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by

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MEMBERSHIP AND MOBILITY BUNDLES CHOICE IN MOBILITY-AS-A-SERVICE

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Chapter 1

Introduction

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1.1 Background and motivation

The increase in global population over recent decades[1] has resulted in a rise in car ownership, passenger flow rates, and traffic congestion. As of 2022, there were approximately 1.5 billion vehicles worldwide, with Europe accounting for more than 400 million cars, as illustrated in Figure 1.1[2], and an average European rate of 560 passenger cars per 1,000 inhabitants[3]. Figure 1.2 displays the top five most congested cities in Europe being London, Paris, Palermo, Dublin, and Rome, with drivers spending an average of 98 to 156 hours per year in traffic congestion[4]. The challenges posed by mobility have serious consequences for the quality of life and well-being of urban dwellers. In 2019, road transportation accounted for 68% of greenhouse gas emissions, with cars being the primary source as shown by Figure 1.3 from European Environment Agency in 2020. Additionally, the rate of persons killed in road accidents in the EU was estimated at 42.1 per million inhabitants in 2020[5].

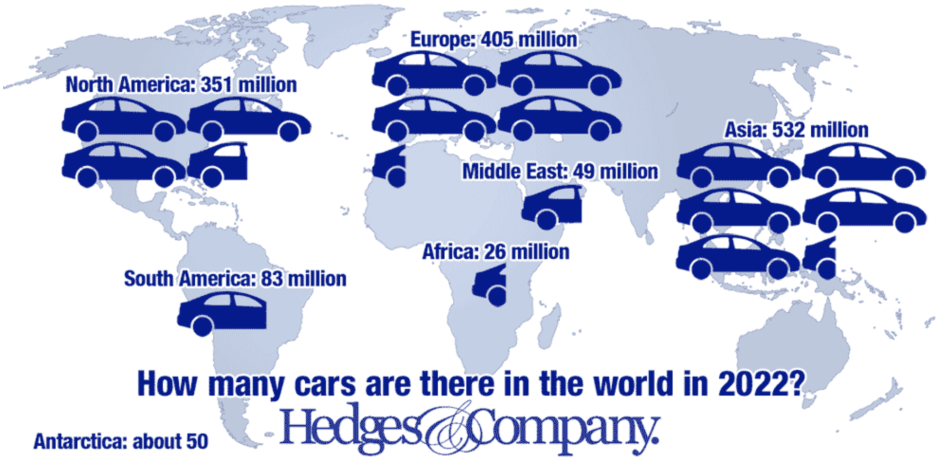

Figure 1.1: Car ownership across continents

The World's population is expected to increase to 8.5 billion people by 2030, according to the United Nations[6]. This projected growth is expected to result in a significant increase in the magnitude of current mobility challenges, particularly in urban areas, where 68% of the population will be

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[1] https://www.worlddata.info/populationgrowth.php

[2] https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/

[3] https://www.acea.auto/figure/motorisation-rates-in-the-eu-by-country-and-vehicle-type/

[4] https://hedgescompany.com/blog/2021

[5] https://ec.europa.eu/eurostat/statistics-explained/index

[6] https://www.un.org/en/global-issues/population: United Nations

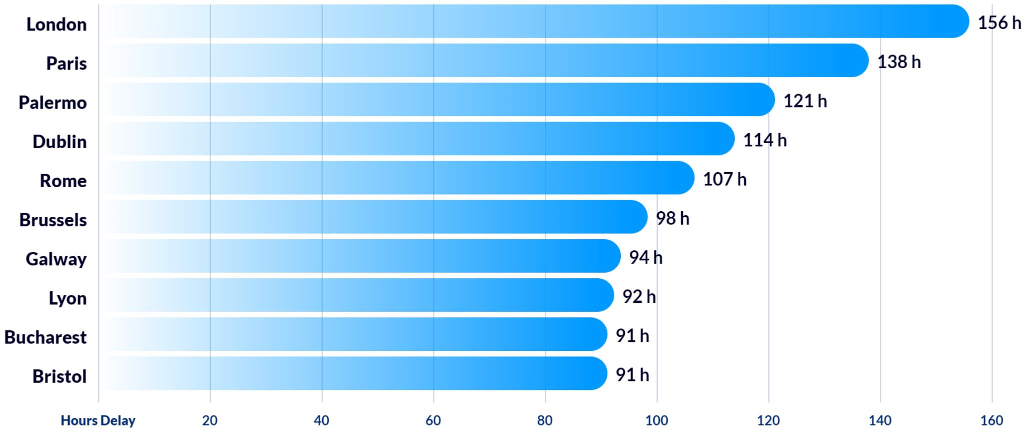

Figure 1.2: Hours delay due to congestion in European cities

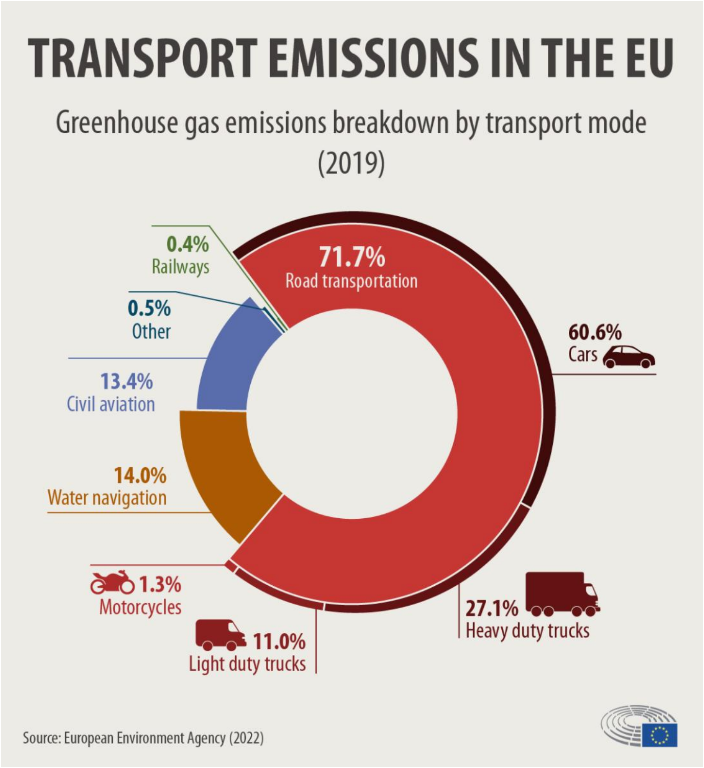

Figure 1.3: European emission by European environment agency

living by 2050. Therefore, there is an urgent need for innovative and sustainable mobility solutions to address these challenges. In their response, many public administrations have started implementing strategies to reduce the use of private vehicles and promote shared transport and mobility services, for instance the European Union (EU) has planned to ban the production of new petrol and diesel cars from 2035[7]. The EU is also taking steps to reduce emissions from cars to reach its climate neutrality goal by 2050, with the Parliament supporting the European Commission's proposal of zero emissions from new cars and vans by 2035, as well as intermediate emissions reduction targets for 2030 set at 55% for cars. To increase the uptake of shared mobility options, the EU has outlined specific strategies such as making connected and automated multimodal mobility a reality, boosting innovation and the use of data and artificial intelligence for smarter mobility, and building a European Common Mobility Data Space[8].

While many public administrations have implemented strategies to decrease private vehicle use and increase shared transportation options, these efforts have posed significant social, economic and logistical challenges[9]. However, the rise of popularity of internet devices such as smartphones and smartwatches has introduced promising solutions to these challenges, with tailored mobility apps that are easy to install and use for journey planning, travel booking, real time information acquisition, etc. [1]. In the last decades, app-based mobility services like Uber[10], Share Now[11], BlaBlaCar[12], FreeNow[13] and oBike[14] have revolutionized the transportation industry by offering competitive alternatives to traditional vehicle ownership models. These services also provide a wealth of real-time data that can be used to enhance the user experience. As consumers become more aware of the various transportation modes available to them, they are increasingly seeking out solutions that provide a balance between convenience, cost-effectiveness, and sustainability [2]. This shift in the paradigm of transportation mode selection has led to an increased demand for customizable solutions that can meet the individual needs and preferences of users [2, 3]. To address this demand, service providers and researchers are developing innovative solutions that leverage technology to offer personalized and flexible transportation options.

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[7] https://www.europarl.europa.eu/news/en/headlines/economy

[8] https://transport.ec.europa.eu/transport-themes/mobility-strategy

[9] European Parliament, https://www.europarl.europa.eu/news/en/headlines/economy

[10] https://www.uber.com/

[11] https://www.share-now.com/

[12] https://www.blablacar.com/

[13] https://www.free-now.com/

[14] https://www.oBike.com

In this light, the concept of Mobility-as-a-service (MaaS) system has emerged (Figure 1.4[15]); MaaS can be described as a user-centered system that aims to offer a comprehensive subscription-based transportation platform by integrating various modes of transportation services. MaaS seeks to provide a viable alternative to car ownership by providing a range of affordable, convenient, and eco-friendly transportation options under a subscription fee. MaaS typically involves a mobile application or web-based platform that provides real-time information about different transportation modes, such as ride-hailing, public transit, bike-sharing, and car-sharing. Users can use the platform to compare prices, travel times, and other factors, and book the most suitable transportation option for their mobility needs. One of the key advantages of MaaS is that it enables users to have a more customized and flexible transportation experience. Rather than being limited to a single mode of transportation, MaaS provides a range of options that users can choose from depending on their needs. Overall, MaaS has the potential to create more sustainable and efficient transportation systems by reducing traffic congestion and encouraging the use of sustainable transportation options. [4, 5, 6].

Ever since its introduction as a novel transportation concept by Heikkila and Hietanen in 2014, MaaS has been widely studied by researchers and practitioners, making it one of the most innovative and disruptive ideas in the transportation industry in the last ten years [7, 8]. From the point of view of the transportation analyst, MaaS is seen as a complex ecosystem where various actors cooperate and compete to provide seamless multi-modal packages to customers through a digital platform that operates on a subscription basis [9, 10]. Hence, the MaaS ecosystem involves different actors, such as policy regulators (Government, public authorities), transport and mobility service providers (MSPs), demanders (or customers), and the MaaS Integrator or Broker [10]. Governments or local authorities typically play the role of regulators, setting accessibility rules and providing subsidies to compensate any financial gaps in the system [9, 11]. MSPs refer to all transport operators who offer transport service capacities. Whereas the MaaS Broker, a new actor in transportation [10, 12], is responsible for gathering and integrating all mobility services into a platform that provides information and payment service packages [9] and is responsible for collecting and distributing the revenues for the financial MaaS ecosystem support. Finally, MaaS customers select the most convenient bundle of services and mode(s) of transportation based on their daily activities, mobility needs, and preferences [10].

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[15] https://mobilab.lu/team/

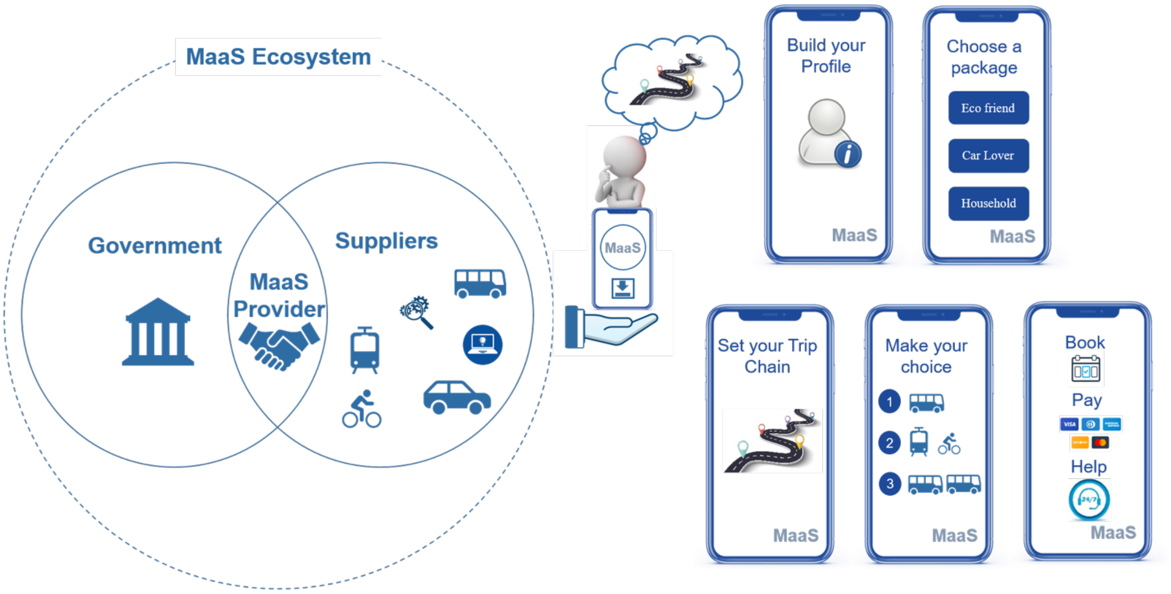

Figure 1.4: MaaS ecosystem

Hence, from the customers' perspective, MaaS holds the potential to transition users' behavior from ownership to *usership* by providing a range of transport services tailored to their needs. Nonetheless, due to the novelty of the MaaS ecosystem, there are still open challenges in modelling and addressing customers' decision-making process to subscribe to MaaS. In the next section, the goals and challenges of customer decision-making process implementation are presented.

1.2 Objective and Scope

Nowadays, the potential of MaaS system implementation is widely recognised. However, the impact on individual travel behavior and choices as well as on the mobility ecosystem, in particular in terms of efficiency and sustainability of MaaS implementation, is yet to be fully grasped and demonstrated.

MaaS is expected to shift part of the users' (perceived) mobility costs from marginal and trip-specific, to fixed by charging a subscription fee which, in the long run, is expected to have an impact on car ownership rates[13, 14]. Vehicle ownership is a long-term strategic decision, involving a significant initial capital investment, including vehicle purchase, and accounts for other costs linked to ownership such as maintenance, insurance, and taxes. However, a challenge is that car owners tend to underestimate the costs of vehicle ownership[15, 16]. Additionally, operational costs for vehicle usage, such as fuel and tolls, influence mobility choices in the short term. This is due to the low marginal costs perceived by owners compared to travel time gains. Conversely, MaaS does not favor any specific mode of transportation, unlike owned vehicles [14]. Therefore, the MaaS subscription fee may need to compete with ownership expenses offering the users a financial advantage over their current mobility budget [15].

Additionally, the subscription fee is inextricably linked to the variety of mobility services included in the MaaS bundle. In fact, the subscription fee should reflect the value proposition of each bundle in terms of the services and benefits provided to the customers. Services included in the MaaS bundle should be able to fulfill users' daily travel choices within an acceptable price that makes customers willing to subscribe to MaaS.

MaaS is further expected to repackage and present mobility services in a manner that might favor alterations in people's perceptions of these services and ultimately promote the use of shared and sustainable mobility services [17, 3, 18, 19, 20]. In order to achieve this goal, MaaS bundle must be carefully designed to include not only various mobility services but also specific incentive schemes, such as discounts for public transport or some free car-sharing booking hours included in the packages [21, 5]. However, to implement these MaaS perspectives, it is further crucial to establish a guaranteed profit generation pattern for bundled services. This is due to the MaaS system comprising various actors who are required to operate in a sustainable and profitable manner [20, 5]. Without achieving financial efficiency, the implementation of MaaS in the market would be unfeasible.

Given the challenges associated with MaaS customers' decision-making process, it is crucial to develop a comprehensive modelling and assessment framework for analyzing and evaluating individual-level travel requirements, mode choices, and mobility costs. It is also essential to quantify the impact of MaaS on the transportation system, both in terms of efficiency and (business and environmental) sustainability. In order to capture the actual market share, the model should allow researchers to profile potential users' travel habits and costs before and after subscribing. Analysts should also be able to design and compare different MaaS bundle schemes within the model in order to assess their impact on MaaS adoption and user travel preferences. By doing so, a better understanding of the real-world conditions and limitations of the MaaS system can be gained, as well as their impact on user behavior and mode choices.

Based on the proposed key objective and challenges of MaaS implementation, the research questions we try to address in this thesis are the following:

RQ 1: Which modelling approach can realistically assess the INTERACTIONS between POTENTIAL CUSTOMERS and their heterogeneous MOBILITY NEEDS and COSTS?

The first question addressed in this thesis revolves around understanding and modeling the interactions between potential users of MaaS and their diverse mobility needs and expenses. Conventional modeling and simulation techniques for transportation may not be able to accurately represent and quantify such interactions. They fall short in describing the variety of travel needs and activities that potential customers may have. For this reason, based on a critical review of the literature, we build a comprehensive MaaS ecosystem framework engaging all the MaaS actors. We specifically focus on the MaaS customer's decision-making model. In this regard, an agent-based model (ABM) is individualized as a potential method to represent the interactions between potential users, taking into account their diverse mobility needs and costs. Furthermore, the ABM enables the calculation of key performance indicators (KPIs) for the analysis of the MaaS market share. The exploration of this question is presented in the second chapter of the thesis, where the proposed ABM approach is elaborated upon.

RQ 2: How is the CUSTOMERS' WILLINGNESS-TO-SUBSCRIBE impacted by the MAAS SUBSCRIPTION FEE? And how much this impact depends on VEHICLE OWNERSHIP COSTS?

To address the second question, we seek to develop a model capable of capturing the effects of MaaS fees and cost of ownership on customers' willingness to subscribe to MaaS system. In line with the previous research question, we want to incorporate MaaS fees as one of the available mobility options for agents within an ABM along with ownership costs. In this way, users actively engage in the possibility of purchasing MaaS subscriptions. The model facilitates a trade-off analysis among MaaS fees and, private and stand-alone mobility service costs. This allows agents to assess the associated costs and evaluate the travel performances offered by the MaaS system while minimizing their daily mobility costs. In this way, through the analysis of KPIs, it is possible to understand customer profiles in terms of mobility attributes and asses the dependencies between MaaS subscription fee and ownership cost. A thorough exploration of the second research question can be found in Chapter 3 of the thesis.

RQ 3: Which features of MAAS BUNDLES SCHEMES affect PRIVATE CAR USE, the number of MAAS MEMBERS, and the REVENUE of the MaaS system?

The final question builds upon the previous research with the aim of expanding the ABM to incorporate a variety of MaaS bundle schemes differing in their mobility characteristics. This advancement enables users to assess different bundle scheme alternatives, taking into account not only the trade-offs between subscription fees and individual costs but also aligning the bundle selection with their specific travel requirements. This methodology extends and offers a comprehensive assessment of KPIs for identifying the most suitable characteristics for MaaS bundles to be offered to users. This approach ensures that the bundle options are tailored to meet the specific needs and preferences of users, ultimately enhancing the appeal of the MaaS system. The KPIs further assess the impact of the incorporation of bundle schemes on the revenue for the MaaS Broker, the shift from ownership costs to MaaS fees, and its effect on private car usage. Chapter 4 of the thesis provides a detailed exploration of this question, discussing the findings and analysis related to the expanded ABM and the design of MaaS bundles.

1.3 Thesis contributions

The main contribution of this thesis is the development of a membership and bundle choice model within the context of a Mobility-as-a-Service (MaaS) system. This thesis proposes a comprehensive modeling framework that considers a broader range of interactions and the development of different building blocks for the MaaS ecosystem model. Following the framework, we propose agent-based simulation (ABM) as the most suitable method for capturing customers' decision-making process in the MaaS system. ABM is capable of simulating the spatial and temporal distribution of individual users, as well as the dynamic availability of shared services included in the MaaS bundle (carsharing availability at the station may vary daily by time). Another advantage of ABM is the ability to dynamically adjust transport mode costs within the network, allowing users to experience the cost variations associated with various modes. While experimenting with new mobility options in the network, users strive to keep travel costs as low as possible.

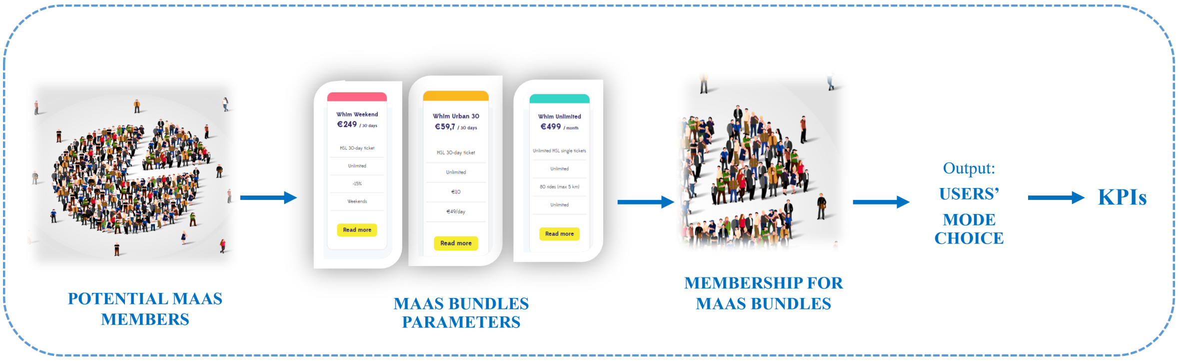

Figure 1.5: Customers’ decision making process in ABM

The decision-making process is simulated by embedding the MaaS bundle and its parameters as a possible travel option for potential MaaS members, as depicted in Figure 1.5. By incorporating and varying the MaaS bundle parameters in the ABM, analysts can create diverse experimental setups to capture key performance indicators (KPIs) that represent the MaaS system’s response to implemented variations. These KPIs encompass MaaS bundle users’ travel habits, the evaluation of a potential car policy in a context where the MaaS system becomes a viable mobility choice, and the MaaS Broker revenue. Moreover, the proposed model is flexible, allowing analysts to compare the KPIs in contexts with and without the MaaS system. The development of this thesis contributes to gaining insights into MaaS adoption and to the scientific debate and understanding of how new MaaS services will reshape the future of transportation and mobility systems.

