     silhouette_score_mm_eu.append(score_mm_eu)
37     stop = time.time()
38     duration = stop - start
39     print(f"K={i}. Took {duration:.2f} seconds to calculate.")
40
41 plt.figure(figsize=(5, 3))
42 plt.plot(range(2, 10), silhouette_score_mm_eu, "-o", color = '#0063D3')
43 plt.xlabel('Number of clusters')

```

```

44 plt.ylabel('SilhouetteScore')
45 plt.ylim(0.2, 0.8)
46
47
48 # experiment 3 Soft DTW
49 silhouette_score_mm_soft = []
50 for i in range(2, 10):
51     start = time.time()
52     km_soft = TimeSeriesKMeans(n_clusters=i, metric="softdtw", max_iter=20,
53                               max_iter_barycenter=10, random_state=0)
54     y_pred_mm_soft = km_soft.fit_predict(X_mm_normalised)
55     score_mm_soft = silhouette_score(X_mm_normalised, y_pred_mm_soft, metric="softdtw")
56     silhouette_score_mm_soft.append(score_mm_soft)
57     stop = time.time()
58     duration = stop - start
59     print(f"K={i}. Took {duration:.2f} seconds to calculate.")
60
61 print("SilhouetteScores with Soft-DTW:", silhouette_score_mm_soft)
62
63 plt.figure(figsize=(5, 3))
64 plt.plot(range(2, 10), silhouette_score_mm_soft, "-o", color = '#0063D3')
65 plt.xlabel('Number of clusters')
66 plt.ylabel('SilhouetteScore')
67 plt.ylim(0.2, 0.8)
68
69 # Final model application: Soft DTW 6 clusters
70 km_soft_normalised = TimeSeriesKMeans(n_clusters=6, metric="softdtw", max_iter=20,
71                                       max_iter_barycenter=10, random_state=0)
72 y_pred_mm_soft_normalised = km_soft_normalised.fit_predict(X_mm_normalised)
73 score_mm_soft = silhouette_score(X_mm_normalised, y_pred_mm_soft_normalised, metric="softdtw")
74
75 X_mm_clusters = X_mm_normalised.copy()
76 X_mm_clusters['cluster'] = y_pred_mm_soft_normalised
77
78 # Visuals clusters
79 colors_clusters = ['#2ca25f', '#FF8200', '#FF0045', '#FFC917', '#0079D3', '#003082']
80
81 def plot_average_week_normalised_clusters(week_df, locations, ax, color=None, alpha=1):
82     combined_index = [f"{weekday}_{time.strftime('%H:%M')}" for weekday, time in week_df.
83                       index]
84     for location in locations:
85         series_values = week_df[location].values
86         ax.plot(combined_index, series_values, label=location, color=color, alpha=alpha)
87     ax.set_xticks(np.arange(0, len(combined_index), step=24))
88     ax.set_xticklabels(combined_index[:24], rotation=45, ha='right')
89     unique_clusters = np.unique(y_pred_mm_soft_normalised)
90     fig, axes = plt.subplots(len(unique_clusters), 1, figsize=(12, 2.5 * len(unique_clusters)),
91                             sharex=True)
92
93     if len(unique_clusters) == 1:
94         axes = [axes]
95
96     for i, (yi, ax) in enumerate(zip(unique_clusters, axes)):
97         cluster_data_normalised = X_mm_normalised[y_pred_mm_soft_normalised == yi]
98         plot_average_week_normalised_clusters(cluster_data_normalised.T,
99                                               cluster_data_normalised.T, ax, color='grey', alpha=0.4)
100
101         # Use the cluster color for the mean line
102         cluster_color = colors_clusters[yi % len(colors_clusters)]
103         ax.plot(km_soft_normalised.cluster_centers_[yi].ravel(), color=cluster_color,
104               linewidth=2, label=f'Cluster_{yi} Mean')
105
106     ax.set_title(f'Cluster_{yi+1}')
107
108     if i == len(unique_clusters) - 1:
109         ax.set_xlabel('Time Intervals') # Set the x-label only on the last subplot
110     else:
111         ax.set_xticklabels([]) # Remove x-axis labels for all but the last subplot

```

```

108         ax.set_ylim(0, 1.05)
109         ax.legend().remove() # Remove the legend
110
111     middle_ax_index = len(unique_clusters) // 2
112     axes[middle_ax_index].set_ylabel('Normalised Accumulation')
113
114     plt.tight_layout()
115     plt.show()
116

```

B.3. Efficiency Evaluation Clusters

```

1 # Find cluster means
2 cluster_aggregates = combined_parking_info.groupby('cluster').agg({
3     'capacity': 'mean',
4     'duration_mean_h': 'mean',
5     'duration_median_h': 'mean',
6     'week_turnover': 'mean',
7     'weekend_turnover': 'mean',
8     'max_occupancy': 'mean',
9     'parking_pressure': 'mean',
10    'parking_price': 'mean',
11    'production': 'mean',
12    'attraction': 'mean',
13    'access_mode': 'mean',
14    'egress_mode': 'mean',
15    'standard_bicycles': 'mean',
16    'non-standard_bicycles_within_racks': 'mean',
17    'non-standard_bicycles_outside_racks': 'mean',
18    'facility_type': 'count',
19    'validation_system': 'count',
20    'price_rate': 'count',
21    'service': 'count'
22 }).reset_index()
23
24 common_columns = combined_parking_info.columns.intersection(cluster_aggregates.columns)
25 numeric_common_cols = combined_parking_info[common_columns].select_dtypes(include=['float64',
26     'int64']).columns