This thesis work is based on conference and journal papers that are listed below:

Journal Papers:

European Transportation Research Review Journal (accepted)

Title: ” MaaS modelling: a review of factors, customers’ profiles, choices, and business models”;[22]

Transport Policy Journal (to be submitted)

Title: ”Impact of subscription fee on MaaS adoption: an agent-based approach;”

Conference papers:

ICOMaaS 2023: 3rd International Conference on Mobility as a Service

Title: ”MaaS modelling: a review of factors, customers’ profiles, choices, and business models”;[23]

hEART 2022: 10th Symposium of the European Association for Research in Transportation
Title: "Comparing MaaS Business Plans Using an Agent-Based Modelling Approach";[24]

CSUM 2022:6th Conference on Sustainable Urban Mobility
Title: "The impact of total cost of ownership on MaaS system appeal using an agent-based approach";[25]

Transportation Research Board (TRB) 103rd Annual Meeting (accepted for presentation)
Title: "Designing MaaS bundle schemes"

1.4 Thesis outline

This manuscript is divided into 5 parts and encompasses 5 chapters (see Figure 1.6). The first part begins with an introduction and background of the MaaS system and arises the research questions. The second part, consisting of Chapter 2, aims to enhance our understanding of the complex dynamics and relationships within a MaaS ecosystem. This chapter serves as a foundational exploration, examining the different decision-making models employed by each actor involved in MaaS, with a particular emphasis on the decision-making process of customers. Chapter 2 aims to answer the first research question. Chapter 3, in the third part, is dedicated to understanding customer willingness to subscribe to MaaS, profiling MaaS potential users, and evaluating the feasibility of MaaS in reducing private car costs. In this way, we try to answer to the second research question. In Chapter 4 which belongs to the fourth part, insights are provided to comprehend the extent to which MaaS bundle schemes can attract market shares and influence user behavior toward shared mobility systems. This chapter aims to give insight to answer the third question. The final chapter aims to present an overview of the thesis outcomes, address the research question, and discuss the limitations and potential areas for future research.

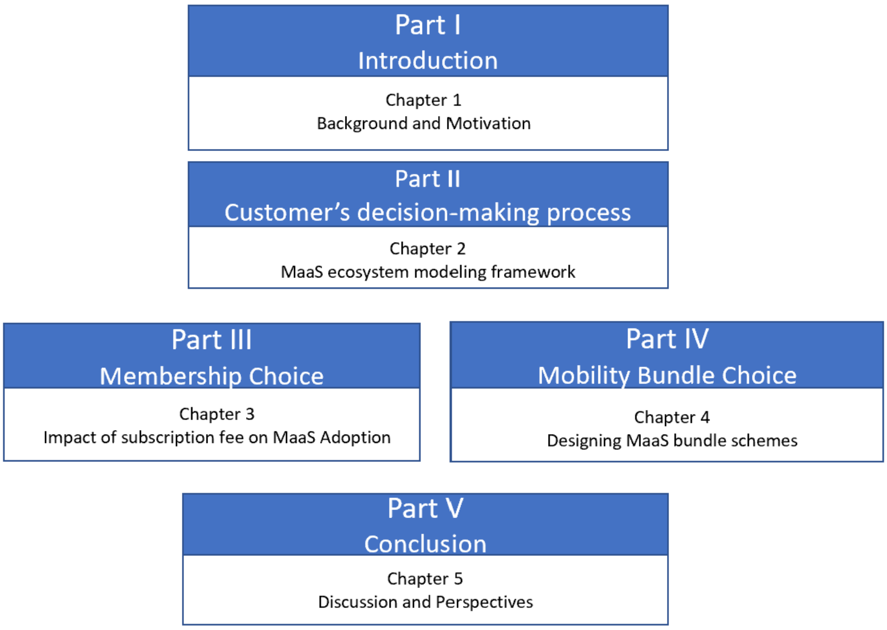

Figure 1.6: Thesis outline

Chapter 2

MaaS ecosystem modelling framework

Highlight of the Chapter

The primary objective of this chapter is to develop a comprehensive MaaS ecosystem framework based on a thorough analysis of the literature. This analysis focuses on three key aspects. Firstly, it aims to identify the critical factors that play a fundamental role in defining a MaaS model. Secondly, it explores the various models that govern the decision-making processes of individual actors within the ecosystem. And thirdly, it analyzes the interactions and interdependencies among all actors in the MaaS ecosystem. By critically examining these aspects, this chapter aims to provide valuable insights and enhance our understanding of the complex dynamics and relationships within a MaaS ecosystem. Furthermore, this chapter serves as the foundation for subsequent chapters by delving into the different models that govern the decision-making processes of each actor, with a specific emphasis on the customer decision-making process.

The work presented in this chapter is based on the papers:
”MaaS modelling: a review of factors, customers’ profiles, choices, and business models”,
ICOMaaS:3rd International Conference on Mobility as a Service

”MaaS modelling: a review of factors, customers’ profiles, choices, and business models”,
accepted for European Transportation Research Review Journal

2.1 Introduction

Since its introduction as a new transportation concept [7, 8], Mobility-as-a-Service (MaaS) has been widely studied among researchers and practitioners, becoming perhaps one of the most innovative and disruptive concepts introduced in the transportation sector in the last decade. MaaS can be seen as a complex ecosystem in which different actors with diverse purposes cooperate and compete to offer seamless multi-modal packages to customers through a subscription-based digital platform [26, 10]. In the MaaS ecosystem, different actors are involved, including policy regulators, mobility service providers (MSPs), customers, and the MaaS Integrator or Broker [10].

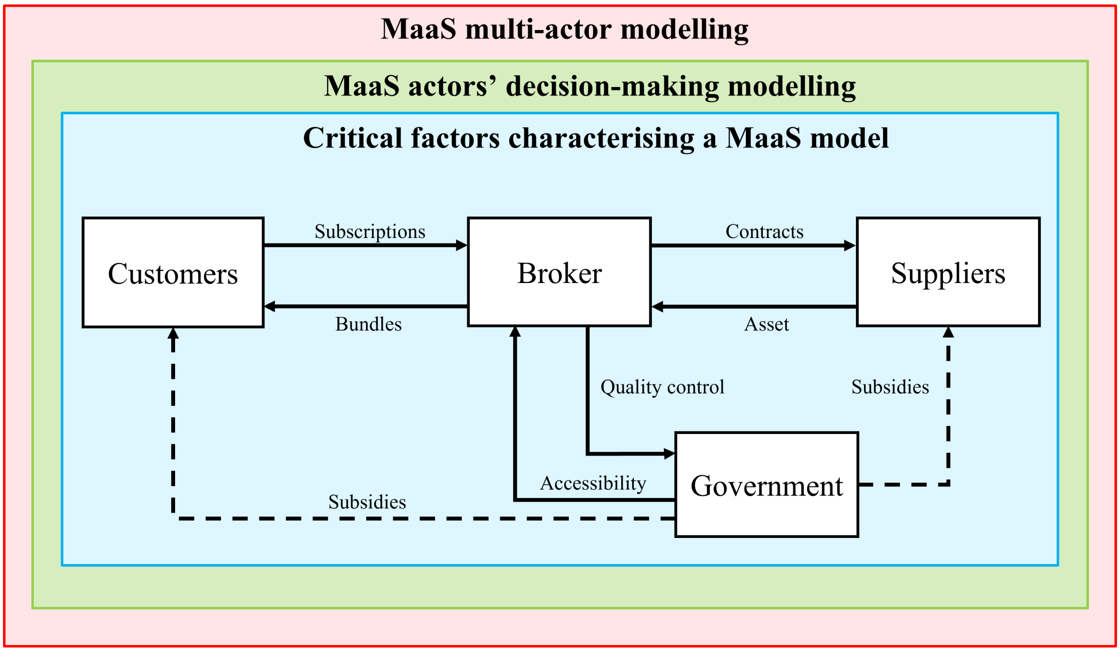

Figure 2.1: MaaS actors' roles and interaction (adapted from Wong et al. [10])

This seamless, multi-modal and personalised mobility concept can alter travellers' perceptions of mobility services, impact personal vehicle ownership and usage, and affect daily activity, mode and route choices. MaaS differs from traditional transportation modes in that it is a multi-modal system with complex and dynamic interactions among actors driven by different and often competing objectives. Conversely, such complexity is not fully encountered when a single transport service is modelled. Therefore, conventional transportation modelling and simulation approaches may not be ready to represent and quantify the multi-level impact of the MaaS system due to the lack of proper characterisation of the demand and supply interactions [3, 27]. It is hence essential to develop a more suited modelling framework to represent the decision-making process at all levels and for all involved players and to develop operational planning strategies to perform MaaS execution. Although some studies have already provided insights into specific modelling requirements of the MaaS actors and their actions [28, 29, 30, 31, 32], a general framework that incorporates all the components needed and their interaction to implement the MaaS system is currently missing. We argue that there is no general modelling framework able to model all the relevant characteristics exhaustively. This study aims to fill this gap by focusing on how to model the relationships among the various actors in a MaaS ecosystem. Using the Wong et al. 2018 [10] scheme (see figure 2.1) as a starting point, potential modifications of the MaaS actors' interactions framework are identified by integrating additional interactions, such as choices for government-supplier or customer subsidies.

We conduct a critical and descriptive analysis of the literature considering the three aspects shown in Figures 2.1 and 2.2, namely (*i*) the critical factors essential to define a MaaS model, (*ii*) the different models for the decision-making processes of each actor, and (*iii*) the interactions between all actors. The present chapter aims to address and provide the basis to answer the following research questions and related sub-questions:

1. **What are the critical factors that characterise a MaaS model?**
   a. What are the customers' critical factors that impact MaaS adoption?
   b. What are the MaaS ecosystem related-factors that define and have an impact on MaaS appeal?
2. **How to model the actors' decision-making process?**
   a. What are the modelling characteristics that are needed to capture MaaS customer travel behaviour?
   b. How to model the interaction between MaaS demand and supply subsystems?
3. **How to model the interactions among MaaS actors?**
   a. What are the relevant modelling aspects to include to capture the interaction between all MaaS actors?
   b. How to model the whole multimodal ecosystem and identify operating conditions and include the institutional overlay for MaaS successful deployment?

The remainder of this chapter is structured to address the above research questions in sequence. First, Section 2 explains the methodology used to select and review the state-of-the-art in the remainder of this section, Section 3 provides a classification and a general analysis of the critical factors determining customers' choices and profiles and relates individual characteristics with socio-demographic and other contextual variables, and finally connects these with MaaS-specific features, including technical design and market characteristics. Section 4 focuses on the MaaS actors' decision-making process, with particular emphasis on customers' choices (subscription choice, willingness to subscribe and to pay, mode choices) and on MSPs' strategic, tactical and operational decisions. Section 5 addresses the question related to multi-actor interaction, the design and assessment of different business models, and the modelling complexity of the two-sided market and the whole multi-modal ecosystem. Finally, Section 6 provides conclusions and general recommendations for future research to fill the identified gaps and challenges.

2.2 Framework and literature review methodology

This study looks at the MaaS actors' interactions from a novel perspective by presenting the MaaS ecosystem in three different subsystems as proposed in Figure 2.1 and 2.2. Figure 2.1 is the starting point in which the 3 areas are depicted, considering additional correlations between actors (dashed arrows), whereas Figure 2.2 represents the proposed framework. The blue area (Critical factors characterising a MaaS model) includes all the relevant input to characterise a MaaS model. The main factors are the socio-demographic characteristics and mobility attitudes that help to describe the Maas user's mobility needs, along with the factors linked to MaaS (e.g. mobility service included in the bundle).

The green area (MaaS actors' decision-making modelling) defines the different models each actor uses to make decisions with a focus on the customers actor. The procedure for becoming a MaaS member is outlined in the green loop. Prior to using the MaaS bundle, consumers must first obtain a membership based on their mobility needs. This allows them to explore the various transport modes and their associated costs (Daily MaaS choice). Users rate their experience throughout the course of daily satisfaction. Based on the daily satisfaction growth, a single can decide whether to keep the membership or cancel it in favour of a more cost-effective mobility option.

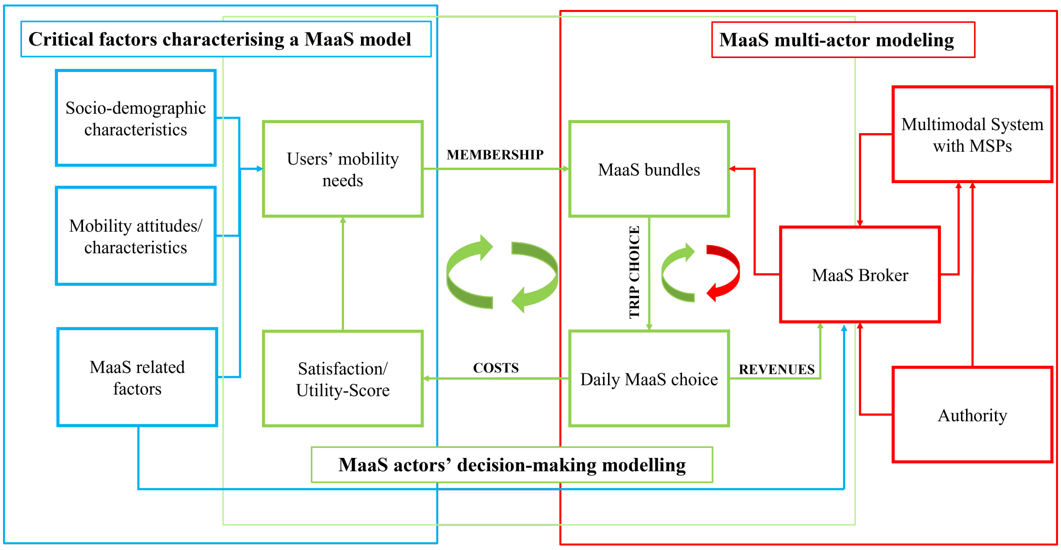

Figure 2.2: MaaS ecosystem modelling framework

Finally, the red area (MaaS multi-actor modelling) aims to understand the interactions and strategies employed by all actors involved in MaaS, including the Broker, the MSPs and the Authority. The demand-supply loop within the customers and MaaS Broker actor is represented by a second loop that overlaps two sections (red and green). In addition to providing the bundle, the Broker also receives payment from potential members' daily mobility costs and membership fees. In accordance with Authority-provided goals and rules, the Broker collaborates with MSPs to deliver and enhance MaaS services.

To provide a thorough overview of the literature on MaaS ecosystem modelling and its key topics, a narrative review is carried out. In this way, this study seeks to respond to the research issues posed in this chapter.

2.2.1 Search strategy

Different databases have been used to find papers around the concept of MaaS modelling, employing ScienceDirect, Springer, Scopus, and Google Scholar sources. Due to the novelty of the topic, conference papers, reports and websites were also included in this study along with peer-reviewed articles. The research was conducted until the beginning of June 2023. Since MaaS is a novel concept that has been gradually considered in recent years, no timeline was considered in searching the papers. However, some broader terms were considered to help find the definitions and modelling details, i.e. multi-modal modelling, new mobility services, two-sided market, etc. Keywords includ-

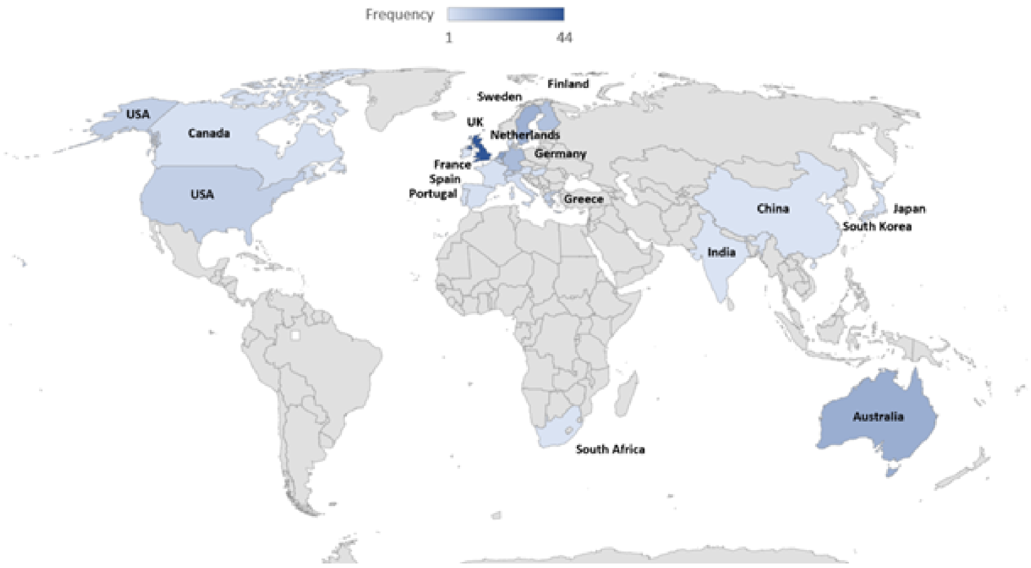

Figure 2.3: Distribution of MaaS studies around the world

ing “Mobility-as-a-Service”, “MaaS”, and combinations of them with the Boolean operators (AND, OR, and NOT) were used to find the main publications. Then frequently related keywords have been found in combination with MaaS, including “Agent-Based Models”, “business models”, “willingness to pay/subscribe”, “mode choice”, and “travel behaviour”. For earlier papers, forward snowballing was used to find the citations to the paper; for newer ones, backwards snowballing helped the authors find the citations in the paper [33]. 260 were categorised according to their methodological approach and variables considered in it.

The relevance of these papers was first evaluated through a preliminary screening to ensure that the studies encompassed relevant MaaS modelling aspects (such as transportation modes, user behavior, service integration and policy and regulation) resulting in 180 papers. The extracted data from the gathered papers include the study’s characteristics, such as the year of publication, geographic location of the study (see Figure 2.3), methodology, selected indicators for MaaS modeling, the relationships of the indicators, goals, and main findings.

The next step of the systematic review used the PRISMA method [34] to further narrow down the studies included in the review (see Figure 2.4). The retained papers were thoroughly analyzed through a full-text review. The included studies contain at least one of the following aspects: (*i*) Modelling of one or more MaaS subsystems; (*ii*) Mobility services or a subject in the field of mobility; (*iii*) Influencing factors of a MaaS model are studied.

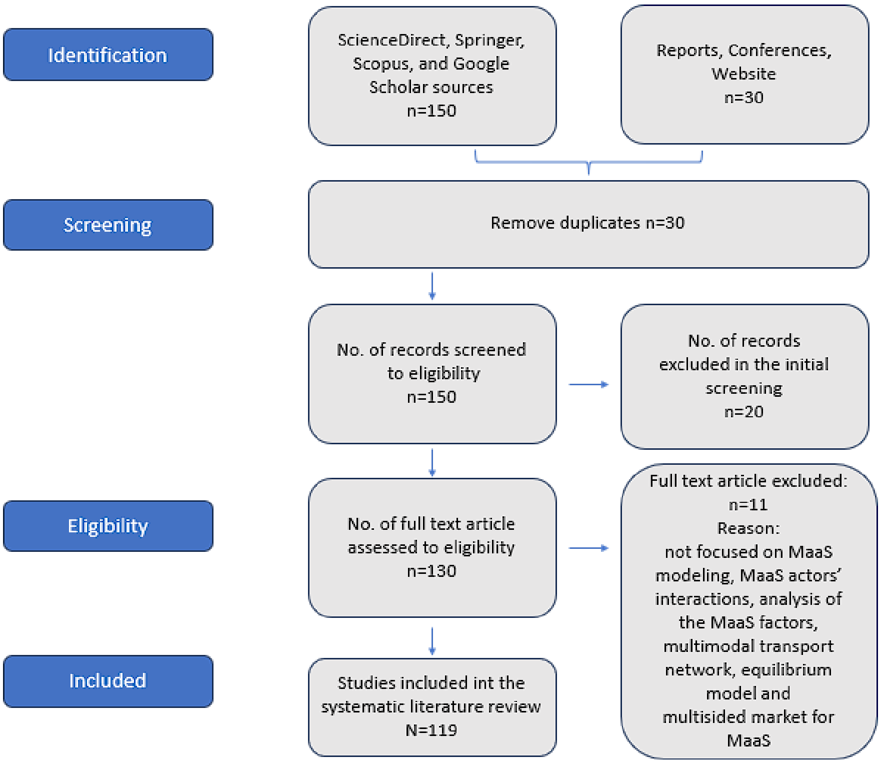

Figure 2.4: PRISMA method flowchart for studies selection

Thereafter, n = 130 studies were checked for eligibility to be included in the review. The main inclusion criteria of the search were based on studies that focused on MaaS modeling, MaaS actors' interactions, analysis of the MaaS factors, multimodal transport network, equilibrium model and multisided market for MaaS. Therefore, studies that did not use a focus were excluded. The authors carefully reviewed the identified studies and agreed on their incorporation in the review. Application of the inclusion and exclusion criteria reduced the total number of articles (n = 119). In the next section, the most critical factors for characterising a MaaS model will be discussed in detail.