27 overall_mean_common = combined_parking_info[numeric_common_cols].mean().to_frame().T
28 overall_mean_common['cluster'] = 'overall_mean'
29 cluster_aggregates_common = pd.concat([cluster_aggregates, overall_mean_common], ignore_index=True)
30
31 # Test variance numeric values
32 columns_to_test = ['capacity',
33     'week_turnover',
34     'weekend_turnover',
35     'max_occupancy',
36     'parking_pressure',
37     'production',
38     'attraction',
39     'access_mode',
40     'egress_mode',
41     'duration_mean_h',
42     'duration_median_h',
43     'parking_price',
44     'standard_bicycles',
45     'non-standard_bicycles_within_racks',
46     'non-standard_bicycles_outside_racks']
47
48 descriptive_stats = {}
49 anova_results = {}
50
51 for column in columns_to_test:
52     filtered_data = combined_parking_info.dropna(subset=[column])
53     descriptive_stats[column] = filtered_data.groupby('cluster')[column].describe()
54
55     anova_clusters = [filtered_data[filtered_data['cluster'] == cluster][column] for cluster

```

```

    in filtered_data['cluster'].unique())
56 if all(len(cluster_data) > 1 for cluster_data in anova_clusters):
57     anova_results[column] = f_oneway(*anova_clusters)
58 if column in anova_results:
59     print(f"{column}: F-statistic={anova_results[column].statistic:.4f}, p-value={
        anova_results[column].pvalue:.5f}")
60
61 colors_clusters = ['#2ca25f', '#FF8200', '#FF0045', '#FFC917', '#0079D3', '#003082']
62 sns.set_theme(style="whitegrid")
63 for column in columns_to_test:
64     plt.figure(figsize=(6, 4))
65     ax = sns.boxplot(x='cluster', y=column, data=combined_parking_info.dropna(subset=[column
        ]), hue='cluster', palette=colors_clusters)
66     ax.legend().remove()
67     plt.tight_layout()
68     plt.show()
69
70
71 # Test categorical variables
72 contingency_table_facility_type = pd.crosstab(combined_parking_info['cluster'],
        combined_parking_info['facility_type'])
73 contingency_table_validation = pd.crosstab(combined_parking_info['cluster'],
        combined_parking_info['validation_system'])
74 contingency_table_price_rate = pd.crosstab(combined_parking_info['cluster'],
        combined_parking_info['price_rate'])
75 contingency_table_service = pd.crosstab(combined_parking_info['cluster'],
        combined_parking_info['service'])
76
77 chi2, p, dof, expected = chi2_contingency(contingency_table_facility_type)
78
79 chi2v, pv, dof_v, expected_v = chi2_contingency(contingency_table_validation)
80
81 chi2_t, p_t, dof_t, expected_t = chi2_contingency(contingency_table_price_rate)
82
83 chi2_s, p_s, dof_s, expected_s = chi2_contingency(contingency_table_service)
84
85
86 sns.set_theme(style="whitegrid")
87 colors_clusters = ['#2ca25f', '#FF8200', '#FF0045', '#FFC917', '#0079D3', '#003082']
88 unique_clusters = sorted(combined_parking_info['cluster'].unique())
89 cluster_color_map = {cl: colors_clusters[i] for i, cl in enumerate(unique_clusters)}
90 clusters_sorted = sorted(combined_parking_info['cluster'].unique())
91 hatch_styles = ['--', '', '|||']
92 variables_context = ['facility_type', 'validation_system', 'price_rate', 'service']
93 for i in range(len(variables_context)):
94     plt.figure(figsize=(6, 4))
95     grouped = combined_parking_info.groupby(['cluster', variables_context[i]].size().unstack
        (fill_value=0)
96     bar_width = 0.8 / len(grouped.columns)
97     x = range(len(clusters_sorted))
98     unique_clusters = sorted(combined_parking_info['cluster'].unique())
99     cluster_color_map = {cl: colors_clusters[i] for i, cl in enumerate(unique_clusters)}
100     for i, col in enumerate(grouped.columns):
101         plt.bar(
102             [pos + i * bar_width for pos in x],
103             grouped[col].reindex(clusters_sorted),
104             color=[cluster_color_map[cl] for cl in clusters_sorted],
105             hatch=hatch_styles[i % len(hatch_styles)],
106             label=col,
107             edgecolor='black',
108             width=bar_width)
109
110     plt.xticks([pos + bar_width * (len(grouped.columns) / 2) for pos in x], clusters_sorted)
111     plt.xlabel("Cluster")
112     plt.ylabel("Number")
113     plt.grid(axis='x')
114     plt.legend(loc='upper_left')
115     plt.tight_layout()
116     plt.show()

```



Average Week per Location

This appendix provides an overview of the selected average week for each bicycle parking facility location included in the analysis. For each location, the year and the specific time period of the representative week are listed, along with the day and time at which the maximum occupancy was recorded during that period. These selections form the basis for the temporal usage pattern analysis described in chapter 5 and ensure that results are based on consistent and representative conditions across all facilities.

Table C.1: Average week selection per location

Location	Year	Period	Max day
Alkmaar	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Alkmaar Noord	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:45
Almelo	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30
Almere Busplein-fietsenstalling	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:30
Almere Landdrostdreef	2024	[2024-09-09], [2024-10-06]	Thursday, 13:30
Alphen aan den Rijn	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:00
Amersfoort Centraal	2024	[2024-09-09], [2024-10-06]	Thursday, 13:30
Amersfoort Mondriaanplein	2024	[2024-09-09], [2024-10-06]	Thursday, 13:30
Amersfoort Schothorst	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:15
Amsterdam Amstel	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:00
Amsterdam Bijlmer	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:45
Amsterdam Centraal IJboulevard	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:30
Amsterdam Centraal IJzijde West	2023	[2023-09-11], [2023-10-08]	Sunday, 12:45
Amsterdam Centraal Stationsplein	2023	[2023-09-11], [2023-10-08]	Saturday, 19:30
Amsterdam Centraal Stationsplein Oost	2024	[2024-09-09], [2024-10-06]	Saturday, 15:45
Amsterdam Muiderpoort	2024	[2024-09-09], [2024-10-06]	Thursday, 17:15
Amsterdam RAI	2024	[2024-09-09], [2024-10-06]	Tuesday, 14:00
Amsterdam Sloterdijk	2024	[2024-09-09], [2024-10-06]	Thursday, 13:15
Amsterdam Zuid Mahlerplein	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:00
Amsterdam Zuid Strawinskylaan	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:15
Amsterdam Zuid Zuidplein	2024	[2024-09-09], [2024-10-06]	Thursday, 13:15
Apeldoorn	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Arnhem Centrumzijde	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:30
Arnhem Sonsbeekzijde	2023	[2023-09-11], [2023-10-08]	Thursday, 12:30
Assen	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30
Baarn	2024	[2024-09-09], [2024-10-06]	Thursday, 13:00
Barendrecht	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Bergen op Zoom	2023	[2023-09-11], [2023-10-08]	Tuesday, 16:15
Bilthoven	2023	[2023-09-11], [2023-10-08]	Thursday, 13:00
Breda Belcrum	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Breda Centrum	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30

Location	Year	Period	Day
Castricum	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:45
Culemborg	2023	[2023-09-11], [2023-10-08]	Tuesday, 14:30
Den Haag CS KJ Plein	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:00
Den Haag CS Stichthage	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:00
Den Haag Holland Spoor	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:15
Den Helder	2023	[2023-09-11], [2023-10-08]	Friday, 16:30
Dordrecht	2023	[2023-09-11], [2023-10-08]	Thursday, 13:00
Driebergen-Zeist	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:00
Ede-Wageningen	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Eindhoven Noordzijde	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:00
Eindhoven Zuidzijde	2024	[2024-09-09], [2024-10-06]	Thursday, 13:15
Enschede	2024	[2024-09-09], [2024-10-06]	Thursday, 12:15
Goes	2023	[2023-09-11], [2023-10-08]	Tuesday, 08:15
Gouda	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:15
Gouda Zuidzijde	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:00
Groningen	2024	[2024-09-09], [2024-10-06]	Thursday, 14:15
Haarlem Carré	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30
Harderwijk	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:15
Heemstede-Aerdenhout	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30
Heerenveen	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:00
Heerhugowaard	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30
Heerlen	2023	[2023-09-11], [2023-10-08]	Thursday, 15:15
Helmond	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:00
Hengelo	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:45
Hilversum	2024	[2024-09-09], [2024-10-06]	Thursday, 13:30
Hoofddorp	2024	[2024-09-09], [2024-10-06]	Thursday, 13:15
Hoogeveen	2024	[2024-09-09], [2024-10-06]	Tuesday, 11:45
Hoorn	2024	[2024-09-09], [2024-10-06]	Tuesday, 14:45
Kampen	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30
Leeuwarden	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:15
Lelystad Centrum	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:15
Maarssen	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:00
Maastricht	2023	[2023-09-11], [2023-10-08]	Thursday, 12:45
Meppel	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30
Middelburg	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30
Naarden Bussum	2024	[2024-09-09], [2024-10-06]	Monday, 13:45
Nijmegen	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Oss	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30
Rijswijk	2024	[2024-09-09], [2024-10-06]	Tuesday, 14:30
Roermond	2024	[2024-09-09], [2024-10-06]	Tuesday, 13:00
Roosendaal	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30
Rotterdam Centraal	2024	[2024-09-09], [2024-10-06]	Thursday, 14:30
Schiedam-fietsenstalling	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30