2.3 Critical factors characterising a MaaS model

Determining the input data and variables is one of the first and most important parts of modelling. The input of a MaaS model is the data that should be collected or measured from both the demand and supply sides. So, the data includes both user and provider's information [35]. The data is then used to define the critical factors of a MaaS model, which are categorised into three groups: 1) socio-economic characteristics, 2) attitudes and habits of the travellers, and 3) MaaS-related factors. For each category, the definition and the measurement of the included factors are analysed. The reviewed literature reveals that the factors have effects on each other.

2.3.1 Socio-economic factors

The main socio-economic factors analysed in the context of MaaS modelling include age, education level, gender, employment status, income, and car ownership [21, 27, 36, 37, 30]. Among these factors, car ownership is a key factor that is expected to be influenced by MaaS adoption. This factor is strongly correlated with the other parameters, including age, gender, employment, education, and income [36, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49]. It is revealed in the literature that gender, age, car ownership, and education of people affect employment [44, 46, 48]; and employment, gender, and education affect income [41, 44].

2.3.2 Attitudes and habits of the travellers

Various factors influence the adoption of MaaS, including privacy [50, 51], environmental concern [52, 53], lifestyle [53], health-related habits [54, 55, 56], innovativeness and tech-savviness [57]. Age, gender, education, and income affect lifestyle choices [58, 59, 60]. User preferences and travel choices, such as willingness to pay [12, 16, 61, 30], mode preferences [62], and current travel costs [16], play a crucial role. Total Cost of Ownership (TCO) studies help compare ownership costs with MaaS [15].

2.3.3 MaaS-related factors

Service-related factors significantly impact the adoption of MaaS. Payment options, such as pay-as-you-go and monthly packages, influence user decisions [4, 63, 64]. Price of MaaS packages is another important attribute to consider [2]. The size and duration of MaaS packages, along with the level of spatial and temporal coverage, are crucial for competition with private cars [65, 66, 27]. Integration of mobility services, modes, operators, and institutions is a key objective of MaaS, offering various levels of integration from basic to full [67, 68, 69]. Booking, ticketing, and planning functionalities are critical in a MaaS platform [70]. Maximum integration is desirable for optimal MaaS implementation.

2.4 MaaS actors' decision-making modelling

This section provides a discussion of the current MaaS decision-making models for MaaS actors, which are developed based on the critical factors described in the previous section.

With MaaS models, we refer to analytic, simulation-based, or data-driven approaches that are developed to estimate and predict the decision-making process driving the choices of all the MaaS actors. A substantial portion of the literature in this area focuses on the decision-making process of customers, specifically on the two points listed below :

1. *MaaS subscription choice models.* This is a mid-term decision-making process since it involves choosing, e.g. a monthly subscription, which determines and, to some extent, limits the possibility of using mobility services on a daily or weekly horizon (e.g., a limited number of hours for renting a shared vehicle included in the MaaS package to be used within the subscription month);
2. *MaaS mode choice models*, which aim to explain or forecast one or more daily travel decisions, i.e. which sequence of modes, including but not limited to just MaaS services, should be selected by the users to fulfill their planned daily activities taking into account the characteristics of the MaaS package (e.g. a limited number of trips or access time for a service).

MaaS customers' models involve strategic, long-term, and tactical pre-trip decisions, which are tightly connected. This section reviews the existing literature on such models and the travel demand emerging from individual choices and their interactions with the supply characteristics, leaving the decision-making models of the other relevant actors (service providers, authorities) to the next section.

2.4.1 MaaS demand models

The MaaS modelling paradigm intends to capture a wide range of travel demands, including different user profiles by capturing their heterogeneous mobility needs [25]. Given the wide range of mobility needs that MaaS bundles should meet, it is crucial to characterise MaaS demand in terms of the spatial and temporal distribution of both users' mobility requirements and mobility options offered by MaaS [65, 20]. Thus, customers' travel patterns involve a variety of destinations and activities, all of which require adequate accessibility and flexibility in the combination of various modes offered within the bundle. Conversely, lack of availability of services in the bundle or poor quality levels could affect customers' decisions; a bad experience of being unable to access certain services might cause consumers to reconsider their subscriptions. Demand and bundle design characteristics are the main variables in a MaaS decision-making model and are mutually dependent [71]. Therefore, it is essential to model how different users' travel requirements and the availability of mobility services within the bundle interact. MaaS models should also consider varying mobility demands over the course of numerous days, e.g. a weekend schedule may vary from a typical working day. In this way, a MaaS decision-making model needs to consider a long-term horizon to capture the variety of mobility needs within a daily trip and across multiple days [6].

MaaS demand emerges from individuals' subscription and mode choices decisions. To fully explain mode choice, trip chains need to be described at individual levels, and services need to be modelled at the vehicle level to assess resource utilisation. Considering that MaaS packages include new mobility services, such as on-demand, autonomous, and shared services (e.g., car-sharing services), the capacity and availability of those services must be carefully represented. Moreover, bundle design might include different business models to capture different mobility needs. For instance, the service usage within the subscription might have time-limited access or a discounted cost per trip, following business models tested and implemented in different cities [5].

In this context, conventional travel demand modelling approaches are not suitable to model MaaS demand. The traditional and well-established trip-based model cannot represent users' trip chain and mode choicesxs decisions. At the same time, a tour-based framework might be incapable of modelling the variety of users' activities over different days [72]. Additionally, one of the most significant barriers to characterising, forecasting, and optimising MaaS demand is a lack of real data to support it, as the MaaS system is not yet available in the market or has not been implemented long enough to observe its long-term impact on transport and mobility patterns. For this reason, the main approaches in the literature to model the MaaS potential demand rely on either stated-revealed preference surveys or collecting data and observations during pilot projects.

Stated-preference survey-based approaches

In survey-based approaches, participants share their mobility habits and socio-demographic characteristics with the modellers. Successively, the interviewees are asked to state their preferences in hypothetical scenarios in which different MaaS bundle options are proposed. These scenarios include a selection of available mobility services and costs, which the analyst can set or the participants can choose among a set of predefined options (e.g., [9, 21, 2, 73]). Besides MaaS scenarios, the participants' current travel choices are also collected to relate them to the interviewees' travel habits.
The survey approach is typically adopted to generate data and validate and calibrate discrete choice

models, which are meant to estimate the MaaS individuals' decision-making process. In the literature, few studies focused on estimating models for understanding users' willingness to subscribe to MaaS and their preferences for bundle types, including additional features and a set of individual characteristics, such as transferability, vouchers or designing unlimited usage of specific services within the bundle ([21, 12, 4, 2, 73, 74]). Guidon et al. [75] conducted a discrete choice experiment to study consumers' cost evaluation for single or bundled services. By introducing in the survey further questions concerning participants' perceptions or behavioural attitudes or intentions, they investigated bundles' impact on users' willingness to subscribe to MaaS ([57, 16, 76, 77, 78, 79, 80, 81, 82, 83]).

Further characterisations of end-user profiles were proposed by employing a cluster analysis process involving attitudinal factors, such as attitude towards car usage or public transport, towards shared mobility services, or towards technologies (e.g. [16, 15, 65, 76, 77, 84]). Conversely, estimation of willingness to subscribe to MaaS within specific target groups (e.g., aged people) have been performed [17, 2]. However, due to some simplifications of discrete choice models, the representation of users' potential travel decisions might not be fully realistic. For instance, a multinomial logit model relies on the independence of irrelevant alternatives (IIA) and assumes that the alternative with the highest utility is more likely to be chosen by the respondent without considering the interaction among sequential daily choices (e.g. [21, 4, 73, 17, 85]). Moreover, multinomial logit does not fully consider the variety of travel needs among users. Hence it is limited in the way it can capture users' heterogeneity, which is essential to estimating MaaS potential demand [21]. To overcome those limitations, several studies in the literature employ a mixed logit approach, in which the correlations in unobserved factors and different tastes across interviewees are incorporated (e.g. [12, 2, 75, 76, 61, 37]). Besides, the inclusion of latent variables in a mixed logit model has been explored through hybrid modelling estimation, in which hidden variables representing attitudes or perceptions of the users are included in the survey. These latent variables try to explain the travel behaviour through some specific attitudinal answers and are successively measured by indicators in the model estimation [86].

Revealed-preference pilot-based approaches

An alternative approach to model the MaaS potential demand and overcome the issues faced by applying a discrete choice model consists of running a pilot project [76]. Pilots aim to gather all information through a real early experience of the new services. This approach allows users to test the MaaS package type and its potential members at specific times and locations. It also helps analysts in giving observations through the investigation of the impact of specific MaaS bundle solutions in reality. Participants are usually recruited before running the pilot and selected to capture the most relevant aspects of MaaS demand in diverse contexts.

Several MaaS pilots and trials have been run around the world using different platforms, for instance, UbiGo in Sweden [87, 13], Tripi in Australia [88], Touring in Belgium [89], and only in the last half-decade commercial operating organisations are providing MaaS as real services (for instance, Whim in Finland and the Netherlands[1], Mobil-Flat in Germany[2], Yumuv in Switzerland[3], Gaiyo in the Netherlands[4], MyCorridor Salzburg-Athens and Korinthos-Amsterdam[5], Smile in Austria[6], and MyCicero in Italy[7]). Generally, in the trials, revealed preference studies are employed to validate and evaluate the potential of MaaS bundles and the users' travel behaviour [71, 87, 90, 91]. For instance, Storme et al. [89] evaluated car owners' readiness to shift from a private car to a MaaS bundle through questionnaires. Strömberg et al. [90] categorised different user groups by applying a cluster analysis. Within the same pilot project, Karlsson et al. [87] analysed in-depth information on the reasoning behind participants' opinions and their experiences by using the MaaS service. To the best of the authors' knowledge, a first joint approach using a discrete choice model and data from a pilot has been employed by Hensher et al. [88] and Ho et al. [63]. During this pilot, diverse subscription plans have been incrementally presented to the participants as a result of a data analysis process over the trial period. Hensher et al. [5] investigated the potential influences of the choice between subscribing to a monthly MaaS bundle and the pay-as-you-go (PAYG) option and how that impact the total monthly car kilometres. Ho et al. [63] estimated a choice model using revealed-stated preferences to assess the interest in MaaS subscription bundles compared to PAYG.

Table 2.1 highlights all papers above-discussed by methods and their focus for both approaches (stated-preference survey-based, revealed-preference pilot-based). The methods are arranged in order of simplicity. However, there is no arrangement for the revealed-preference pilot-based approach. The majority of the study used a hybrid choice model, mixed logit and hybrid choice model within the stated-revealed survey approach. Predictably, the bulk of the pilots were carried out before the COVID-19 pandemic and represent a minor fraction when contrasting the two methodologies.

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[1] https://whimapp.com

[2] https://mobility-talk.com/mobil-flat-in-augsburg-einmal-zahlen-alles-fahren

[3] https://yumuv.ch/en

[4] https://gaiyo.com/?lang=en

[5] http://www.mycorridor.eu

[6] https://smartcity.wien.gv.at/en/smile-2/

[7] http://www.mycicero.eu

Although the reported stated-preference survey-based and revealed-preference pilot-based approaches provided fundamental insights into the MaaS customers' decision-making process and have advanced the understanding of the MaaS users' choices, both approaches are limited in terms of the general representation of mobility requirements and activities performed by participants. The stated-preference survey results might not cover the whole population heterogeneity, as pointed out by Fioreze et al. [78], Ho et al. [4], and Lopez-Carreiro et al. [84]. Survey participants frequently do not accurately reflect the true distribution of demographic characteristics, which may produce biased results. The pilot-sample size is often too small to capture the MaaS demand variety and analyse MaaS potential users' travel behaviour, as underlined by Hensher et al. [5], Sochor et al. [71], and Storme et al. [89].

The pre-selection of pilot participants guarantees just a limited observation of the MaaS making-decision process. Moreover, attitudes employed to analyse users' willingness to subscribe at the time of the survey campaign might change in the future due to different experiences, perspectives, networks and new assessments [76]. Although the MaaS system intends to capture the variation in travel demand by promoting multimodality, the survey strategy does not allow a real experience of the new services, even proposing realistic multi-modal MaaS bundle scenarios. The interviewees' choice is the outcome of previous experiences that do not comprise a multi-modal journey under one subscription fee but rather a trip chain based on time-linked cost. Therefore, hypothetical bias may occur when respondents' stated preferences in a survey do not accurately reflect their real-world preferences and behaviors. Additionally, stated-preference surveys often do not incorporate budget constraints, which are a significant factor in real-world decision-making. Respondents may make choices that are financially unrealistic because they are not constrained by budget limitations in the survey. Currently, there is a lack of sophisticated models that can accurately capture the diverse mobility needs of users and the potential services offered by MaaS. However, some recent research has begun exploring microsimulation approaches to address this limitation and bridge the gap [25, 92].

Table 2.1: Summary of methods, authors and their focus for MaaS demand modelling

Method	Authors, year	Focus
SURVEYS		
Regression analysis	Fioreze et al., 2019 [78]	Attitude among residents towards the introduction of MaaS
	Liljamo et al., 2020 [15]	Estimating the current mobility costs of the respondents and relating their willingness to pay (WTP) for MaaS to their mobility costs
Heteroscedastic non-linear random parameter Multinomial logit	Ho et al., 2018 [4]	Understanding what types of MaaS subscription plans might appeal to potential users
	Ho et al., 2020 [73]	Different business bundle models and their appeals
Error logit component	Feneri et al., 2020 [77]	Understanding the model shift as a result of the availability of MaaS
	Krauss et al., 2023 [74]	Transport supply and mobility behaviour on preferences for MaaS bundles in multiple cities
Multinomial logit	Tsouros et al., 2021 [21]	Exploring demand and WTP for MaaS
	Narayanan et al., 2023 [85]	The development of a joint mode choice model for bike-sharing, car-sharing and ride-hailing services
	Mulley et al., 2020 [17]	The WTP for bundles of mobility services
Mixed logit	Caiati et al., 2020 [2]	Formulating and estimating a discrete choice model for MaaS adoption decision
	Kim et al.,2023 [61]	Understanding relationships of the tourist preference for tourism travel alternatives represented as MaaS
	Matyas and Kamargianni 2018 [27]	Understanding potential modes and features to be included in the MaaS plan and the WTP for these features
	Guidon et al., 2020 [75]	Analysing the difference between bundle and sum-of-parts WTP to determine bundling valuation
	Matyas and Kamargianni, 2019 [12]	Identifying individuals' preferences for the modes in the plans
	Caiati et al., 2020 [93]	Explore potential MaaS adoption considering age groups and life stages of potential users
Latent class	Alonso et al., 2020 [76]	Identifying factors relevant for MaaS adoption
	Veer et al., 2023 [37]	Providing in sights into which factors influence the intention to use MaaS among private vehicle owners
	Kim et al., 2022 [83]	Understanding how people's lifestyle associated to WTP

Hybrid choice model	Polydoropoulou et al., 2020 [80]	Individualising preferences for MaaS
	Matyas and Kamargianni, 2021 [65]	Examining individual preferences for MaaS packages
	Kim et al., 2021 [79]	Identifying users' preference for intermodal options under MaaS adoption
	Schikofsky et al., 2020 [81]	Understanding motivational mechanisms behind the intention to adopt MaaS
	Lopez-Carreiro et al., 2021 [84]	Identifying a set of attitudinal and personality factors relevant for MaaS adoption
	Vij et al., 2020 [16]	Understanding consumer demand and willingness to pay for MaaS
	PILOTS	
Statistic analysis	Storme et al., 2019 [89]	Exploring car usage reduction in return for a monthly mobility budget, which they could spend on MaaS services
	Musolino et al., 2023 [91]	Capturing the main behaviour variables of MaaS transport users
"before", "during", "after" questionnaires	Sochor et al., 2016 [71]	Insights from a six-month field operational test
	Strömberg et al., 2018 [90]	Analysing who is the potential MaaS customer
	Karllson et al., 2016 [87]	Insights from the trial and evaluation of an example of MaaS
The binary choice model	Hensher et al., 2021 [5]	Investigating the potential for changes in monthly car use in the presence of a MaaS program
Mixed logit with correlated random parameters	Ho et al., 2021 [63]	Assessing the interest in MaaS subscription bundles compared to PAYG

2.4.2 Modelling the MaaS demand-supply interaction

The above-described MaaS choice models allow quantifying the importance of the factors described in section 3 in the users' decision-making process, but they cannot fully capture the interaction between users' preferences and the characteristics and dynamics of the supply system. Hence, to capture the emerging mobility patterns and the demand-supply interactions, a more advanced method is needed which captures the users' mobility needs (i.e., which modes and MaaS packages would the users need to reach their planned locations and activities) and represents users' dynamic response to the performance of the supply system.

In this regard, a model that can represent the interplay between supply and demand is agent-based modelling (ABM) [94, 95]. In the 1970s, the ecological field saw the first use of the ABM [96]. However, there was a significant increase in the number of application disciplines between 2000 and 2002 [97]. Since then, the social, ecological, behavioural, and complexity sciences have praised ABM for its potential to start a ”revolution” [94]. ABM may depict real-world actors as heterogeneous individual agents carrying qualities and behaviours (including interactions with other agents and/or their environment) because it is based on the underlying concept of methodological individualism[94, 95].

Through decision-making processes, agents can exhibit sophisticated behaviour, adapt, and learn from experience using the agent-based method [97]. To roughly achieve intertemporal goals, ABM agents can make use of a range of decision-making representation techniques, including simple behavioural rules, decentralised optimisation, and sophisticated anticipatory learning algorithms [94, 95]. ABM suggests constraints on agent decision-making, although these restrictions exist in all social organisations in the actual world. Additionally, ABM allows spatial and temporal characterization of mobility services in the network (e.i.carsharing car availability at the station) [98]. In the end, the model allows for the microscopic description of each individual agent, enabling the analysis of aggregated behaviour and understanding of population trends [97]. Given the complexity (particularly nonlinearity and heterogeneity) and other characteristics of social-ecological (human-environmental) systems, gives a crucial and suitable technique for developing MaaS modelling systems [99].

The ABM represents agents through characteristics and activities, which are performed in a synthetic network. Agents interact locally in space and network and, adapt their behavior to the current state of themselves and their environment in their pursuit of performing their activities while minimizing their travel expenses and as in any real-world social organisation [97]. Travel costs can be calculated by replicating mobility decisions of the supply in terms of schedules and capacities as they are made in the actual world [100]. These aspects, particularly agents’ flexible and diverse behavioral responses observed in human society or nature, is not easily found in simplified models. This is the reason why ABM enables a realistic mobility model, in particular for a complex systems such as MaaS.

In the context of MaaS system, lately, few authors have employed the ABM approach to model the MaaS demand-supply interaction. Becker et al. 2020, built ABM to assess the impact of supply side characteristics of a potential MaaS scheme on the transport network [14]. They conducted a first joint simulation of carsharing, bike-sharing and ride-hailing in an agent-based simulator presenting a framework to capture welfare variation across supply side characteristics of a potential MaaS scheme. Authors identified KPIs for welfare representation such as energy consumption while fixing the membership of each MaaS supplier as in reality at the simulation moment without considering any membership decision model. Despite the interest of this study, the authors lack establishing a decision-making process for potential MaaS users while focusing exclusively on the capacity variation of potential MaaS suppliers in the network. For instance, Cisterna et al. [101] simulated a MaaS service by endogenising the MaaS subscription and bundle choices within the agent choice set to allow a virtual experience of the service in terms of subscription fee and capacity constraints. Each agent in the ABM perceives the trade-off between the MaaS subscription fees and time-linked mobility service costs. Finally, comparing the outcomes with a scenario in which MaaS was not a mobility option, the authors investigated the impact of MaaS bundle price on MaaS demand in terms of customers' travel attributes. The main limitation of this study lied in the simulation of only one specific bundle, while MaaS should differ in customized bundles according to users' mobility needs.

While Kucharski and Cats [92], instead proposed the MaaSSim agent-based simulator; this model can represent agents' taste variations (heterogeneity), their previous experiences (learning) and available supply information (system control). Within the simulation, agents are individual decision-makers who might be able to reject or accept a specific incoming ride proposed by another type of agent, the drivers. Viceversa, the drivers may opt out of the system or reject incoming travel requests, whereas an intermediate agent, the platform, matches demand with supply to achieve equilibrium. In Cisterna et al. [25] study, car policy as the total cost of ownership (TCO) is embedded in the ABM to identify its impact on MaaS demand. Varying the TCO among diverse scenarios and simulating a specific type of MaaS plan giving unlimited access to the services, the authors identify two potential customers' travel behaviours in terms of modal shift and travel characteristics. The lack of inclusion of variances in MaaS membership fees and bundles by the authors prevented the demand-supply interaction from being included in the model.