Sittard	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:45
Steenwijk	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:15
Tiel	2024	[2024-09-09], [2024-10-06]	Thursday, 12:15
Tilburg Noord	2024	[2024-09-09], [2024-10-06]	Thursday, 13:00
Tilburg Zuid	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:30
Utrecht Centraal Jaarbeursplein	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:45
Utrecht Centraal Knoop	2024	[2024-09-09], [2024-10-06]	Thursday, 13:15
Utrecht Centraal Sijpesteijn	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:30

Location	Year	Period	Day
Utrecht Centraal Stationsplein	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:30
Utrecht Overvecht-fietsenstalling	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:00
Utrecht Vaartsche Rijn Oosterkade	2023	[2023-09-11], [2023-10-08]	Tuesday, 14:45
Utrecht Vaartsche Rijn Westerkade	2024	[2024-09-09], [2024-10-06]	Tuesday, 11:45
Venlo	2023	[2023-09-11], [2023-10-08]	Thursday, 13:00
Voorburg	2023	[2023-09-11], [2023-10-08]	Thursday, 17:15
Weert	2024	[2024-09-09], [2024-10-06]	Tuesday, 12:15
Weesp	2023	[2023-09-11], [2023-10-08]	Thursday, 12:15
Woerden	2024	[2024-09-09], [2024-10-06]	Thursday, 13:00
Wormerveer	2023	[2023-09-11], [2023-10-08]	Tuesday, 13:00
Zaandam	2024	[2024-09-09], [2024-10-06]	Thursday, 12:45
Zaltbommel	2023	[2023-09-11], [2023-10-08]	Monday, 12:45
Zwijndrecht	2023	[2023-09-11], [2023-10-08]	Tuesday, 12:15
Zwolle Hanzeland	2023	[2023-09-11], [2023-10-08]	Thursday, 12:15
Zwolle Stationsplein	2024	[2024-09-09], [2024-10-06]	Thursday, 16:15

D

Locations per Cluster

Table D.1: Bicycle parking locations per clusters

Cluster 1	Cluster 3	Cluster 5
Alkmaar Amersfoort Centraal Apeldoorn Assen Barendrecht Den Haag CS KJ Plein Driebergen-Zeist Gouda Gouda Zuidzijde Haarlem Carré Harderwijk Hilversum Maarssen Utrecht Centraal Knoop Utrecht Centraal Sijpesteijn Weert Weesp Wormerveer Zwijndrecht	Almelo Almere Busplein-fietsenstalling Amsterdam Zuid Strawinskylaan Arnhem Sonsbeekzijde Breda Belcrum Castricum Culemborg Ede-Wageningen Eindhoven Noordzijde Heemstede-Aerdenhout Heerenveen Helmond Hengelo Hoogeveen Naarden Bussum Roermond Schiedam-fietsenstalling Utrecht Overvecht-fietsenstalling Zaandam Zwolle Hanzeland	Alkmaar Noord Almere Landdrostdreef Alphen aan den Rijn Amersfoort Mondriaanplein Amersfoort Schothorst Amsterdam RAI Amsterdam Zuid Mahlerplein Arnhem Centrumzijde Baarn Breda Centrum Den Haag CS Stichtage Groningen Heerhugowaard Hoofddorp Kampen Lelystad Centrum Meppel Middelburg Nijmegen Oss Rijswijk Roosendaal Sittard Steenwijk Tiel Woerden Zaltbommel
Cluster 2	Cluster 4	Cluster 6
Eindhoven Zuidzijde Leeuwarden Rotterdam Centraal Tilburg Noord Tilburg Zuid Utrecht Centraal Jaarbeursplein Utrecht Centraal Stationsplein Utrecht Vaartsche Rijn Oosterkade	Amsterdam Centraal IJzijde West Amsterdam Centraal Stationsplein Oost Amsterdam Muiderpoort Amsterdam Zuid Zuidplein Den Helder Dordrecht Goes Zwolle Stationsplein	Amsterdam Amstel Amsterdam Bijlmer Amsterdam Centraal IJboulevard Amsterdam Centraal Stationsplein Amsterdam Sloterdijk Bergen op Zoom Bilthoven Den Haag Holland Spoor Enschede Heerlen Hoorn Maastricht Utrecht Vaartsche Rijn Westerkade Venlo Voorburg

Categorical Variables Macro Context

This appendix tabulates the proportions, observed and expected counts for the chi-squared test results for the categorical variables across the six clusters. These details support the macro-level cluster comparisons in chapter 6.

Table E.1: Observed and expected counts facility type

		guarded	unguarded	total
1	O	11	8	19
	E	7.8	11.2	
2	O	8	0	8
	E	3.3	4.7	
3	O	4	16	20
	E	8.2	11.8	
4	O	4	4	8
	E	3.3	4.7	
5	O	8	19	27
	E	11.1	15.9	
6	O	5	10	15
	E	6.2	8.8	
total		40	57	

Table E.2: Observed and expected counts price rate

		1st 24h free	paid	total
1	O	15	4	19
	E	17.24	1.76	
2	O	6	2	8
	E	7.26	0.74	
3	O	19	1	20
	E	18.14	1.86	
4	O	8	0	8
	E	7.26	0.74	
5	O	25	2	27
	E	24.49	2.51	
6	O	15	0	15
	E	13.61	1.39	
total		88	9	97

Table E.3: Observed and expected counts validation system

		bike-lane	hand-scanner	self-service	total
1	O	1	10	8	19
	E	2.5	5.1	11.4	
2	O	3	5	0	8
	E	1.1	2.1	4.8	
3	O	3	1	16	20
	E	2.7	5.4	12.0	
4	O	2	2	4	8
	E	1.1	2.1	4.8	
5	O	1	7	19	27
	E	3.6	7.2	16.1	
6	O	3	2	10	15
	E	2.0	4.0	9.0	
total		13	26	58	97

Table E.4: Observed and expected counts service

		N	Y	total
1	O	11	8	19
	E	13.52	5.48	
2	O	2	6	8
	E	5.69	2.31	
3	O	18	2	20
	E	14.23	5.77	
4	O	4	4	8
	E	5.69	2.31	
5	O	22	5	27
	E	19.21	7.79	
6	O	12	3	15
	E	13.82	1.39	
total		69	28	97

Macro Context and Outcome per Location

This appendix provides a overview of both contextual and outcome metrics for the 97 bicycle parking facilities analysed. Table F.1 lists the available facility attributes: type, capacity, service level, pricing, validation system and types of bicycles (production and attraction levels per station are not made public). They were selected because they represent the operational and policy settings that shape user behaviour. Table F.2 presents the corresponding performance indicators: mean and peak occupancy, turnover (weekday and weekend), parking pressure. Those are chosen to quantify how effectively each facility meets demand.

Table F.1: Overview of the macro context variables per bicycle parking facility

Location Name	Facility Type	Capacity	Service	Price Rate	Validation System	Standard bicycles	Non Standard (in racks)	Non-Standard
Alkmaar	guarded	1854	Y	paid	handscanner	0.710	0.229	0.062
Alkmaar Noord	unguarded	611	N	1st 24h free	self-service	0.711	0.286	0.003
Almelo	unguarded	600	N	1st 24h free	self-service	0.870	0.115	0.015
Almere Busplein-fietsenstalling	unguarded	660	N	1st 24h free	self-service	0.821	0.175	0.004
Almere Landdrostdreef	guarded	2783	Y	1st 24h free	bikelane	0.780	0.174	0.046
Alphen aan den Rijn	unguarded	1171	N	1st 24h free	self-service	0.731	0.220	0.049
Amersfoort Centraal	guarded	1892	Y	1st 24h free	handscanner	0.724	0.263	0.013
Amersfoort Mondriaanplein	unguarded	619	N	1st 24h free	self-service	0.800	0.197	0.004
Amersfoort Schothorst	unguarded	352	N	1st 24h free	self-service	0.766	0.234	0.000
Amsterdam Amstel	guarded	3095	Y	1st 24h free	bikelane	0.730	0.255	0.015
Amsterdam Bijlmer	unguarded	255	N	1st 24h free	self-service	0.749	0.233	0.018
Amsterdam Centraal IJboulevard	guarded	3966	N	1st 24h free	bikelane	0.719	0.281	0.000
Amsterdam Centraal IJzijde West	guarded	798	Y	1st 24h free	bikelane	0.776	0.224	0.000
Amsterdam Centraal Stationsplein	guarded	6100	Y	1st 24h free	bikelane	0.751	0.249	0.000
Amsterdam Centraal Stationsplein Oost	guarded	1025	Y	1st 24h free	handscanner	0.715	0.225	0.060
Amsterdam Muiderpoort	unguarded	319	N	1st 24h free	self-service	0.751	0.229	0.020

Amsterdam RAI	guarded	821	N	1st 24h free	handscanner	0.665	0.318	0.017
Amsterdam Sloterdijk	guarded	431	N	1st 24h free	handscanner	0.811	0.184	0.005
Amsterdam Zuid Mahlerplein	guarded	2872	N	1st 24h free	handscanner	0.680	0.290	0.030
Amsterdam Zuid Strawinskylaan	guarded	3704	N	1st 24h free	bikelane	0.665	0.303	0.032
Amsterdam Zuid Zuidplein	guarded	907	Y	1st 24h free	handscanner	0.693	0.307	0.000
Apeldoorn	guarded	1593	Y	1st 24h free	handscanner	0.706	0.276	0.018
Arnhem Centrumzijde	guarded	3543	Y	1st 24h free	handscanner	0.855	0.129	0.016
Arnhem Sonsbeekzijde	unguarded	826	N	1st 24h free	self-service	0.883	0.115	0.002
Assen	guarded	2252	Y	1st 24h free	handscanner	0.793	0.174	0.033
Baarn	unguarded	730	N	1st 24h free	self-service	0.717	0.261	0.022
Barendrecht	unguarded	301	N	1st 24h free	self-service	0.759	0.223	0.018
Bergen op Zoom	unguarded	750	N	1st 24h free	self-service	0.742	0.255	0.003
Bilthoven	unguarded	475	N	1st 24h free	self-service	0.754	0.236	0.010
Breda Belcrum	guarded	2617	Y	1st 24h free	bikelane	0.750	0.244	0.006
Breda Centrum	guarded	1641	N	1st 24h free	handscanner	0.759	0.241	0.000
Castricum	unguarded	588	N	1st 24h free	self-service	0.803	0.185	0.012
Culemborg	unguarded	1138	N	1st 24h free	self-service	0.767	0.216	0.016
Den Haag CS KJ Plein	guarded	6900	N	1st 24h free	handscanner			
Den Haag CS Stichthage	guarded	1434	Y	paid	handscanner	0.716	0.277	0.007
Den Haag Holland Spoor	unguarded	1051	N	1st 24h free	self-service	0.823	0.175	0.002
Den Helder	unguarded	170	N	1st 24h free	self-service	0.759	0.241	0.000
Dordrecht	unguarded	1171	N	1st 24h free	self-service	0.687	0.240	0.073
Driebergen-Zeist	guarded	3178	Y	1st 24h free	handscanner	0.732	0.236	0.032
Ede-Wageningen	guarded	5264	Y	1st 24h free	bikelane	0.759	0.232	0.010
Eindhoven Noordzijde	guarded	779	N	paid	handscanner	0.788	0.212	0.000
Eindhoven Zuidzijde	guarded	1072	Y	paid	handscanner	0.810	0.190	0.000
Enschede	unguarded	510	N	1st 24h free	self-service	0.808	0.185	0.008