While some models presented in the literature have started filling the gap in knowledge of Maas decision-making modelling, there remain different challenges to be addressed. A more sophisticated model is needed to capture the dynamic response between demand and supply, optimise MaaS bundles in terms of mobility services and their service characteristics, and provide competitive subscription fees. Moreover, the MaaS choice might not solely depend on the single user's choice but on a set of travel requirements, which may depend, for instance, on family members. Hence, a model able to represent the influence of other users' choices on an individual mobility decision is still missing. MaaS systems might also be employed in different domains, such as for private companies and municipalities. Therefore, a more general and flexible MaaS decision-making model is needed to forecast the MaaS demand within diverse backgrounds. Additionally, interactions with different actors need to be addressed in a MaaS decision-making model; for instance, the possibility of applying subsidies such as car policies to encourage users' modal shift toward MaaS development, or a specific allowance for selected mobility services within bundles.

2.5 MaaS multi-actor modelling

A successful MaaS implementation relies on understanding the interactions and decision-making of all actors in the ecosystem, including the Broker, the Mobility Service Providers (MSPs), and policymakers (road authorities, government). Policymakers are responsible for service availability, supply capacity, and defining supportive policies. Modeling collaboration and inclusion of transport operators under local authority regulation is crucial to assess MaaS feasibility in a specific context. The literature has analyzed aspects related to the relevance of suppliers joining MaaS [102], the role of public transport [11], and direct collaboration with the government [20]. However, a comprehensive model that captures the complex interaction between services and actors, considering competition versus cooperation strategies, is yet to be introduced. In this section, we examine the literature on MSPs and government involvement to understand the essential next steps for a comprehensive assessment of this system, as shown in Figure 2.1. Specifically, we focus on (i) different types of business models defining the relationship between MaaS Broker and MSPs, (ii) developing MaaS as a platform-based system, and (iii) incorporating government and user choices in a multi-modal context.

2.5.1 MaaS Business Models

In the MaaS ecosystem, each actor involved usually has a distinct business model based on the "product" they are selling. A business model represents how a company creates customer value [103]. When joining a MaaS system, companies need to adapt and change their Business Model (BM) in order to have a profitable service [102]. Understanding this adaptation, how to maintain their identity inside the MaaS market, and if it is possible to define a general BM, valid for different MSPs and scalable to multiple locations is still unclear.

One of the main aspects that must be taken into account that affects the definition of a general BM is the interaction between MSPs and the MaaS Broker. The MaaS Broker is considered the central actor operating between MSPs and users [68]. To understand the role of this new figure, Eckhardt et al. [103] studied different pilots and mobile applications developed in Europe. They can identify three types of MaaS Broker models: commercial, public, or public-private partnership (PPP). It's important to note that all mobility services in a MaaS system should be fully integrated, including ticketing, payment, planning, booking, mobility packages, customer support, and regulation. These services should be accessible through a single mobile application. Examples of such applications have been mentioned in Section 3.

The MaaS Broker plays a crucial role in gathering relevant MSPs in the analyzed area and creating packages tailored to users' needs. To accomplish this, the Broker must establish appropriate business contracts with MSPs. According to Eckhardt et al. [103], service agreements can involve re-sold services based on fare lists or fixed percentage reductions, while negotiated services rely on bilateral agreements for fare determination. Existing mobile applications offer practical examples of these agreements. For instance, MaaS Global, the developer of the Whim App[8], purchases mobility services in advance (e.g., bus, taxi, bike rides) based on users' monthly trips and profiles, combining them into packages for profit. In Berlin, the Jelbi App[9], operated by Berliner Verkehrsbetriebe (BVC), handles contracts with MSPs, enabling seamless integration for users to directly pay for each mobility service within the app. Trafi company facilitates this integration, while the payment process is not handled by Trafi and BVG; they solely provide platform integration. The type of agreement adopted depends on factors such as the analyzed area, regulations, and the willingness of MSPs to participate. Consequently, a MaaS model needs to be comprehensive enough to capture the various business agreements between MSPs and the MaaS Broker.

In a recent study by Van den Berg et al. [104], an economic framework was developed to analyze mobility services within a supply chain structure. The study explored different business models in a competitive transportation market involving two MSPs, considering scenarios both with and without a MaaS platform. Although this approach may have limitations when applied to large-scale and complex networks, we believe that embracing such economic studies is valuable for conducting ex ante analysis of different business scenarios. By employing an economic framework that predicts potential outcomes based on the adoption of various business strategies between MSPs and the MaaS Broker, it becomes possible to guide MSPs in selecting the most profitable option.

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[8] https://whimapp.com

[9] https://www.jelbi.de/en/home/

2.5.2 Modelling the demand-supply interaction as a two-sided market

As pointed out by Calderón and Miller [105], some authors have proposed the two-sided market (or multi-sided platform) concept to model the interaction between users and MSPs in a MaaS context. Using this approach, a platform (or several) supports the interaction between different sides and, unlike usual transportation models, it has to be attractive to MSPs and users [106]. In their discussion paper, Meurs and Timmermans [106] define important factors to consider when modelling MaaS as a multi-sided platform. The customers can choose to use the MaaS application, where several services are offered, or directly purchase each mobility service separately. Utility functions can be defined for each service, considering classical mode choice characteristics related to the mobility service and to the users, but also taking into account new aspects connected to uncertainty and trust. MSPs, instead, might participate in the platform only if the service becomes profitable. Each MSP seeks to maximise their profit function, which depends on “the number of users of the services, price/fares of the trips, the marginal costs of the trips per traveller as well as fixed costs of the service provider and costs of the platform”. The authors believe that this profit depends on three main factors: (*i*) demand, (*ii*) costs, and (*iii*) competition strategy. It seems extremely important to quantify the impact of competition between different MSPs joining the MaaS platform to understand their willingness to participate. In this context, the authors suggest game theory to study the behaviour of all MSPs at equilibrium. Albeit the interesting suggestions, the work of Meurs and Timmermans [106] does not include a precise modelling solution. Djavadian and Chow [107] present a practical approach that utilizes an agent-based day-to-day adjustment process to model MaaS as a two-sided transport market. The model incorporates flexible transport services (FTSs) such as ridesharing, car-sharing, and taxis, which serve as first/last mile options for complementing transit services during a trip. FTSs are considered sellers in the two-sided market, while users act as buyers of these services. The model extends Djavadian and Chow’s work [108] by adjusting both passenger and vehicle fleets, as well as the FTS operating policies. However, it is worth noting that this model does not encompass all the concepts that define the MaaS concept in its entirety. Instead, it primarily focuses on the integration of FTSs as part of the first/last mile connectivity within a larger transportation network. Specifically, we believe that a representative model of MaaS should include:

- a multi-modal system with all modes of transport included;
- encode directly in the model the concept of mobility subscription to capture cooperation between MSPs;
- a multi-actor system able to analyse the impact of Government' polices on different MSPs' strategies subject to users' heterogeneous modal choices inside a MaaS platform.

2.5.3 Multi-modal multi-actor system

It is clear that, in order to model a multi-modal and multi-actor system such as MaaS, classical transportation approaches have to be extended. Following this purpose, in their literature review, Pham et al. [109] seek to identify the accessibility indicators that can influence the interaction between the different MaaS actors in order to develop a conceptual framework to model them. The main findings of this study underline the presence of several gaps in the transportation literature. In particular, current models do not consider (*i*) psychological indicators to quantify demand-supply interaction; (*ii*) dynamic pricing; (*iii*) monthly service users to optimise the offer; (*iv*) the efficiency of the entire transport system; and (*v*) MSPs' point of view when defining packages and mobility options based on users' preferences and available services.

Kamargianni et al. [110] proposed an initial step towards a more comprehensive modelling framework for MaaS. Their framework comprises several components that address the structuring of the business ecosystem, replication of MaaS platform functionalities, and modelling of demand response using agent-based modelling within a multi-modal network. This general framework is combined with the SimMobility simulation model[10], which is an agent-based, activity-based, multi-modal simulation platform capable of representing individual travel decision-making and transportation system operations across different time scales. However, it is important to note that the cited work does not provide a real-world application of the proposed framework. Additionally, the role of government or local authorities in the development of the MaaS system does not appear to be emphasized in this particular framework. Further research and application are necessary to explore the practical implementation and the integration of government policies and regulations within the MaaS context. The government plays a vital role in the MaaS system by implementing subsidies, taxation policies, defining the role of public transport, and supporting the MaaS market and business viability. Pagoni et al. [111] emphasize the need for improved regulations at both the European and national levels to foster

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[10] https://mfc.mit.edu/simmobility

the development of MaaS in Europe. Additionally, the presence of private service providers is crucial for MaaS to become a viable alternative to private car usage [112]. Dandl et al. [113] propose a tri-level model where the government sets regulations, transit service designs, and plans to maximize social welfare at the highest level. A single MSP operates at the second level, aiming to maximize profit by adjusting service designs based on the decisions of the upper level. At the lowest level, users optimize their utility by choosing paths and modes of transport.

However, this model does not consider the MaaS concept or the dynamics of competition and cooperation among different MSPs in the transportation network. Bandiera et al. [114] proposed a multi-modal network design approach using a supernetwork framework to incorporate various mobility services and packages. They formulated the problem as a Mathematical Program with Equilibrium Constraints (MPEC), considering profit maximization for MSPs at the upper level and user assignments based on traffic network equilibrium at the lower level. This approach allows studying the strategies of individual MSPs in competitive or cooperative transportation markets. Recently, Najmi et al. [115] developed a multi-class, multi-modal, multi-provider market equilibrium model to analyze ride-sharing, ride-sourcing, and transport operator dynamics. Expanding this model within the MaaS context can provide insights into different scenarios.

Despite the fact that MaaS modelling has advanced in the last years, a model able to generally encode all the different aspects listed above is still missing. Many are the challenges to overcome to study the complex MaaS ecosystem. Preliminary studies on the applicability of MaaS should be done considering:

- the area under exam;
- the list of the different MSPs available;
- define who undertakes the role of the MaaS Broker;
- the government's involvement with the entity of subsidies and regulations.

Moreover, this model should consider that each MSP wants to maximise its profit and maintain its identity inside the market. For this reason, it is extremely important to understand the impact of different business agreements between the MaaS Broker and MSPs and in which conditions cooperation and competition between MSPs reach an equilibrium point for the entire MaaS system. These studies could be carried out through economic frameworks that try to understand different ”what if” scenarios, expanding models such as the ones developed by Bandiera et al. [114] and Najmi et al. [115] in the context of a multi-modal and multi-actor equilibrium models.

2.6 Discussion and Conclusion

To model the various components of a Mobility-as-a-Service (MaaS) ecosystem, it is necessary to understand the behavior of all actors involved in offering and utilizing the services. This challenging task requires gaining a better understanding of the relationships between critical factors that influence MaaS adoption. These factors serve as essential inputs for behavioral and econometric models used to forecast MaaS demand in different future scenarios and contexts.

By predicting the behavior of emerging users in combination with supply characteristics, new models and sustainable plans can be evaluated, thereby supporting the implementation of MaaS in different scenarios and for various customer segments. This chapter proposes a generic framework for MaaS ecosystems (refer to Figure 2.2), achieved through a critical analysis of existing literature. The aim is to contribute to the understanding and development of different building blocks for MaaS ecosystem models.

The framework describes the main 3 areas analysed in this chapter. While there is already a substantial number of papers analyzing the main critical factors influencing MaaS adoption (blue area in Figure 2.2), providing a solid foundation for developing MaaS models, the connections between these factors and their resulting impacts on forecasting MaaS appeal remain uncertain. Notably, discrete choice modeling, calibrated and verified through surveys and small-scale pilot projects, has been the dominant method employed in consumer choice models in existing literature (green area in Figure 2.2). Although these models offer valuable insights into MaaS adoption, they may not fully encompass the diverse travel requirements and preferences of users. Moreover, current decision-making models lack the capability to represent the dynamic interplay between supply and demand in a MaaS ecosystem. Additionally, there is a paucity of studies that have developed decision-making models for various stakeholders within the MaaS ecosystem, including government agencies, mobility service providers (MSPs), and MaaS brokers (red area in Figure 2.2). The need to extend traditional techniques to a multi-actor level has become increasingly apparent. Despite offering some guidance for addressing research questions, this study has certain limitations.

The proposed framework in this chapter does not include the arguably second generation of MaaS, known as Mobility-as-a-Feature (MaaF), which includes not only mobility services but also non-transport features. By incorporating a wide range of essential non-transport mobility services, MaaS appeal could be increased. Additionally, MaaF offers a transition from a dominant multi-modal perspective to a multi-service perspective. To achieve this, MaaF should be driven by organizations without a direct vested interest in transport supply ownership but with an extensive customer base to focus on delivering comprehensive integrated activity solutions that encompass appropriate transport options.

Furthermore, this study did not analyze additional non-transport services, so the proposed framework could be revised and enhanced to accommodate the new generation of MaaS. Similarly, the study did not thoroughly evaluate the potential of MaaS in rural areas. Furthermore, the development of the MaaS ecosystem relies on an integrated multimodal platform that aims to incorporate real-time traffic and route planning information. However, this study did not investigate existing literature on MaaS platform implementation.

Lastly, this chapter critically examines the existing literature on MaaS actors, as proposed by Wong et al. (2021) [20], focusing on three areas of study. Its objective is to provide valuable insights and enhance our understanding of the complex dynamics and relationships within a MaaS ecosystem. In addition, it seeks to shed light on knowledge gaps regarding the general complexity of the MaaS ecosystem as well as any specific subsystems (or areas) that are suggested in the framework, as represented by the research questions and the individual building blocks that they are built of. Future research is expected to model all actors and their intricate interactions within the presented comprehensive framework, enabling the update of traditional planning models to address the specificities of MaaS.

In conclusion, this chapter establishes the groundwork for subsequent chapters in this thesis, which explore the decision-making models of the actors, with a specific emphasis on the customer decision-making process.

Chapter 3

Impact of subscription fee on MaaS adoption: an agent-based approach

Highlight of the Chapter

Based on the findings of the previous chapter this research simulated the effects of MaaS fees and cost of ownership on customer behavior. Three distinct customer profiles were identified based on subscription fee ranges, with different preferences and behaviors regarding MaaS adoption. Customers who frequently traveled long distances and used multiple transportation modes were more likely to subscribe to MaaS at higher fees, leading to a reduction in private car usage. Users who relied on cars and public transport for short distances were more inclined to subscribe to MaaS at lower fees but less likely to give up car ownership. In the long term, a MaaS system can become profitable and competitive, and subsidizing the system could lead to a greater reduction in car users. Implementing car policies that increase the total cost of ownership could further drive users towards the MaaS system, but this may require higher subscription fees to generate revenue.

The work presented in this chapter has been described in the following papers:
"The impact of total cost of ownership on MaaS system appeal using an agent-based approach", CSUM Conference 2022: Advances in Mobility-as-a-Service Systems

"Impact of subscription fee on MaaS adoption: an agent-based approach", to be submitted to Case Studies in Transport Policy Journal

3.1 Introduction

Mobility-as-a-service (MaaS) emerged in 2014 [7, 8] as a one-stop service solution, and while no clear consensus for a general definition exists, it has been described as a system in which a wide range of mobility services are provided to customers through a single digital platform [116, 27, 77, 78, 65]. MaaS is defined as a subscription-based system in which customers gain access to a variety of services for a set fee, such as a monthly fee or a pay-per-use scheme [77, 78, 65]. The system features a single digital interface that aims to integrate all services payment, booking and ticketing processes in order to provide users with a seamless multi-modal journey [18, 10, 5]. This interface is usually managed by a new actor called MaaS Broker (or MaaS provider), who ensures multimodality by evaluating and combining all transportation and no-transportation services (e.g. coupons) into a MaaS package (or plan) via the digital interface [27].

Three types of MaaS Brokers exist: commercial, public, or public-private partnership (PPP) entities. The first type can adopt a reseller model when selling transport services on the market, or an integrator model, which includes ticketing, planning, etc. In the second case, a public transit operator could integrate other transport services into the system. Lastly, the PPP model usually includes logistics services, and the public actor includes different actors and service [117].

With the MaaS service, consumers can employ a tailored portfolio of mobility services to satisfy their travel needs without being biased toward a particular owned form of transportation [14]. The MaaS subscription fee should become competitive with ownership expenses considering that car owners tend to underestimate the costs of vehicle ownership [15, 16], giving potential users a financial advantage over their current mobility budget [14].

To become competitive, MaaS should capture numerous user profiles mobility portfolios, which are based on users' travel needs meant to meet schedules that range greatly from one another [15]. As a result, modeling the impact of subscription fees on users' willingness-to-subscribe (WTS) to MaaS is essential to represent the heterogeneity of users' mobility needs and mobility budgets at the individual level [65] . Furthermore, due to their inherent dynamic availability and accessibility, mobility services included in the subscription fee, such as carsharing (the reservation of another person may prevent a car from being available at a carsharing station), taxi, or on-demand modes, must be geographically and temporally represented in the modelling process [14]. On the other hand, it's crucial that such a modelling process provides reliable macro-level key performance indicators (KPIs) that aid in understanding the MaaS system's appeal in the global market and its potential goals toward shifting to shared mobility in order to support policy making and understand emerging behaviour and trends.

Numerous studies have been carried out on MaaS potential schemes for assessing sustainability goals system and willingness-to-pay (WTP) for MaaS [3, 88, 118]; despite those studies, it is currently unknown how to model MaaS to comprehend how subscription fees affect market attractiveness and WTS to the MaaS service.

Therefore, the purpose of this study is to assess the impact of subscription fee ranges on potential MaaS adoption through a case study-based simulation framework in which vehicle ownership costs are embedded, allowing users to perceive and experience the trade-off between MaaS fees and private-modes cost. The study also individualizes potential customers' travel characteristics based on the subscription fee range, providing future trends for MaaS market attractiveness, its business and environmental sustainability, and its implications for cities transport and mobility policy goals.

The remaining sections of this chapter are structured as follows: Section 2 provides a literature review on users' willingness-to-pay (WTP) in MaaS studies. Section 3 outlines the research methodology. In Section 4, the research findings are summarized, focusing on a comprehensive case study conducted in the Brandenburg region surrounding the metropolitan area of Berlin, Germany. The section also highlights the trend of users' willingness-to-subscribe (WTS) to MaaS as a car replacement within a profitable business model. Finally, conclusions and limitations are discussed in Section 5.

3.2 State of the Art

Willingness-to-pay (WTP) for Mobility-as-a-Service is primarily defined in the literature as the act of purchasing a MaaS-specific bundle configuration allowing access to a specific mix of transport modes and their related characteristics (for instance unlimited bus trips, free or discounted access to bike sharing, a limited number of taxi rides, some free or discounted booking hours of car sharing, etc.) [78, 65, 84, 21]. In this study we will also use the term willingness-to-subscribe (WTS) to refer to the intention to become member of a MaaS platform and for a specific multimodal bundle.

Several studies have assessed WTP for MaaS systems highlighting an overall strong users' sensitivity to subscription fee values in relation to the offered services [4]. A study performed in the Netherlands found MaaS users willing to pay a monthly fee of 150-180 € [93, 119], while a study in the UK estimated WTP to be between 120 €-200 € for offering basic to unlimited PT, bike sharing, taxi and carsharing within the bundles [80].

Focusing on specific users' profiles, infrequent car users, high-income bikers, and public transport users are reported as the most likely profiles to adopt MaaS, and willing to spend up to 64% of their mobility budget [15, 4, 65]. In terms of ownership costs, studies highlighted that a clear reduction in private car usage through real-world MaaS adoption may be difficult [89], so it is still unclear whether a change in users' travel patterns may be possible through MaaS promotion [90, 73]. On the other hand, it is clear that users' lack of awareness of their ownership costs reflects their low willingness to subscribe to MaaS [16, 78, 84].

Despite existing studies provide already relevant insights into MaaS adoption and WTP, they present some limitations in providing a full spectrum and to reveal the complexity of the users' willingness to subscibe to MaaS services. For example, in stated-preference surveys participants' selection of hypothetical MaaS bundles scenarios is based on an exogenous and predefined choice of bundles, or is based on their prior expectations centered on a single-mode trip rather than the actual multimodal journey costs that MaaS seeks to provide [2, 4, 73]. Furthermore, analysts frequently modify scenarios by using a specific set or ranges of MaaS subscription costs and mobility services that at best resemble the interviewees' current mobility behaviours [2, 27]. As a consequence, analysts may underestimate the participants' choice of scenarios in response to a change in these ranges, since respondents' attitudes may change over time as a result of potential exposure to novel and distinctive experiences, perspectives depicting a transitory attitude rather than a potential future behaviour [15, 65, 78, 84, 83]. Finally, survey samples are also frequently small in size and limited in range to fully represent users' heterogeneity and cover the broad range and mix of MaaS bundles and prices that could be offered in practice [78, 65, 90, 89].

Alternative solutions are to be sought to assess willingness-to-subscribe and capture mobility patterns emerging from demand-supply interactions in the MaaS multimodal system. Such solutions should be capable of estimating and forecasting which modes and MaaS packages users will look for to reach their planned visited locations to perform their daily activities. Additionally, the model should capture the variety of users' dynamic responses to the supply system's performance while assessing MaaS market penetration.