Goes	unguarded	500	N	1st 24h free	self-service	0.755	0.235	0.010
Gouda	guarded	2100	Y	paid	handscanner	0.777	0.184	0.038
Gouda Zuidzijde	unguarded	744	N	1st 24h free	self-service	0.746	0.251	0.003
Groningen	guarded	1459	Y	paid	handscanner	0.818	0.169	0.012
Haarlem Carré	unguarded	969	N	1st 24h free	self-service	0.602	0.377	0.021
Harderwijk	guarded	1463	Y	1st 24h free	bikelane	0.628	0.369	0.003
Heemstede-Aerdenhout	unguarded	550	N	1st 24h free	self-service	0.655	0.278	0.067
Heerenveen	unguarded	852	N	1st 24h free	self-service	0.807	0.151	0.043
Heerhugowaard	unguarded	312	N	1st 24h free	self-service	0.772	0.228	0.000
Heerlen	unguarded	104	N	1st 24h free	self-service	0.889	0.111	0.000

Helmond	unguarded	1846	N	1st 24h free	self-service	0.800	0.199	0.001
Hengelo	unguarded	306	N	1st 24h free	self-service	0.871	0.123	0.006
Hilversum	guarded	1342	Y	paid	handscanner	0.681	0.308	0.011
Hoofddorp	unguarded	533	N	1st 24h free	self-service	0.690	0.267	0.043
Hoogeveen	unguarded	372	N	1st 24h free	self-service	0.775	0.217	0.008
Hoorn	unguarded	583	N	1st 24h free	self-service	0.817	0.159	0.024
Kampen	unguarded	397	N	1st 24h free	self-service	0.844	0.145	0.011
Leeuwarden	guarded	3039	Y	1st 24h free	handscanner	0.846	0.152	0.003
Lelystad Centrum	unguarded	358	N	1st 24h free	self-service	0.805	0.184	0.011
Maarsssen	unguarded	1417	N	1st 24h free	self-service	0.656	0.333	0.010
Maastricht	guarded	2642	Y	1st 24h free	handscanner	0.788	0.210	0.002
Meppel	unguarded	1162	N	1st 24h free	self-service	0.707	0.277	0.016
Middelburg	unguarded	388	N	1st 24h free	self-service	0.665	0.330	0.005
Naarden Bussum	unguarded	1406	N	1st 24h free	self-service	0.620	0.333	0.048
Nijmegen	guarded	2136	Y	1st 24h free	handscanner	0.788	0.191	0.021
Oss	unguarded	675	N	1st 24h free	self-service	0.631	0.367	0.002
Rijswijk	unguarded	176	N	1st 24h free	self-service	0.756	0.205	0.038
Roermond	unguarded	1428	N	1st 24h free	self-service	0.732	0.266	0.001
Roosendaal	unguarded	1314	N	1st 24h free	self-service	0.694	0.306	0.000
Rotterdam Centraal	guarded	1086	Y	paid	handscanner	0.819	0.148	0.033
Schiedam-fietsenstalling	unguarded	576	N	1st 24h free	self-service	0.722	0.247	0.031
Sittard	unguarded	558	N	1st 24h free	self-service	0.780	0.220	0.000
Steenwijk	unguarded	94	N	1st 24h free	self-service	0.884	0.107	0.009
Tiel	unguarded	452	N	1st 24h free	self-service	0.667	0.330	0.004
Tilburg Noord	guarded	3692	N	1st 24h free	bikelane	0.712	0.277	0.011
Tilburg Zuid	guarded	3204	Y	1st 24h free	bikelane	0.707	0.292	0.000
Utrecht Centraal Jaarbeursplein	guarded	3933	Y	1st 24h free	handscanner	0.778	0.220	0.002
Utrecht Centraal Knoop	guarded	2746	N	1st 24h free	handscanner	0.786	0.208	0.006
Utrecht Centraal Sijpesteijn	guarded	1097	N	1st 24h free	handscanner			
Utrecht Centraal Stationsplein	guarded	13386	Y	1st 24h free	handscanner	0.777	0.220	0.003
Utrecht Overvecht-fietsenstalling	unguarded	291	N	1st 24h free	self-service	0.723	0.277	0.000
Utrecht Vaartsche Rijn Oosterkade	guarded	595	N	1st 24h free	bikelane	0.749	0.219	0.031
Utrecht Vaartsche Rijn Westerkade	unguarded	147	N	1st 24h free	self-service	0.798	0.192	0.010
Venlo	unguarded	651	N	1st 24h free	self-service	0.701	0.299	0.000
Voorburg	unguarded	252	N	1st 24h free	self-service	0.807	0.123	0.070
Weert	unguarded	498	N	1st 24h free	self-service	0.760	0.240	0.000
Weesp	unguarded	964	N	paid	self-service	0.648	0.277	0.075

Woerden	unguarded	1123	N	1st 24h free	self-service	0.702	0.291	0.008
Wormerveer	unguarded	760	N	1st 24h free	self-service	0.652	0.340	0.008
Zaandam	unguarded	566	N	1st 24h free	self-service	0.736	0.244	0.020
Zaltbommel	unguarded	193	N	1st 24h free	self-service	0.736	0.264	0.000
Zwijndrecht	unguarded	365	N	1st 24h free	self-service	0.655	0.345	0.000
Zwolle Hanzeland	unguarded	809	N	1st 24h free	self-service	0.822	0.173	0.005
Zwolle Stationsplein	guarded	4990	Y	1st 24h free	bikelane	0.736	0.262	0.002

Table F.2: Overview of the macro outcome indicators per bicycle parking facility

Location Name	Occup. (count)	Parking Price	Weekend Turnover	Week Turnover	Occup. (max)	Parking Pressure	Duration (mean)	Duration (median)
Alkmaar	599	1.566	0.196	1.032	0.191	0.084	19.19	9.63
Alkmaar Noord	325	0.076	0.220	2.117	0.507	0.454	48.69	10.23
Almelo	460	0.049	0.295	3.477	0.687	0.480	38.99	9.59
Almere Busplein-fietsenstalling	268	0.126	0.450	3.227	0.632	0.833	47.11	9.89
Almere Landdrostdreef	568	0.099	0.213	1.314	0.221	0.097	15.54	9.46
Alphen aan den Rijn	431	0.315	0.194	1.751	0.378	0.200	30.37	9.43
Amersfoort Centraal	1697	0.150	0.527	3.916	0.754	0.349	20.84	9.28
Amersfoort Mondriaanplein	544	0.074	0.480	3.955	0.808	0.456	27.90	9.68
Amersfoort Schothorst	239	0.062	0.214	3.122	0.707	0.512	37.72	10.01
Amsterdam Amstel	2221	0.307	0.547	3.318	0.613	0.386	31.40	9.92
Amsterdam Bijlmer	223	0.096	0.587	3.877	0.804	0.677	55.06	9.73
Amsterdam Centraal IJboulevard	2593	0.383	0.660	3.486	0.595	0.378	26.26	9.71
Amsterdam Centraal IJzijde West	606	0.485	0.333	2.761	0.820	0.594	53.79	12.19
Amsterdam Centraal Stationsplein	3343	0.429	0.720	3.057	0.572	0.527	33.02	10.19
Amsterdam Centraal Stationsplein Oost	748	0.390	0.536	3.185	0.630	0.508	48.44	10.57
Amsterdam Muiderpoort	345	0.183	0.441	3.763	1.029	0.883	91.39	11.63
Amsterdam RAI	409	0.186	0.343	2.611	0.475	0.336	29.28	9.23
Amsterdam Sloterdijk	412	0.769	0.263	1.423	0.261	0.270	68.67	11.12
Amsterdam Zuid Mahlerplein	1204	0.185	0.266	2.142	0.375	0.217	21.71	9.06
Amsterdam Zuid Strawinskylaan	1541	0.282	0.209	2.368	0.513	0.306	29.15	9.72
Amsterdam Zuid Zuidplein	833	0.408	0.671	4.558	0.784	0.626	28.11	10.62
Apeldoorn	1564	0.142	0.461	4.230	0.824	0.282	14.95	9.19
Arnhem Centrumzijde	1909	0.192	0.487	2.919	0.456	0.286	17.81	9.09
Arnhem Sonsbeekzijde	633	0.152	0.342	3.598	0.840	0.761	57.50	9.99

Assen	1043	0.216	0.300	2.356	0.419	0.166	17.11	9.23
Baarn	272	0.086	0.207	1.822	0.379	0.275	45.11	9.45
Barendrecht	282	0.077	0.285	3.274	0.671	0.363	39.29	9.06
Bergen op Zoom	298	0.098	0.121	1.681	0.352	0.369	42.88	10.85
Bilthoven	407	0.117	0.492	3.746	0.875	0.937	60.33	9.36
Breda Belcrum	1713	0.217	0.486	3.596	0.684	0.364	20.42	9.79
Breda Centrum	1297	0.245	0.154	3.328	0.754	0.344	23.18	10.06
Castricum	335	0.073	0.269	2.202	0.546	0.633	55.49	9.83
Culemborg	855	0.087	0.253	2.653	0.513	0.422	35.78	9.55
Den Haag CS KJ Plein		0.234	0.192	1.281	0.223	0.114	15.66	9.28
Den Haag CS Stichthage	1166	1.600	0.504	3.116	0.618	0.277	20.69	9.51
Den Haag Holland Spoor	582	0.108	0.298	2.255	0.527	0.774	61.08	10.04
Den Helder	54	0.334	0.152	1.920	0.621	0.483	70.22	13.94
Dordrecht	655	0.050	0.121	0.737	0.288	0.213	147.41	23.89
Driebergen-Zeist	1519	0.157	0.377	2.595	0.453	0.215	15.71	8.72
Ede-Wageningen	2270	0.189	0.229	2.269	0.420	0.231	26.23	9.79
Eindhoven Noordzijde	273	1.857	0.000	0.607	0.166	0.076	30.40	10.03
Eindhoven Zuidzijde	801	1.644	0.468	2.212	0.422	0.205	21.90	9.98
Enschede	395	0.152	0.575	4.335	1.012	0.780	53.64	9.88
Goes	298	0.097	0.087	2.188	0.505	0.400	54.38	14.59
Gouda	678	1.516	0.111	0.873	0.175	0.063	16.71	9.01
Gouda Zuidzijde	709	0.051	0.406	4.624	0.922	0.519	27.42	9.63