Currently, there is no approach that accurately and comprehensively captures the heterogeneity of users' mobility behaviors and costs, which is necessary to comprehend the impact of subscription fees on WTP and WTS for MaaS. Traditional transportation models, such as trip-based and tour-based approaches, may not be suitable as they rely on aggregated variables and indicators for a specific time period, thereby overlooking the diverse travel patterns of users and their adaptations to new mobility options. These models fail to consider individual activity-travel patterns across different days [72]. On the other hand, disaggregated microscopic models, such as agent-based models (ABMs), provide a more detailed representation of users' travel patterns at both temporal and spatial levels, allowing for the capturing of individual trips and activities [120, 98].

Among the available microscopic models, ABMs are particularly well-suited for simulating individual user behavior and forecasting MaaS adoption with a realistic level of detail. ABMs enable agents to exhibit complex behavior, adapt, and learn from experience through realistic decision-making processes that aim to minimize travel costs [97]. ABMs can also represent time-dependent mobility patterns at the user level by simulating transportation options based on the spatial and temporal distribution of mobility services, taking into account scheduling and capacities [98]. By employing ABMs, analysts can generate key performance indicators (KPIs) at both the agent level (e.g., distance traveled, travel times) and the aggregate level (e.g., modal split, total kilometers traveled per transport mode), thereby capturing the potential demand characteristics of MaaS and understanding the factors influencing its adoption and its impact on shifting behavior towards sustainable mobility alternatives.

The main contribution of our approach is to provide a framework for evaluating various scenarios that may differ in terms of parameters such as offered transport modes and their costs, MaaS bundle compositions, subscription fees, and more. This is achieved by utilizing a synthetic yet realistic representation of a specific virtual context. Few studies in the literature have used an ABM approach to study MaaS systems; for example, Becker et al. [14] adopted it to assess the welfare impacts of

MaaS systems. Nishida et al. [121] examined the costs and benefits of introducing on-demand shared services on a MaaS digital platform. Recently, Kucharski and Cats [92], developed MaaSSim, a new open-source ABM simulator that can represent agents' taste variations and previous experiences, as well as supply availability information.

Although the above methods represent insightful approaches to assess MaaS systems, they do not systematically study and evaluate the potential users' WTS to MaaS and the potential profiles of the MaaS members in relation to specific prices and bundles. In fact, all agents were considered eligible for access to all modes, and no subscription fees were considered in those past works [14, 121].

More recently, Cisterna et al. [25] provided a first approach to understand the impact of the total cost of ownership (TCO) on MaaS appeal using an ABM approach. They examined the sensitivity of MaaS adoption across TCO ranges through the endogenization of TCO in the private car users' trip-cost function and a fixed MaaS subscription fee. Starting with the methodology developed by Cisterna et al. [25], this paper seeks to extend previous results by addressing the following research questions:

1. What impact does the subscription fee have on willingness-to-subscribe to a MaaS bundle?
2. What are the typical customers profiles and their travel characteristics and preferences across subscription fee ranges?
3. To what extent and under what conditions can MaaS become competitive and contribute to shift travellers towards more sustainable mobility alternatives?
4. To what extent and under what conditions can MaaS generate revenues contributing to its business sustainability?

To address the aforementioned research questions, this study examines the impact of subscription fees on WTS to a MaaS bundle using a synthetic experiment through the extension of a calibrated ABM case study around the city of Berlin [25]. By varying the subscription fee parameter around a benchmark value [2] and using a single type of bundle that allows agents to freely use the bundled services, we assess users' mobility behavior to prices variation. Following the determination of the MaaS fee's impact, this paper generates and analyses different KPIs such as customers' modal split, average and total kilometers traveled, average travel time by mode, average total number of trips, and average kilometers traveled per mobility service within the MaaS bundle. Finally, this paper discusses trends and conditions pertaining to the long-term sustainability of the MaaS business model and its profitability by looking at the generated revenue for each price value.

3.3 Methodology

We draw inspiration from the ODD (Overview, Design and Details) protocol created by Grimm et al. 2020 for the agent-based model [122] in order to facilitate replication of the methodology given in this thesis. Without being overly technical, ODD was created to make it simpler to write and interpret ABM descriptions and to aid in model replication. The ODD protocol follows an inverted pyramid structure that first provides a general overview of the simulation's objective before progressively going into more specifics. The protocol is divided into three categories: Overview, Design, and Details, each of which has a number of smaller components [122]. The following section outlines the ABM's overarching goal or objective and offers the methodology for the Overview, while the Design section attempts to describe the generated model. Ultimately, the Details section provides enough information for readers to comprehend the model and its reasoning in its entirety and, theoretically, to re-implement it in its entirety [123].

3.3.1 Overview

Purpose and Pattern

Real-world users can complete their daily tasks on a budget by choosing from a variety of mobility options. Users naturally choose their travel mode in order to meet their needs in terms of performance (such as arriving on time to work), cost of ticketing or travel, and discomfort associated with using that option. Users often change their mobility habits when a new mobility option better fulfills their needs than the previous one did, reaching a point of satisfaction where they no longer want to change their habits until a further new mobility alternative might appear on the market. The agent-based model can represent a natural paradigm like this one at the individual level, making it a useful simulation tool for assessing innovative transportation systems like MaaS.

In this study, an agent-based modeling approach is utilized, employing the open-source software MATSim [124]. MATSim simulates the travel choices of individuals (or agents), including the selection of transportation modes, routes, and departure times. These agents are characterized by predefined socio-demographic attributes and daily activity patterns.

Entities, State Variables, and Scales

This subsection aims to list the different types of entities, variables and temporal and spatial resolution of the model[122].

Agents/Individuals:

The ABM used in this thesis has one type of agent. The state variables for each agent include socio-economic characteristics such as ID number, age, gender,car availability and economic status. Besides, agents define plans containing their activity chains which represent the daily goals agents want to accomplish in real life [124].

Spatial Units:

The ABM is a platform for dynamic spatial-temporal simulation. Each agent is represented at a temporal level which rules, action, are defined into minutes, hours, seconds, and spatial level through coordinates. Same occurs for transport modes simulated.

Environment:

The agents represent people in the city of Berlin [120, 125]. Therefore, a Map (or network) of the Berlin and Brandenburg region was simulated, where agents travel by choosing diverse mobility services to reach activities (destinations) has been simulated. In this way, agents interact and affect each other choices on the network. There are four possible activities for agents within the network: home, work, leisure, shopping, or other type activities [126].

Action:

Agents act by assessing their preferences and the travel distance and then moving from one activity to another in order to maximise their satisfaction. Each agent represents a travel in the environment as in real life and has a defined combination of activities. To do so, agents and vehicles need to move in the defined environment in which each agent performs their daily tasks (or experienced plan), and obtains an experienced score (or economic function) which represents their satisfaction level [127].

Process overview and scheduling

Inspired by ODD protocol [122], an ABM can be broken down into a number of submodels. The ABM presented in this thesis extends the carsharing model presented by Giorgione et al. 2019 [120] into MaaS membership and bundle model.

In the ABM MATSim model proposed in this thesis agents perform their daily tasks by experiencing a certain level of daily satisfaction. Such performance and experience are repeated within subsequent iterations (iteration loop), to allow users to experience diverse mobility services available in the network in order to find strategies that increase their score, till an equilibrium is achieved, where scores are not (significantly) improving from one iteration to the next. To solve this complex problem involving optimisation of thousands of agents, a co-evolutionary algorithm is used to achieve a stable state (equilibrium) [124, 128]. This metaheuristic method typically divides a large problem into smaller subcomponents and solves each one separately to solve the larger problem (the system equilibrium). Every agent (subcomponent) constantly re-evaluates its daily activity schedule as it competes for space-time slots on the synthetic transportation infrastructure with all other agents. By performing optimisation in terms of distinct scoring functions and within the context of an agent's set of plans, the co-evolutionary algorithm achieves a (stochastic) user equilibrium state. As a result, the stochastic equilibrium is reached when agents achieve a stable level of satisfaction with their plans (experienced score) and no longer tend to modify them [129].

3.3.2 Design Concepts

The Design Concepts section describes how 7 concepts important for the design of ABM were considered in the model [122].

Basic Principles

This subsection aims to describe an iteration loop in which agents interact with each other to reach an equilibrium in which they are satisfied with their mobility choices. The iteration process to update the agents' experienced plan is schematically represented and explained by the conceptual framework in Figure 3.1. This process is built by Controller Events (or just events) which are the main-user facing classes of MATSim, are repeated until the agents' average score stabilizes and the system equilibrium is reached [129]. It should be noted that the number in the blue square in Figure 3.1 represents the number assigned to each controller event. In our approach, a new Controller Event named MaaS

Scoring (Controller Event 6) is plugged-in into the loop [25]. Prior to the start of the loop, each agent in MATSim possesses a memory that contains multiple daily plans [124].

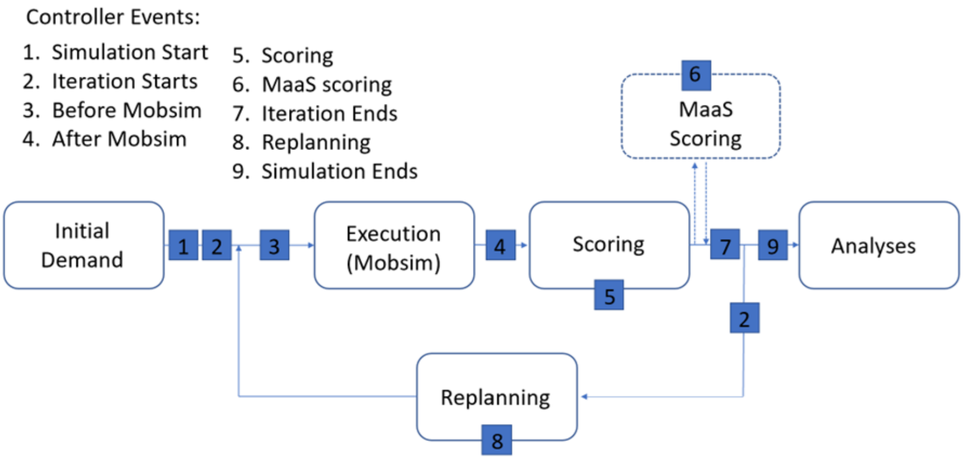

Figure 3.1: MATSim conceptual framework [128, 129]

Each plan consists of a sequence of daily activities and an associated score. During each iteration of the loop, the agent selects a plan from its memory before the network loading simulation begins using Mobsim (1-2 Controller Events). The mobility simulation is then initiated, and the plan is executed in the synthetic network, where agents travel on the network using their chosen transportation modes to fulfill their daily tasks (3-4 Controller Events). After the plan is executed, the actual performance is evaluated to calculate the experienced plan and its corresponding score in Controller Event 5 (see next section). At this stage, the MaaS subscription fee can be incorporated through the new MaaS Scoring module (Controller Events 6). The detailed methodology for calculating the Scoring of the experienced plan and MaaS scoring will be explained in the Details section. Following the evaluation of the experienced plan, the Replanning event [127, 126] (Controller Event 7) allows agents, through pre-defined strategies, to change their travel behavior. The selected strategies involve modifying an agent's plan from memory and designating one as the chosen option, modifying an agent's plan by a re-routing process, changing the transport mode of a single trip or for the entire trip chain as well as shifting the departure time of daily activities. This Event, hence allows agents to experience diverse travel alternatives available in the network that differ from their mobility habits represented by their experienced plans stored in the memory. After a certain number of iterations, an equilibrium is reached where the agents can no longer unilaterally improve their plans and relative scores, thus, as a result, the average population score stabilises.

Emergence

The number of agents who choose to subscribe to the MaaS bundle incorporated in the set of daily agents' mode options are the model's emerging outcome. The model provides the identity of each possible MaaS user by printing a file containing the MaaS member ID at the end of each simulation.

Adaptation

In the ABM model agents mimic observed behaviours by following a predetermined set of rules. For example, each activity is assigned a certain time period. During the daily simulation, agents are permitted to switch their means of transport for each trip chain or for one single trip in order to complete the task on time. Agents may also change the start and end times of each activity (up to three minutes each), depending on the mode of transport and the amount of time needed to get to the activity destinations. Additionally, a driving permit is required for agents to use a car.

Learning

Agents can update their travel choices based on a previous decision to increase their daily satisfaction, in terms of travelling (e.g. arriving late to the destinations) and performing their daily activities. In this way, they change the decision-making process based on what they learned from the previous decisions and they reached the most satisfactory travel choice.

Sensing

Agents perceive the other agents and the environment around them, gathering information for their decisions both locally and globally. Agent locally senses the single activities performances but at the same time, he/she is sensitive to other mobility choices which interact with the local and single decisions.

Interaction

The model assumes that agents will interact directly. To get to the next location, an agent will switch modes, for example, if they wish to reserve a carsharing vehicle but it is not available in the network. If they opt for public transport, they will ride with other agents unless the bus's capacity is exceeded in this case they will opt for other transport means. Agents who select a car based on availability will interact on the network regarding perceived traffic congestion [130] and, as a result, journey time. Agents affect and engage with one another inside the network in this manner. [98].

Stochasticity

In term of stochasticity, the presented model reach a stochastic equilibrium in which the agent aims to maximize their daily satisfaction [129]. Randomness is introduced by selecting a number of plans in the agents' memory to make the models more suitable for depicting real-world variations [130].

3.3.3 Details

This section aims to provide detail sufficient for readers to fully understand the model and its rationale and, in principle, re-implement it.

Initialization

The primary steps for initialization of the ABM model are creating or collecting a synthetic population with attributes along with the network. This study starts for the ABM carsharing model, (MATSim version 12.0 [1]) in which carsharing services module is integrated to capture carsharing preferences in the population (the model in MATSim started in the 2009 with Ciari [98], and it was extended by Giorgione et al. 2019 [120]) to implemented an extension for MaaS systems. In the next section, more detailed descriptions are provided.

Input Data

In this subsection, we identify any external input data required for the model implementation.

Network

To facilitate the simulation, MATSim requires a synthetic infrastructure represented by a network file composed of nodes and links. The basic network for this thesis is obtained from the previous scenario in MATSim from Giorgione et al.2019 [120]. The network is obtained by importing the Berlin and Brandenburg region's OSM (Open Street Map) map into JOSM (Java Open Street Map), an extendable OSM and Java editor[2]. After the map is loaded, an ad-hoc MATSim plugin transforms it into a network that the program can read, complete with a basic link and node properties [120].

Additionally, data on public transit and carsharing services in Berlin were obtained from reliable sources [3](see Figure 3.2). Besides private car, walking, cycling, and public transit services, the study simulates an urban car-sharing system that incorporates both free-floating and two-way services [4].

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[1] https://matsim.org/apidocs/carsharing/12.0/index.html

[2] Nico Kühnel. Network Editor for JOSM. 2014

[3] https://berlintransitmap.de/

[4] https://berlin.stadtmobil.de/privatkunden/stationen/,https://www.share-now.com/de/en/berlin/

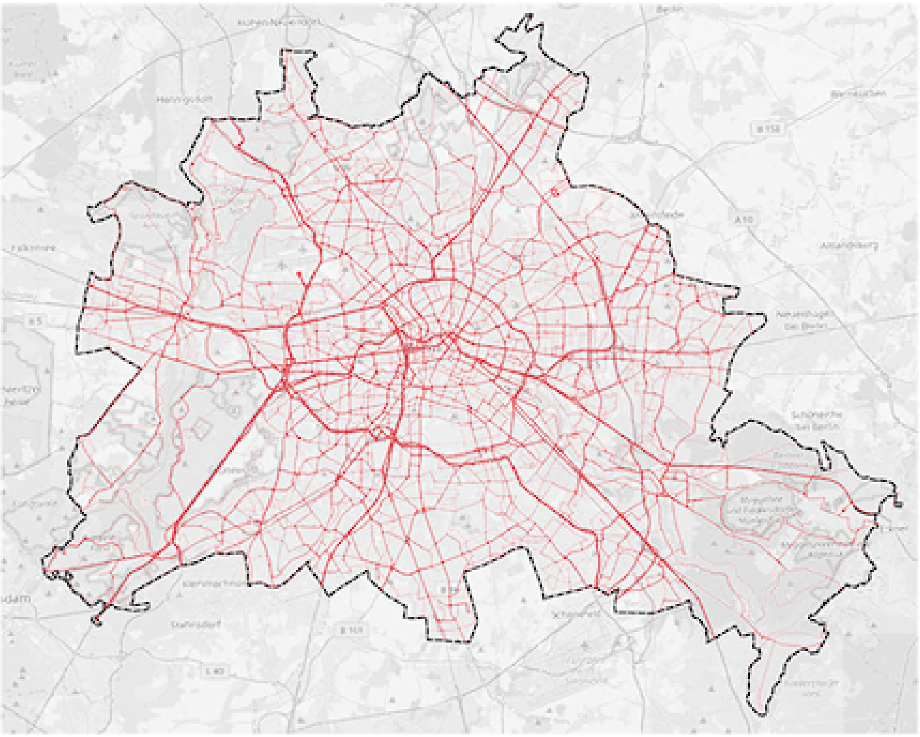

Figure 3.2: The Berlin city transport network [120]

For two-way carsharing, 62 stations with two cars each are considered, while 160 cars are distributed in the service areas for the free-floating carsharing service.

Synthetic population

The synthetic population (plan file in MATSim) used in the study is also based on the work of Giorgione et al. [120] and includes 25,560 residents from Berlin's central area. The plan file is generated by census data along with a complete list of respondents' activity chains. Giorgione et al.2019 extended the previous synthetic population from Zimnke et al. 2019 [125] by adding essential attributes to it. Those attributes are age, car availability, employment (yes or no), ID number of each agent, income, gender, and value of time. Additionally, each agent has an activity chain description (agent's plan) with each type of activity with its starting-ending time and link location on the network and GPS coordinates. The trip is described by a leg in which the mode choice, departure and travel time are displayed along with the route chosen identified by the link and GPS coordinates of the network.

Configuration

The input configuration file (config file), which links the analyst and MATSim, is used to configure the simulation. It consists of multiple software modules and groupings of parameters and strategies. This thesis kept the config file strategy from Gorgione et al. 2019 which is calibrated for carsharing module in MATSim. Such strategies enable users to switch modes for each trip chain or single trip (SubtourModeChoice, CarsharingSubtourModeChoiceStrategy) along with randomness of single trip choice and agent's satisfaction maximization. Here, additional parameters are specified for the constants used to represent the scoring function (shown in detail in the next section) and previously calibrated [120, 98], giving the agents more options for how to adjust their plans. Finally, in the configuration file the number of iterations to reach the equilibrium is set to 700.

Submodels

The Sub-models refer to sub-processes that together form the ABM [122]. In this thesis, the main submodels that form the ABM framework (Figure 3.1) are Event 5:Scoring and Event 6:MaaS Scoring. The latter includes the total cost of ownership implementation.

Event 5: Scoring

The experienced score (Controller Event 5 in Figure 3.1) is calculated after agents perform their daily activities and travel choices in the synthetic reality (Mobsim) see 3.1.

In MATSim, the experienced score is calculated by the sum of all utilities obtained by the daily activities performed $\sum_{q=0}^{N-1} S_{act,q}$ and the travel (dis)utilities $\sum_{q=0}^{N-1} S_{trav,(mode)q}$, where N is the number of activities and q indicates the trip induced by the activity as shown in Equation 3.1 [127]:

$$S_{experinced} = \sum_{q=0}^{N-1} S_{act,q} + \sum_{q=0}^{N-1} S_{trav,(mode)q} \tag{3.1}$$

The travel (dis)utilities by each mode are calculated as shown by Equation 3.2:

$$S_{trav,(mode)q} = \alpha_{t,mode} + \beta_{t,mode} * T \tag{3.2}$$

$S_{trav,(mode)q}$ is the generic daily experienced score of travelling by a generic transport mode originally available in MATSim (such as public transport or car) where:

- α_{mode} is the mode-specific constant that represents the part of the utility that is not considered by the variables in the utility, or it represents a fixed trip cost (e.g. public transport ticket);
- $\beta_{t,mode}$ is the marginal utility or discomfort for the time spent travelling on that mode [127];
- T is the travel time between two sequential activity locations q and $q+1$;

Table 3.1 shows the value implemented in the simulation for each parameter in the Equation 3.2.

Parameter	Walking	Bike	Private car	Public Transit
α_{mode}	-0.4	-0.4	0.0	-4
$\beta_{t,mode}$	0.0	-26	-6.0	-6.0

Table 3.1: Alpha and Beta values

Equation 3.3 represents the daily experienced score of travelling by the time-based pricing system. In this system, the users are charged based on the travel time service usage commonly used in carsharing services [5] where:

$$S_{trav,q,time\_based} = \alpha_{\text{cs}} + \beta_{c,cs} * (c_t * t_r) + \beta_{t,walk} * (t_a + t_e) + \beta_{t,cs} * T \tag{3.3}$$

- α_{cs} is the carsharing-specific constant that represents the part of the modal utility that is not considered by the variables in the utility;
- $\beta_{c,cs}$ is the marginal utility of the time spent travelling by carsharing, previously calibrated [131, 120];
- c_t cost linked to time travelled.Those costs are determined based on the current prices (€/min) offered by carsharing companies in Berlin [6];
- t_r is the total reservation time;
- $\beta_{t,walk}$ is the marginal utility or discomfort of an additional unit of time spent walking, as shown in Table 3.1 for walking mode;
- t_a access time to the car;
- t_e egress time to the car;

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[5] https://www.share-now.com/

[6] https://berlin.stadtmobil.de/privatkunden/stationen/,https://www.share-now.com/de/en/berlin/

- $\beta_{t,cs}$ represents the marginal utility of an additional unit of time spent traveling with carsharing, [131, 120];

- T is the actual (in vehicle) time;

Table 3.2 displays the value of the calibrated parameters for time-based pricing systems in Equation 3.3.

Parameter	Free-floating	Two-way
α_{cs}	0.0	-0.4
$\beta_{c,cs}$	1	1
c_t	0.20	0.22
$\beta_{t,cs}$	-0.1	-6.0

Table 3.2: Alpha and Beta values for time-based pricing systems

Within the experienced score calculation of score (or utility) of modes available in the network are separately simulated. Thus, agents experience single-mode cost when they choose it.

Event 6: MaaS Scoring

The MaaS system is simulated as a potential mobility option by editing the experienced score function in its travel (dis)utilities part ($\sum_{q=0}^{N-1} S_{trav,(mode)q}$), previously calculated in the Scoring Event 5. In particular, an agent is eligible to access a MaaS bundle, if his/her experienced plan during generic iteration t contains at least one of the services included in the MaaS bundle. The eligibility is based on the assumption that users are affected by their predetermined travel choice and they seek similar choices within the bundle [110, 10, 83] To do so, a screening process of each agent's mode choice through the experienced plan is performed within MaaS Scoring event and before calculating the MaaS score [25]. If agents are eligible to subscribe to a MaaS bundle they have the option of paying the subscription bundle cost, ($Cost_{\text{MaaS,bundle}}$) and access to the bundle services. Once the accessibility to the MaaS system is given, the , $S_{\text{MaaS}_{(t)}}$, at the generical iteration t is calculated as shown below in the Equation 3.4:

$$S_{\text{MaaS}} = S_{\text{experienced}} + Cost_{\text{included}} - Cost_{\text{MaaS,bundle}}, \tag{3.4}$$

where $Cost_{\text{MaaS,bundle}}$ represents the subscription bundle fee and $Cost_{\text{included}}$ denotes the costs of the stand-alone services included in the bundle, paid by the agents in their experienced score $S_{\text{experienced}}$ and reimbursed to agents after subscribing to the MaaS plan. Such expenses are quantified by only selecting the time-linked cost c_t (for instance, travel time t for carsharing) and the trip-based ticket cost of MaaS services α_{mode} as calculated in the Scoring Event 5 (subsection above) [127, 98] and displayed by Equation 3.2 and 3.3. Conversely, costs linked to the discomfort of travelling calculated in Scoring Event 5 ($\beta_{t,mode}$) are retained because they are linked to the perception of the mode rather than a specific predefined cost.

The MaaS bundle in this study assumes that subscribers have unlimited access to the modes of transportation included in the bundle. Different bundling schemes involving price discounts and access time limits will be explored in the next chapter. The transport modes in the selected bundle are: public transit, free-floating and two-way carsharing. Following Sherman et al. [132], the MaaS subscription fee is assumed to be a fixed daily cost. Such daily cost is based on a benchmark monthly subscription fee of 150 €, resulting in a daily benchmark cost of 7.50 € assuming 20 working days in a month from the previous study [2].

Total Cost of Ownership

The MaaS Scoring event incorporates the total cost of car ownership (TCO) into the agent's travel cost, which is an additional expense per kilometer and is separate from determining MaaS subscription eligibility. This integration of TCO into the scoring system aligns with previous research by Vij et al. and Becker et al. [16, 14] aiming to increase drivers' awareness of their car-related expenses. To calculate the TCO, Eisenmann et al. [133] conducted a study using a national travel survey. Their research determined the average total cost of ownership per kilometer as 0.30 €/km, which serves as the basis for the calculation. The TCO covers both the costs associated with acquiring a car and its ongoing operation. This includes operational expenses such as daily fuel and lubricant costs, as well as additional costs like car depreciation (based on the initial purchase price), repair and maintenance expenses, taxes, and insurance. Conversely, costs such as garage rental, parking fees and highway tolls as long as washing car costs are not considered [133]. By considering the daily depreciation cost, this comprehensive definition of TCO enables the MaaS Scoring system to accurately integrate long-term car purchasing decisions into the day-to-day choices made by MaaS users. Since the TCO is a cost linked to the travelled distance, the screening process within the MaaS Scoring event further counts the agent's car trips and their travel distance.

In summary, the MaaS Scoring event provides 3 different scores: 1) in case an agent does not employ a private car but is eligible to subscribe to the MaaS bundle, Equation 3.4 will be applied; 2) if the agent employs a private car and is eligible to subscribe to MaaS, the MaaS score will be calculated as shown in Equation 3.5 below:

$$S_{\text{MaaS,TCO}} = S_{\text{experienced}} + Cost_{\text{included}} - Cost_{\text{MaaS,bundle}} - TCO * \sum_{q=0}^{q,\text{car}} I_{q,\text{car}} * d, \tag{3.5}$$

where $I_{q,\text{car}}$ is a Boolean variable to indicate whether or not the trip induced by activity q is made by car or not, along with the distance travelled d.

For both options 1 and 2 a comparison between experienced and MaaS score is performed. Conversely, 3) if the agent is not eligible to subscribe to MaaS but employs a private car, Equation 3.6 provides the additional cost of owning a car to the experienced score:

$$S_{\text{TCO}} = S_{\text{experienced}} - TCO * \sum_{q=0}^{Q,\text{car}} I_{q,\text{car}} * d. \tag{3.6}$$

In the last case, the experienced score will be only updated of TCO additional cost S_{TCO}, and added to the agent's plans memory.

The Overview, Design, and Detail sections were presented above as a comprehensive guide (ODD protocol [122]) for understanding and replicating the model implemented in this thesis.

In the following section, we present the simulation results for all 21 MaaS fee scenarios based on MaaS subscription fees range from 0 to 15 € per day. The fees are varied marginally by 10% for each scenario, from -100% (no monthly fee) to +100% (15.00 €/day) relative to the benchmark fee of 7.50 € [2], in order to analyze customers' sensitivity to the MaaS price. The first section (4.1) provides information on the impact of the MaaS subscription fee on users' WTS by displaying the number of agents who purchase MaaS. While the second section (4.2) examines the travel characteristics of MaaS members, the third section (4.3) delves into MaaS sustainability goals and provides an understanding of the potential competitive remuneration of a MaaS Broker. Finally, section 4.4 provides a discussion of the main findings and draws potential policy implications.

3.4 Results

In this chapter, we present the simulation results of all 21 MaaS fee scenarios. The first section (5.1) gives insights into the impact of the MaaS subscription fee on users' WTS showing the number of agents that purchase MaaS thus willing to subscribe to the MaaS bundle. The second section (5.2) analyses the MaaS members' travel characteristics prior to and after subscribing to MaaS suggesting possible user profiles willing to subscribe to MaaS depending on the service fee. The third section (5.3) provides insights into MaaS sustainability goals and conditions in which the MaaS service may become competitive in terms of ownership. Finally, the fourth section (5.4) gives an understanding of the potential competitive remuneration of a MaaS Broker.

3.4.1 Impact of MaaS subscription fee on willingness-to-subscribe to MaaS

Figure 3.3 depicts the percentage of MaaS users in the population sample (x-axis) across the 21 MaaS fee scenarios (y-axis) simulated varying the subscription fee from 0 to 15 €/day. Straightforwardly, the percentage of MaaS users decreases as the fee increases in general, with a significant share of generated agents using the MaaS system for at least part of their daily mobility (40%) when offered with no fee, and only 6% being willing to use MaaS when offered with a high fee of 15 €/day. Within these extreme scenarios, three distinct trends can be observed, ordered in the figure from top to bottom: the first range (*high*), consists of the scenarios with a relatively high MaaS fee ranging between 12 and 15 €/day. The second (*medium*) contains the scenarios with MaaS fees between around 5.25 € and 11.25 €/day, while the third (*low*) is characterized by MaaS fees below 5.25 €/day. As shown one can observe, that there is a noticeable doubling of the percentage of MaaS users moving from the group *high* to the *medium* (i.e. the demand jumps from around 6.5% to 12.5%). Such an increase may be the result of more users willing to subscribe to the MaaS system attracted by a more competitive fee in relation to the cost of the alternatives (private car, public transport and carsharing offered as pay-as-you-go). Conversely, the percentage of users in the group *high* remains almost constant which may indicate that there is a specific category of agents with a high willingness to subscribe. Within the *medium* range, around 1% more MaaS members are gained for each 1€ less fee price.

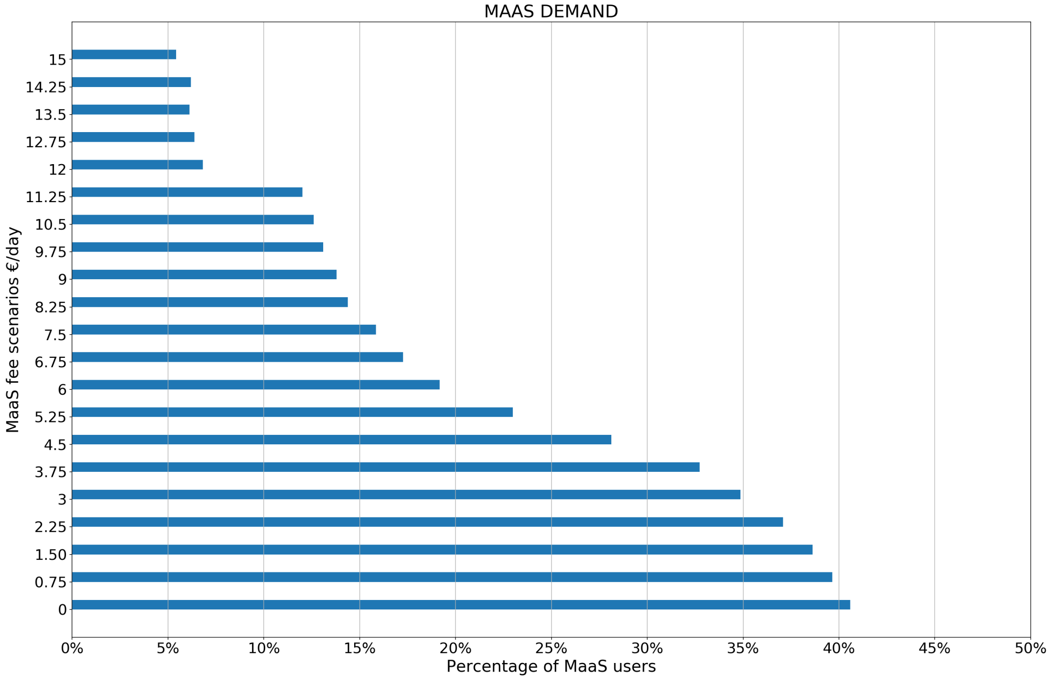

Figure 3.3: Percentage of MaaS members across MaaS Fee scenarios

Although the shift is less sharp, a significant change in trend can be also observed when the MaaS fees move from *medium* to *low* (e.g.,approximately 19% to 28%) moving from a fee of 6 € to a fee of 4.5 €/day, and an equally significant increase in the percentage of the number of users is shown in the *low* (e.g. approximately 28% to 40%). Hence, the simulated price range provides a clear variation in WTS between a relatively expensive service (up to twice more expensive than the benchmark fee), and a free membership scenario (representing for instance a fully subsidised MaaS platform), suggesting that choosing the right fee for the MaaS system would make a huge difference in the overall MaaS adoption.

3.4.2 Analysis of MaaS customers' profiles

An analysis of agents' behaviour before and after the subscription is performed to assess the modal shift induced by the MaaS subscription and to profile the potential MaaS users across fee ranges. To do so, we first show the mobility statistics of the entire population in a scenario without the introduction of any MaaS service. To simulate this scenario, we run the simulation process in Figure 3.1 in which, in the MaaS Scoring event, only the TCO is embedded. Such a scenario, from now on, is referred to as the NoMaaS scenario.

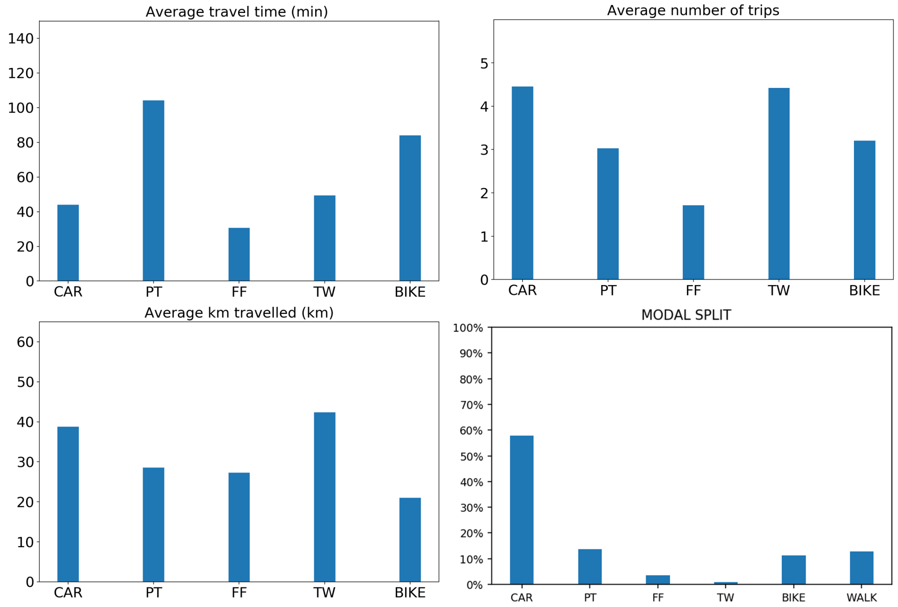

Figure 3.4: KPIs and modal split of all agents in NoMaaS scenario

Figure 3.4 shows the different KPIs of all 25560 agents in the NoMaaS scenario. The KPIs are users' modal split, average kilometers traveled, average travel time by mode, the average total number of trips, and average kilometers traveled per transportation mode (with the exception of walking mode). The modal split is computed by dividing the number of trips for each transport mode by the sum of all trips performed by the agents. The main transport mode used is private car (with more than 55% of all trips), followed by public transit with 12%, whereas carsharing services (free-floating and two-way) are overall employed by less than 5% of the trips. The active modes (walk and bike) represent around 24% of the users' modal split in the NoMaaS scenario.

On average, private cars and two-way carsharing vehicles are utilized for approximately 4 trips per day, with an average travel time of 40 minutes and an average distance of 40km per day. This indicates that two-way carsharing is primarily employed as a substitute for private cars and serves as the exclusive mode of transportation for the entire trip chain. This is supported by the fact that the total agents have an average trip chain of approximately 4 trips per day inside a 41 daily kilometer travelled. Public transit users, on the other hand, take fewer trips on average (around 3 trips per day) compared to private car users. Public transit is often used in combination with other modes to complete the daily trip chain. However, public transit users spend more than double the amount of time traveling compared to car users, with travel times exceeding 100 minutes. Free-floating (FF) carsharing is utilized for a smaller number of trips on average (1.6 trips), as users have the flexibility to leave the car anywhere on public streets and are not required to return it to the same location they picked it up from. This suggests that the service is typically used for only a portion of the agents' daily plans. Carsharing users cover distances that are comparable to those of private cars and public transport (around 30 to 40km), indicating that they are primarily used for longer-distance trips.

We are currently directing our attention to comparing the behavior of users who have subscribed to MaaS services with their travel patterns before MaaS was introduced. The single figure, labeled as Figure 3.5, displays the modal split in the NoMaaS scenario at the top, while the bottom section depicts the modal split of MaaS users after they subscribed to the service. Consequently, by comparing the two parts of the figure, we can observe the mode shift of the users across different price ranges.

Comparing the two results from Figure 3.5 a clear shift from private car (in blue) to public transit (in orange) is observed for users subscribing to the MaaS service. On the contrary, the usage of active modes (walk in magenta and cycling in grey) substantially decreases once users subscribe. The decrease is more evident in the group *high* in which their usage falls below 5% after subscribing, in favor of a more substantial use of carsharing services. Such results might indicate a potential substitution of active modes by MaaS services. Hence, considering the high fees, users might tend to employ MaaS to satisfy all possible trips during the day since they are offered with no usage limits (user's opportunistic choice). Whereas the shift of two-way carsharing usage (in red) is not too noticeable before and after MaaS introduction, free-floating usage strongly increases covering more than 10% of the trips in most of the scenarios. In the NoMaaS scenario the FF service was never employed by more than 3% of the trips. Such results might further suggest that MaaS subscribers may find it more convenient to use the free-floating carsharing services instead of using (and in turn owning) their own private car.

Combining the statistics related to the number of MaaS members shown in Figure 3.3 and the modal split changes displayed in Figures 3.5 interesting policy implications can be derived: whereas with high MaaS fees the share of MaaS members is relatively small, (around 5-7%), with lower fees, for instance with 4.5 €/day, nearly 30% of the agents is willing to subscribe, which means around 7000 agents in the simulation. For all the simulated scenarios more than 10% up to 15% of the trips are done by carsharing, indicating that each shared car in the fleet is continuously used, as opposed to private cars that would be needing a parking space most of the time the owner is performing an activity and hence not using it. This confirms that offering MaaS at affordable fees may reduce the

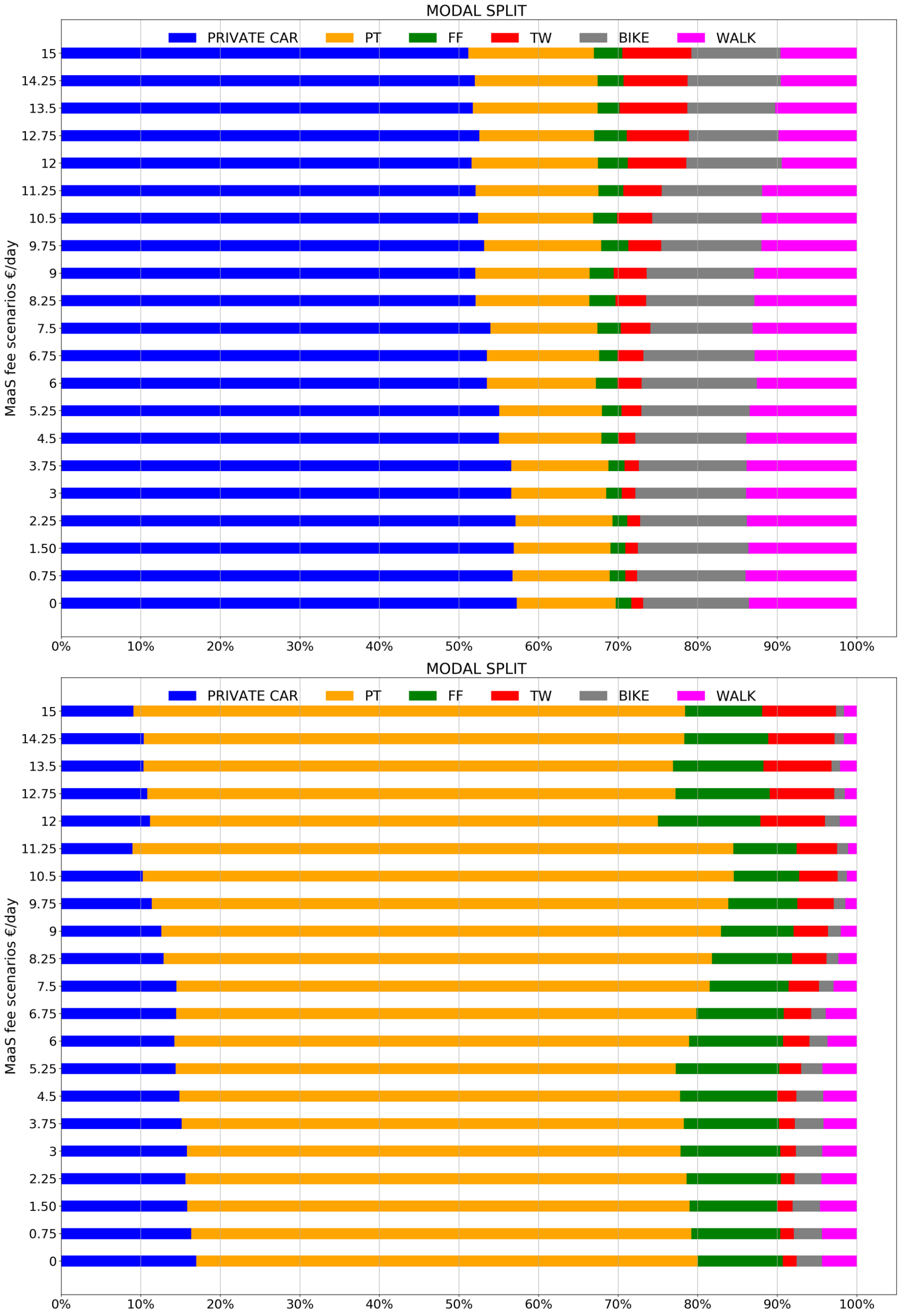

Figure 3.5: Modal split of MaaS users in NoMaaS scenario (top figure) and in MaaS scenario (bottom figure) across MaaS fee scenarios

total number of cars in the network, as well as the need for parking spaces, hence it would be beneficial for sustainable mobility targets. Moreover, considering the higher negative impact that high MaaS fees create on active mobility, it would be sensible to discourage the implementation of high MaaS prices, for instance by considering offering subsidies to the mobility service providers joining the MaaS platform.