Groningen	1123	1.957	0.026	0.912	0.225	0.099	27.27	10.16
Haarlem Carré	756	0.058	0.390	3.460	0.736	0.437	36.87	9.64
Harderwijk	653	0.158	0.225	2.759	0.515	0.216	14.97	8.91
Heemstede-Aerdenhout	406	0.084	0.276	2.827	0.728	0.752	49.31	9.65
Heerenveen	657	0.114	0.184	3.108	0.643	0.362	36.35	9.77
Heerhugowaard	298	0.082	0.512	5.049	1.026	1.128	45.36	10.15
Heerlen	72	0.105	0.281	2.781	0.659	0.760	51.49	10.60
Helmond	1025	0.102	0.307	2.664	0.506	0.593	60.37	9.64
Hengelo	317	0.099	0.563	4.775	0.987	1.158	42.65	9.40
Hilversum	938	1.490	0.350	2.252	0.431	0.180	18.99	8.99
Hoofddorp	277	0.054	0.201	2.181	0.471	0.258	36.48	9.69
Hoogeveen	374	0.098	0.273	3.769	0.751	0.441	47.70	9.70
Hoorn	289	0.353	0.385	2.120	0.408	0.389	34.22	9.77
Kampen	179	0.095	0.206	2.567	0.506	0.287	29.59	9.19
Leeuwarden	1523	0.305	0.291	2.087	0.325	0.203	17.84	9.64

Lelystad Centrum	435	0.076	0.750	6.793	1.333	0.984	32.13	10.01
Maarsse	393	0.067	0.182	1.717	0.329	0.222	23.97	9.02
Maastricht	1141	0.415	0.369	2.206	0.347	0.281	23.35	9.57
Meppel	631	0.084	0.157	2.162	0.427	0.236	33.76	9.49
Middelburg	218	0.095	0.143	2.436	0.496	0.746	49.51	9.50
Naarden Bussum	610	0.092	0.289	2.146	0.438	0.436	39.70	9.48
Nijmegen	854	0.221	0.453	2.821	0.518	0.228	18.49	9.60
Oss	664	0.077	0.354	5.000	0.997	0.597	27.00	8.98
Rijswijk	78	0.068	0.107	1.456	0.318	0.155	40.63	9.63
Roermond	710	0.079	0.215	2.501	0.496	0.329	37.68	9.82
Roosendaal	581	0.055	0.216	2.575	0.562	0.361	39.13	9.75
Rotterdam Centraal	918	1.669	0.193	1.060	0.202	0.107	23.77	9.37
Schiedam-fietsenstalling	417	0.080	0.396	3.372	0.715	1.043	53.49	9.69
Sittard	418	0.085	0.205	3.196	0.697	0.282	36.01	9.60
Steenwijk	215	0.090	0.720	8.619	1.864	1.595	34.19	9.52
Tiel	273	0.090	0.230	2.704	0.563	0.313	36.21	9.39
Tilburg Noord	1327	0.173	0.425	2.269	0.360	0.178	20.01	8.49
Tilburg Zuid	2432	0.284	0.687	4.575	0.807	0.480	25.09	9.61
Utrecht Centraal Jaarbeursplein	473	0.204	1.088	5.748	0.834	0.536	16.15	9.13
Utrecht Centraal Knoop	1567	0.149	0.321	2.263	0.437	0.160	14.20	9.50
Utrecht Centraal Sijpesteijn		0.178	0.622	4.821	0.907	0.403	15.12	9.71
Utrecht Centraal Stationsplein	12750	0.240	0.728	3.963	0.601	0.390	17.41	9.48
Utrecht Overvecht-fietsenstalling	184	0.084	0.273	2.695	0.569	0.593	57.06	9.93
Utrecht Vaartsche Rijn Oosterkade	351	0.192	0.445	2.314	0.344	0.190	15.88	8.77
Utrecht Vaartsche Rijn Westerkade	104	0.191	0.248	2.291	0.476	0.455	61.97	9.93
Venlo	421	0.095	0.278	3.162	0.631	0.764	47.89	10.46
Voorburg	57	0.120	0.076	0.841	0.188	0.375	54.08	10.13
Weert	346	0.072	0.345	5.022	1.008	0.745	43.46	9.73
Weesp	159	1.120	0.067	0.508	0.096	0.057	26.41	8.80
Woerden	774	0.057	0.363	3.577	0.696	0.492	42.16	9.01
Wormerveer	388	0.057	0.286	2.608	0.490	0.399	28.07	9.42
Zaandam	250	0.064	0.248	1.855	0.348	0.209	32.60	9.48
Zaltbommel	197	0.060	0.466	5.841	1.082	1.045	33.79	8.72
Zwijndrecht	194	0.044	0.245	3.332	0.665	0.392	27.26	9.65
Zwolle Hanzeland	415	0.097	0.227	2.606	0.611	0.493	43.76	10.16
Zwolle Stationsplein	3578	0.273	0.366	3.345	0.679	0.454	35.54	11.27



AI Acknowledgement

Artificial intelligence tools were used to support this thesis in a supplementary manner. ChatNS and ChatGPT were employed to stimulate creativity, clarify ideas and refine written language. Additionally, AI assistance was used for programming tasks and the development of clear and effective data visualisations in Python. All analytical reasoning, methodological decisions, and conclusions are entirely based on own knowledge and critical judgement.