We now analyse the main KPIs for the four motorised modes of transport (private car, PT, two-way and free-floating carsharing). Figure 3.6 shows the indicators for private car users in the NoMaaS scenario (in black) and MaaS (in blue) for the different scenarios. For low fee scenarios, the users who continue to use private cars slightly decrease their average travel time (-10 minutes) and number of trips (1 trip less on average) due to low subscription fees. Group *medium* users experience a more significant reduction (-30 minutes), whereas group *high* users reduce their average number of trips and travel time substantially, as result of the more significant reduction of the distances travelled by private car. High subscription fees may therefore determine a substantial reduction in the number of trips, travel time, and km traveled for private car users, but the reduction of private car usage is more evident for price ranges, especially looking at the total km travelled, again indicating the potential benefits of MaaS for achieving sustainable mobility targets.

Figure 3.7 shows the same KPIs previously discussed for private cars, but for public transit. The difference between the use of transit for the NoMaaS and MaaS scenarios is less distinct, hence we only show the average travel time and number of trips. Group *high* shows the highest average travel time, with users spending over 160 minutes on public transit trips and a higher average number of trips (4 trips on average) compared to the other groups.

Figure 3.8 depicts the KPIs for two-way carsharing. The average number of trips remains high due to the nature of a station-based service for group *high* but the service is used essentially as before the introduction of the service. Conversely, the uptake of free-floating services is shown in Figure 3.9. Since the usage of this service has increased significantly with respect to the NoMaaS scenario, this can be seen as a clear value added service for MaaS users. Figure 3.9 shows an increase in average travel time, km travelled, and number of trips with increasing MaaS subscription fees. This trend is accompanied by a reduction in average travel time within each group, suggesting diverse usage of the free-floating service among users. Group *high* uses the service for more than 2.5 up to 3 trips on average, which counterbalances the same reduction in private car trips. On the other hand, users

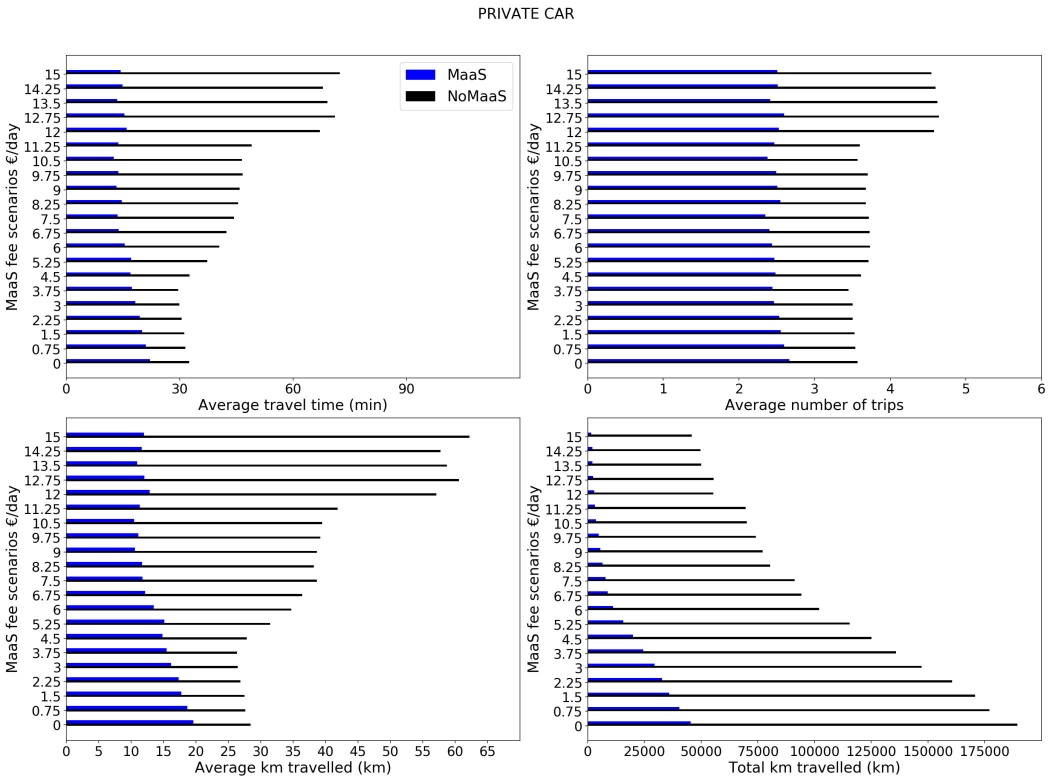

Figure 3.6: Private car KPIs across MaaS fee scenarios

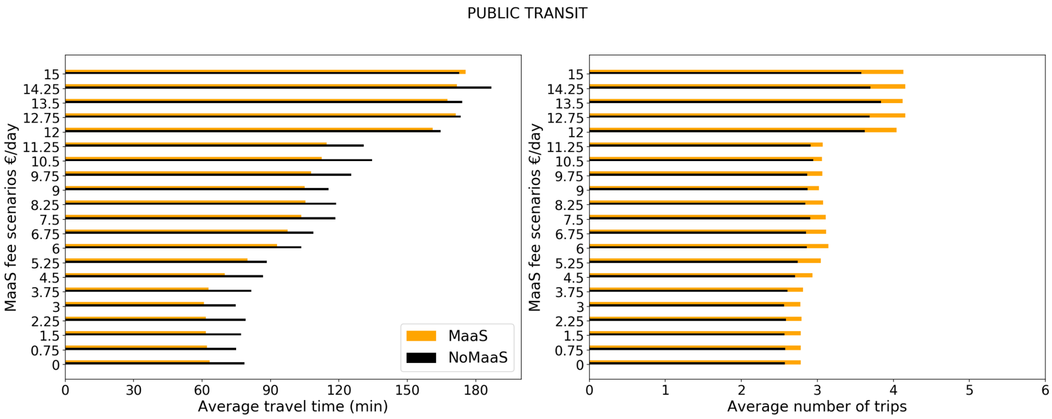

Figure 3.7: Public transit KPIs across MaaS fee scenarios

who pay less for their subscription use the service for shorter trips and distances and for fewer trips. Therefore, group *high* users (which are on the other hand less in number) may perceive free-floating as a potential substitute for private car trips, while other groups may use it occasionally to cover short trips that were previously covered by other modes (e.g. walking, cycling and public transit).

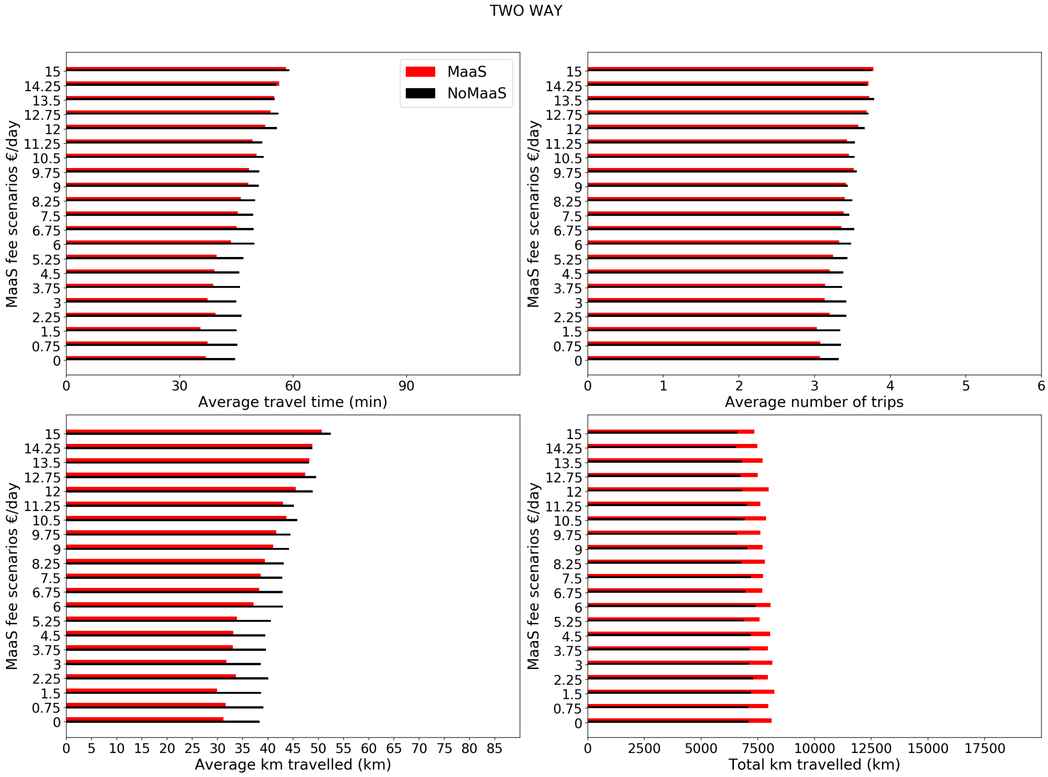

Figure 3.8: Two-way KPIs across MaaS fee scenarios

Finally, we study the sensitivity of the MaaS willingness to subscribe to changes in TCO values (Figure 3.10). For this figure, we considered the benchmark price of 7.5 €/day for the MaaS fee. In Figure 3.10, we can observe that a decrease in TCO from the benchmark of 0.30 €/km has little or no significant effect on the number of MaaS members, indicating that up to the benchmark value, the TCO is not considered as a cost impacting the use of private cars. Instead, when TCO is doubled to 0.60 €/km, the number of members increases substantially, nearly doubling the number of members when TCO is doubled from the benchmark value). This could suggest that car policies that increase ownership costs, such as increased taxes or fuel prices, would in turn push people to move to MaaS.

3.4.3 The impact of Cost of ownership on MaaS appeal

Additionally, as a result of the endogenization of the total cost of ownership in the methodology, this study illustrates the sensitivity of MaaS demand to changes in TCO price (Figure 3.10), through the same initialization presented in this study in terms of bundle type and benchmark subscription fee.

Figure 3.10 demonstrates that a decrease in the total cost of ownership (TCO) from the benchmark value of 0.30 €/km does not lead to a decline in the number of MaaS subscribers. Instead, the demand

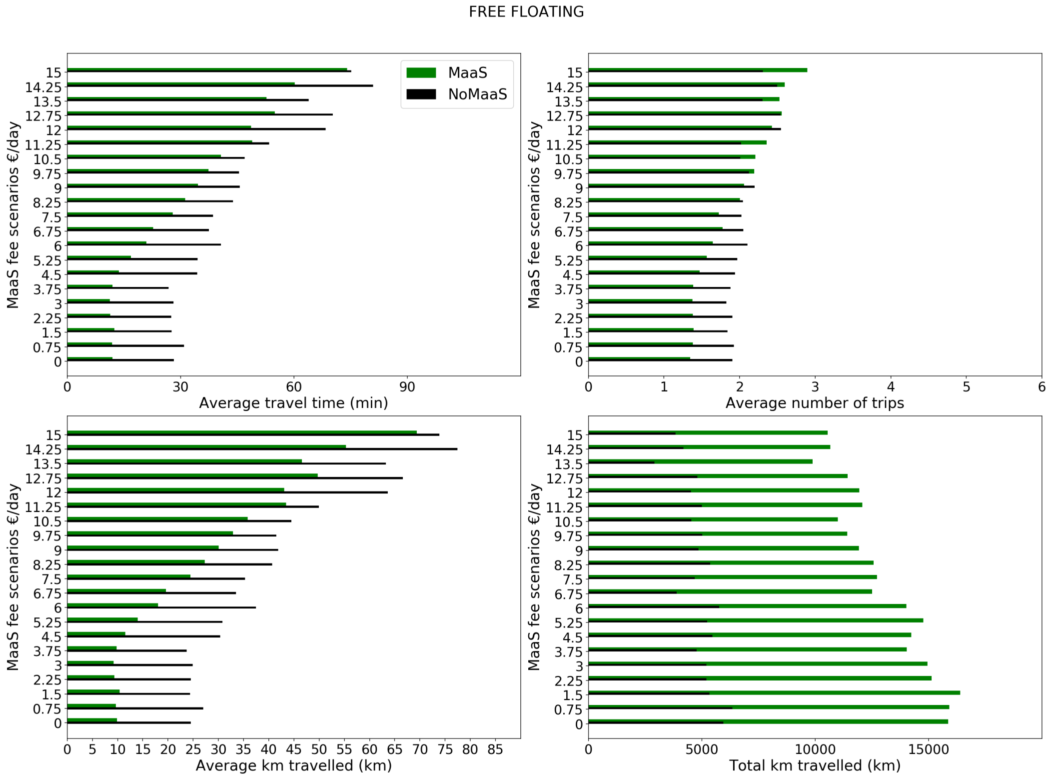

Figure 3.9: Free floating KPIs across MaaS fee scenarios

for MaaS remains relatively stable, indicating a slight deviation from a more realistic scenario where TCO is 0.00 €/km and users are unaware of their actual expenses. Conversely, a significant increase in the number of MaaS users (approximately 30% of the population) is observed when TCO doubles to 0.60 €/km. This suggests a potential shift in car policy or cost of ownership, where the MaaS system could serve as a long-term substitute for private car ownership.

Figure 3.11 depicts the aggregate number of trips per transport mode for MaaS members in different TCO scenarios. At a reference cost of 0.30 €/km, car trips constitute nearly 8% of the total trips, with public transport covering over 80% of them. As the TCO approaches zero, the percentage of car trips rises to around 19% of the total, while the proportion of public transport trips experiences an inverse pattern, decreasing to approximately 70%. MaaS members do not utilize active modes like walking and cycling when the TCO falls below the benchmark cost. Conversely, in scenarios where the TCO exceeds the benchmark, the overall number of car and public transport trips remains relatively stable, with a slight uptick in the proportion of trips made by active modes. The number of trips facilitated by carsharing services remains relatively consistent across all TCO scenarios.

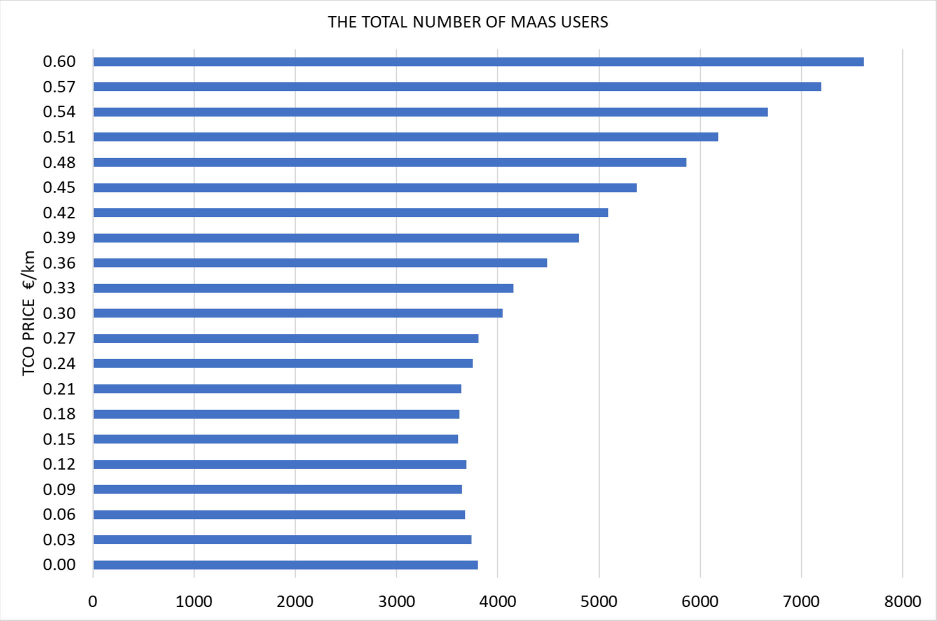

Figure 3.10: The total number of MaaS users across TCO variation

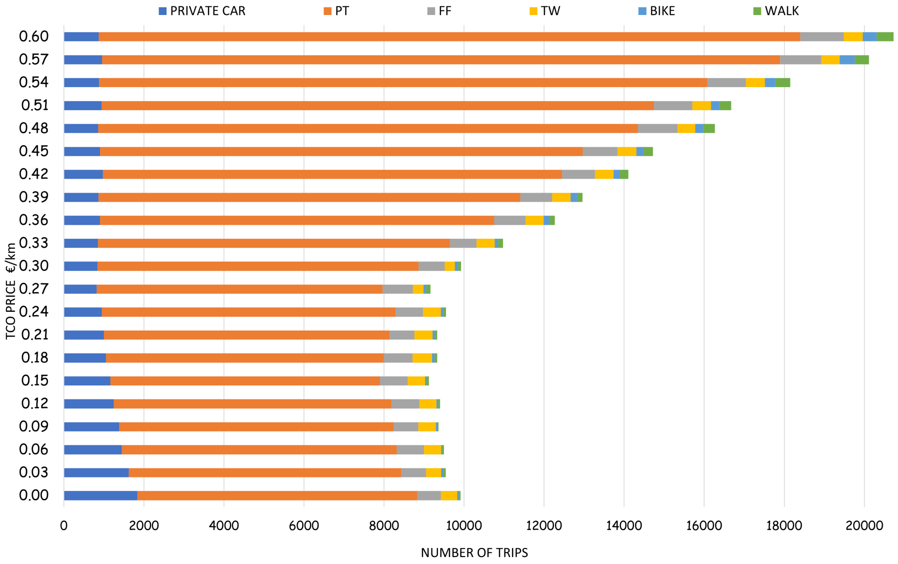

Figure 3.11: Distribution of trips for each transport mode for MaaS members across TCO variation

Regarding average travel time, a linear increase is observed when using public transport, with MaaS users experiencing approximately 20 minutes longer travel time, on average, in the 0.60 €/km scenario compared to the benchmark scenario. Travel time using public transport does not consistently change as the TCO decreases to zero, whereas travel time using car modes exhibits a linear decrease as the TCO increases. Interestingly, travel time for free-floating services generally decreases with higher TCO, while travel time for active modes increases. The analysis does not reveal a clear trend in travel time for active modes when the TCO decreases. Two-way services, however, do not exhibit any specific travel time trend across TCO scenarios. Similarly, the average number of trips per transport mode is examined. As anticipated, the number of trips taken by public transport increases as the TCO rises, whereas the number of car and free-floating trips decreases.

The subsequent section provides further insights into the sustainability goals of MaaS and the conditions under which it can compete with the cost of car ownership, potentially replacing private car ownership. The authors also examine whether competitive MaaS fees can lead to a profitable MaaS system for the MaaS Broker.

3.4.4 Analysis of MaaS potential revenues

Figure 3.12 displays the differential (in percentage) in the total number of private car users for TCO=0.3 €/km (in the blue right y-axis) and the revenue (in the red left y-axis) across MaaS fee scenarios. The revenue is simply calculated by the number of MaaS members times the subscription fee for each MaaS fee scenario, whereas the decrease in the number of private car users may reflect users' reluctance to purchase a new car.

The study indicates that there is a peak in revenue at around 4.5 €/day and another at around 11.25 €/day, with revenues remaining within a relatively narrow range of 32000-34000 euros in between these two peaks. However, there is a significant difference in the number of car users using their own cars and using modes within the MaaS system between these two fee ranges. At 4.5 €/day, 16% fewer users travel with their own car, while at 11.25 €/day, the percentage drops to only 6%, suggesting that the 4.5 €/day fee might be a better subscription fee to encourage a reduction of private car ownership and usage. A slight decrease in the fee toward 3.75 €/day may result in a further 2% reduction in the total number of car users with only a small reduction in revenue of less than 1000 euro/day (-3% compared to 4.5 €/day).

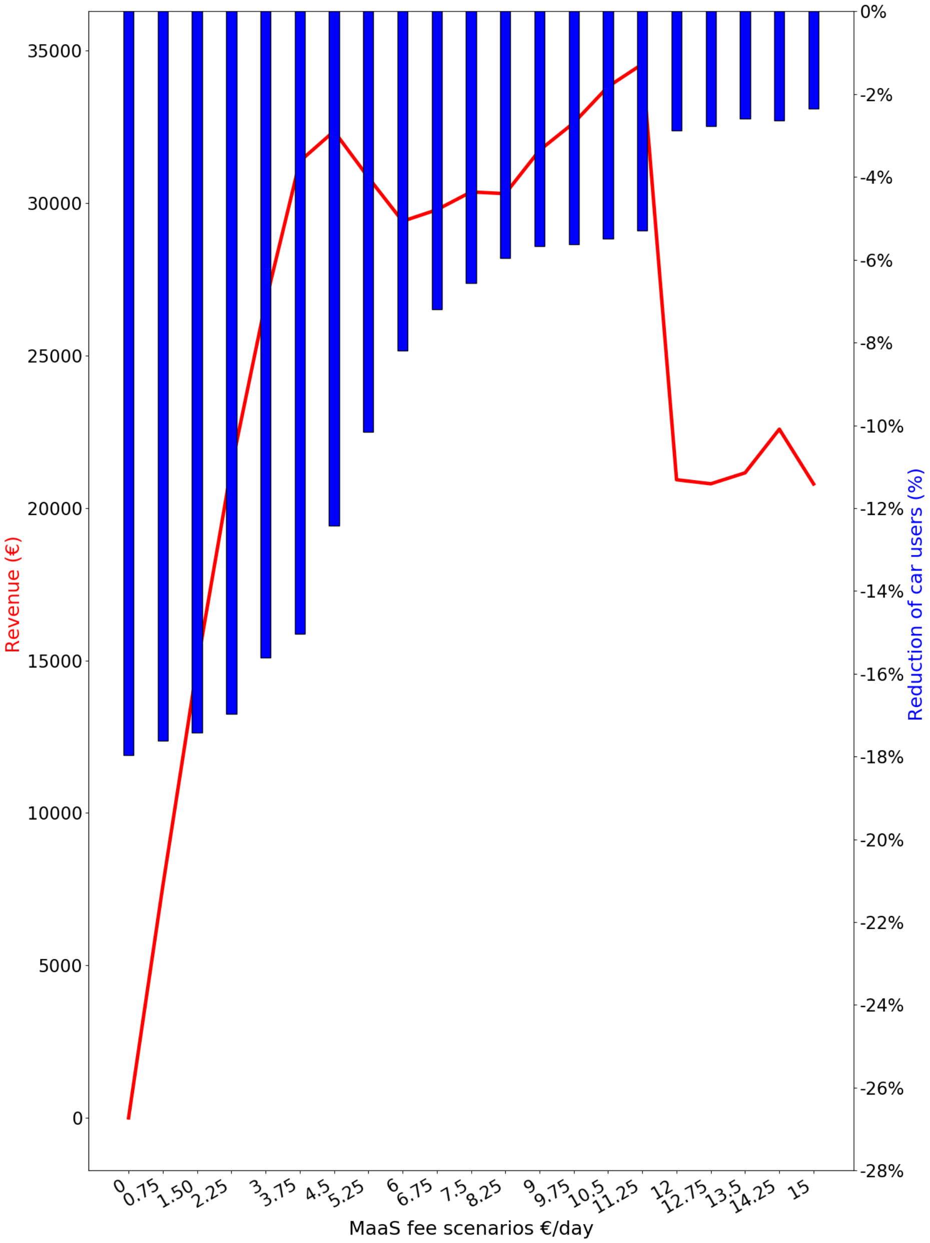

Figure 3.12: The difference in the total number of private car users for the benchmark value of TCO=0.3 €/km, and the revenue with varying MaaS fees

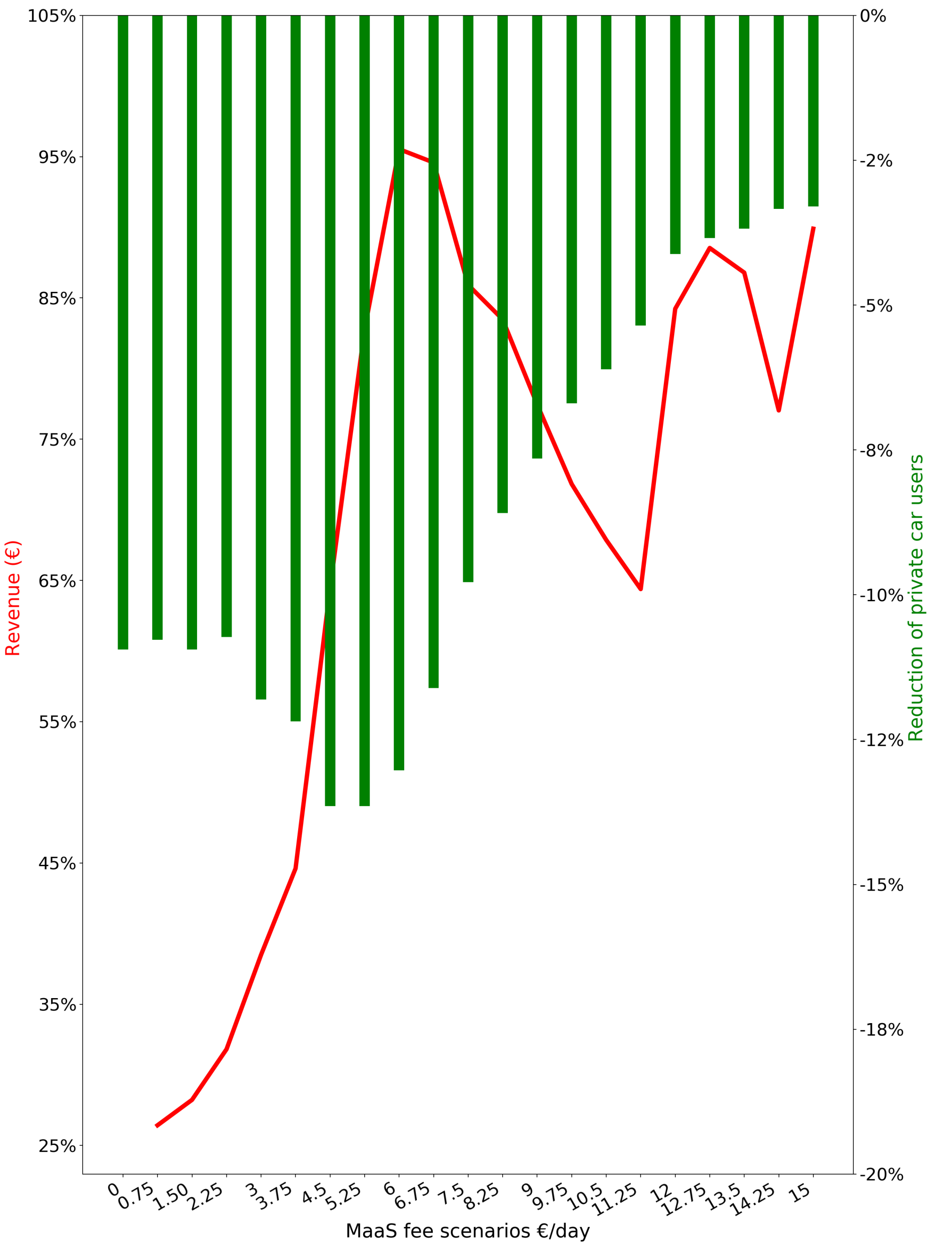

Figure 3.13: The differential of the difference of the total number of private car users and revenue in MaaS and NoMaaS scenarios for TCO=0.3 and TCO=0.6 €/km across MaaS fee variation

Therefore, a subsidy policy, which may incentivise a reduction in the MaaS subscription fee to e.g. 3.75 €/day could facilitate a more impactful change in users' travel behavior. On the other hand, looking at the revenue peak at 11.25 €/day, a consistent revenue reduction of about 50% is observed for higher subscription fees (21000 € with 12 €/day), which represents a risky choice for the MaaS operator since demand uncertainty and fluctuations may result in more significant losses in revenues. The study also found that the second revenue peak at 11.25 €/day does not achieve the same sustainability goal in terms of reducing the total number of car trips since the MaaS demand is lower than the other peak, along with the number of car trips reduction. We further study how a TCO variation (for instance by an increase in car ownership taxes) might increase MaaS broker revenue and reduce car users on the network (to meet a sustainability goal).

Figure 3.13 depicts the variation between the TCO from 0.60 and 0.30 €/km across MaaS fee scenarios (x-axis on the bottom) in terms and increment of revenue (in red on the left y-axis) and decrement of car users differences from MaaS to NoMaaS scenario (green histogram in the right y-axis). The majority of the number of car users deducted from the network is displayed between the 4.5 and 6 €/day scenarios with more than 13% of users abandoning the idea of purchasing a car when the TCO is 0.60 €/km compared with TCO 0.30 €/km.

We can observe that the revenue peak has shifted to the right, at around the 6 €/day scenario, for which there is more than 95% of the revenue increment with respect to TCO 0.30 €/km as a consequence of attracting a substantially higher number of MaaS members.

Such an output might offer insights into potential sustainable policies (via an increase in TCO) that might result in a larger shift away from car ownership and toward the MaaS system. Such policies might allow the MaaS system revenue to increase through higher subscription fees from potential members.

3.5 Discussion

This study simulated the impact of MaaS fees and cost of ownership using an agent-based model to capture MaaS's willingness to subscribe, to profile its potential users, and its feasibility as an instrument to reduce private car usage. Furthermore, this study assessed the conditions of the MaaS system to increase revenues. The results have revealed, for the specific case study of Berlin, 3 diverse customer profiles across the analysed subscription fee range.

Users who have long-distance travel and multimodal trip chains users are more willing to subscribe to higher fees. The high fee encourages them to utilise all available transportation options in the bundle and substantially lowers the number of kilometres driven by car. However, this high group represents a niche profile that is distinct from the average behavioral mode of the population prior to MaaS as a mobility option. Users who mainly employ car and public transport for short-distance trips are inclined to subscribe to cheaper fees (below 5.25€/day). This user profile, after subscribing to MaaS, employs carsharing as an opportunistic mode to cover short distance trips (last-mile). This target of users is the least affected by TCO variations, and they keep driving after subscribing and therefore are the least apt to renounce owning a car in favor of the MaaS system. It may be therefore more indicated to offer MaaS at medium-low fees in order to foster sustainable mobility and favor the uptake of MaaS.

Overall, MaaS subscription may promote a modal shift away from private cars but also may negatively affect active modes. Generally, a free-floating service may be the added value service of subscribing to the MaaS system while public transit may be the main service within the bundle as postulated by previous studies [15, 4, 65, 27]. This study also reported that a MaaS system could become remunerative and competitive in the long-term. Additionally, we showed that a potential subsidy to the MaaS system may increase the reduction of car users and reduce the subscription fee proposed to the users. On the other hand, implementing a car policy that increases TCO could shift even more users away from car ownership and toward the MaaS system. Additionally, implementing such a policy may suggest increasing subscription fees to rise revenues but at the same time, users would face a higher membership fee.

3.6 Conclusion

This chapter presents an analysis of the influence of MaaS fees on the potential adoption of MaaS and customers' willingness to subscribe, using an agent-based approach and a case study focused on Berlin, Germany. The research provides valuable insights into the required subscription fees and total cost of ownership (TCO) levels necessary for a competitive MaaS system, allowing for an examination of the impact of subsidies and car policies on MaaS demand. The proposed methodology can be applied to assess MaaS attractiveness in different networks and environments.

However, the study has certain limitations regarding the analysis of the number and variety of embedded mobility services and bundle types. In this particular case study, a single MaaS package was simulated, consisting of public transit, two-way carsharing, and free-flowing carsharing services. Future research should consider a wider range of services within the bundle, as it may lead to varying levels of MaaS attractiveness among the population. Additionally, future studies should explore different bundle schemes and business models that account for the unique characteristics of each mobility service, such as offering discounted prices or setting time budget usage limits within the subscription [5, 15].

Furthermore, it is expected that future MaaS services will encompass not only mobility services but also a diverse range of features catering to household needs rather than individual user preferences[134]. Therefore, future studies should incorporate these diverse product offerings. Despite these considerations, the current study has already provided valuable insights into the potential attractiveness and adoption of MaaS, contributing to the understanding of how car policies can be applied to achieve sustainability and profitability objectives.

Chapter 4

Designing MaaS bundle scheme

Highlight of the Chapter

This chapter builds upon the methodology presented in the previous chapter by incorporating a range of MaaS bundle schemes, in addition to considering subscription and ownership costs. This improvement enables users to assess different bundle options, taking into account not only the trade-offs between subscription fees and stand-alone costs but also the suitability of each bundle for their specific travel needs. The study consists of two main parts. Firstly, we simulate two types of MaaS bundle schemes, specifically focusing on those with a similar number of subscribers, in order to analyze MaaS demand profiles. Secondly, we employ an efficient experimental design to examine how feature variations of MaaS bundle schemes may impact MaaS demand, subscribers' daily satisfaction, MaaS Broker's revenue, and the potential decrease in private car usage. The findings suggest that public transit serves as the foundational service within the MaaS bundle, particularly when offered at a highly discounted cost. On the other hand, carsharing services, when provided with a generous time allocation and subscription fees, may primarily impact MaaS Broker revenue. Ultimately, potential subscribers are more interested in the mobility alternatives presented within the bundle as a replacement for their private vehicle, rather than an increase in price compared to what they currently own.

The work presented in this chapter has been described in the following paper:
"Comparing MaaS Business Plans Using an Agent-Based Modelling Approach",
hEART 2022: 10th Symposium of the European Association for Research in Transportation

" Designing MaaS bundle schemes",
Accepted for presentation in Transportation Research Board (TRB) 103rd Annual Meeting

4.1 Introduction

MaaS has gained significant attention as an innovative solution to address future mobility challenges [12, 81]. It represents a user-centric concept that revolutionizes the delivery and consumption of mobility services. The MaaS Broker, a key player in this concept [10], brings together various mobility services under a single subscription-based platform. The ultimate objective of MaaS is to repackage and present these services in a manner that alters individual perceptions and promotes the adoption of shared mobility [17, 135, 87, 19, 10].

In order to achieve this goal, MaaS bundle schemes must be carefully designed to include not only various mobility services under subscription fees but also their specific mobility characteristics, such as discounts for public transit or limitations on car-sharing booking hours. These bundle characteristics are expected to elicit a different response in terms of subscriber profiles, who are typically car owners that are deeply ingrained in their personal vehicle habits [16, 15]. Despite the high costs associated with car ownership, many individuals often underestimate these costs and continue to use their private vehicles. To overcome this challenge, MaaS bundle characteristics must be designed to alter these habits and increase demand for the services offered. This will not only encourage users to abandon their private vehicles, but also provide them with a more diverse range of mobility options that can help to reduce traffic congestion, minimize carbon emissions, and improve the overall quality of life in urban areas.

It is critical to study and assess different bundle schemes in order to understand the appeal of the MaaS system. A comprehensive model is required to analyse and evaluate the individual-level travel requirements, mode choices, and mobility costs, considering the diversity of users' mobility needs. The model should also enable the design and comparison of different MaaS bundle schemes, in order to determine their potential demand share [15]. Furthermore, the mobility services included in the bundle, such as carsharing, taxis, or on-demand modes, must be represented in the model in a manner that reflects their dynamic availability and accessibility, which are dependent on both geographic location and temporal factors [14]. On the other hand, it is also crucial that the model provides macro-level key performance indicators (KPIs) in order to support and understand emerging policies and trends to develop the MaaS system.

Recent years have witnessed a surge in academic studies and commercial trials testing and evaluating different MaaS plans [134, 4, 64, 71, 89, 90, 93]. However, there is still a significant gap in our understanding of which varieties of MaaS bundle schemes to offer and their impact on the the customers' mobility characteristics. Existing studies, although insightful, often yield contradictory outcomes, emphasizing the need for a more robust and comprehensive approach to modeling MaaS bundles and accommodating diverse user mobility needs [6].

To address these objectives, this study utilizes an agent-based model that simulates users' daily travel needs and activity schedules. The incorporation of MaaS bundle schemes into the users' daily mode choice set enables the agents to experience the trade-off between the cost of bundles and standalone services. Additionally, the study incorporates the Total Cost of Ownership (TCO) to accurately reflect the cost of vehicle ownership, considering its sensitivity to MaaS subscriptions [16].

The aim of this study is twofold: First, it investigates the travel characteristics of MaaS bundle schemes subscribers by offering them mobility services through various access options within MaaS schemes. The objective is also to understand the extent of the MaaS share that these schemes may attract and their potential to shift users' behaviour toward a shared mobility system. In particular, we compare two ways of bundling the services, namely by offering a discount to the basic pay-as-you-go (PAYG) system, or by providing free but limited usage of the modes within the bundles. Second, through an experimental efficient design [136] this study aims to examine how different features of the MaaS bundle schemes affect MaaS KPIs. In particular, we vary MaaS fees, TCO values and bundle types and assess their impact on the MaaS Broker revenues (business goal), the MaaS market attractiveness and customers' satisfaction (users' goal), and the MaaS potential of shifting users' behavior from car usage to MaaS services (sustainability goal). Through the analysis of the KPIs trend, we assess potential features of the MaaS bundle schemes to give insights and recommendations for the MaaS system development in the market.

The remainder of this paper is organized as follows. Section 2 describe the state of the art of the MaaS bundle scheme and provide some limitation of the current studies. Section 3 describes the extension of the methodological approach detailed described in the previous chapter, while section 4 discusses the results and gives insights on the features of MaaS bundle schemes to impact MaaS demand, MaaS Revenue and reduce car usage. Finally, Section 5 provides a discussion of the results through an overview of it and gives recommendations, limitations and future outlooks of the study.

4.2 State of the art

The literature on MaaS bundle schemes is mainly relying on two data collection methods: surveys (stated preference- SP) and pilot projects. Surveys, such as those conducted by [64, 12, 17], present MaaS scenarios with multiple bundle scheme options to interviewees, taking into consideration the current availability of transport modes and the participants' travel patterns. Other surveys have designed bundle schemes based on participants' transport mode usage and driving license status [4, 137, 77], as well as a software bundle designer [75] that compares stand-alone services. The portfolio choice approach was used by Caiati et al. [2] to create scenarios in which participants could choose from seven different modes of transport, with the level of mobility offerings and total price considered. Other designers chose to mimic industry mobility offers [65] or select two types of bundles with different services integrated [74]. On the other hand, several commercial pilot projects have been run, offering specific MaaS schemes, such as those based on household bundles [71, 87]. Hensher et al. [88] developed a more sophisticated method by processing pilot data and individualizing four different MaaS plans, each with a different discount per trip mode. Ho et al. [63] combined both methods by conducting an analysis of MaaS bundle scheme uptake based on the real purchasing decisions of trial participants. Another approach, was elaborated by Kriswardhana et al. 2020[30], who assigns bundle levels to cities involving different transportation modes, and aggregated parameters (e.g. demography, cost of living, modal split, weather conditions, environmental friendliness). Although these various approaches demonstrate the ongoing efforts to understand the attractiveness of MaaS bundle schemes they face some limitations.

MaaS bundle schemes primarily stem from the reliance on hypothetical scenarios and reported travel behaviour, as well as the limited scope of short-term trials. For example, survey participants are often asked to choose a MaaS bundle scenario based on their current travel patterns, which may result in a reduction of hypothetical bias [93, 77, 4, 63, 12, 17]. However, this approach may also limit the accuracy of the results, as participants choose a scenario based on their past single-mode travel experiences rather than a multimodal journey that the MaaS bundle scheme offers [6]. Similar criticisms could be leveled at the subscription fees chosen for bundle scenarios, which reflect the cost of current mobility without considering any possible policy (such as car policies or public subsidies). Additionally, once participants have chosen a scenario, they are unable to experience a different one, hindering the comparison of bundle schemes for the same individual.

To address these limitations, a more comprehensive model that considers the heterogeneity of users' mobility needs and is capable of comparing the potential demand of various MaaS bundle schemes within policy strategies is necessary.

Agent-based models (ABM) appear to be a particularly suitable method for this purpose. ABMs simulate the distribution of mobility services in terms of schedules, capacities, and travel costs, as well as users' mobility decisions. This enables users to distinguish the characteristics of various MaaS bundle schemes and capture changes in demand response to changes in bundle features, such as discounts for public transit trips or limited booking hours for car-sharing and subscription fees. As a result, ABMs can provide valuable insights into the uptake of MaaS bundle schemes and forecast the potential demand for them [97, 100, 120].

The use of agent-based modeling (ABM) has become increasingly popular in studies related to MaaS [14, 121, 92, 25]. However, those studies did not consider the impact of any characteristics of MaaS bundle schemes on MaaS appeal.

The main contribution of this study is to incorporate MaaS bundle selection into the range of travel options available to users through an agent-based model. This research is divided into two parts: Firstly, it aims to explore users' travel behaviour differing in the mobility characteristics of the bundle schemes. This study considers two distinct features of MaaS schemes from the literature, one with a discounted cost per trip mode [134] and the other with a limited number of hours to use modes included in the bundle [21]. To account for the true cost of vehicle ownership (TCO) and expenditure in MaaS adoption, the total cost of ownership is also incorporated into the users' private car choice independently by the MaaS system. While the cost of MaaS subscription will remain constant based on Caiati et al. [93], which enables the comparison of mobility characteristics across schemes. After individualizing MaaS schemes with similar potential demand, the customers' travel characteristics and mobility choices are assessed to comprehend their market penetration. In the second part of this study, we further differ the subscription fee and simulate car policies within the MaaS bundle schemes, through an efficient experimental design. Additionally, the impact of MaaS scheme features on KPIs such as MaaS Broker revenue and reduction of car usage (sustainability goal) are analysed, giving insight into potential policies and recommendations to develop a MaaS system.

4.3 Methodology

This research employs the widely adopted ABM simulator, MATSim, which is an activity-based multi-agent simulator framework developed in Java [124] to simulate different features composing the MaaS bundle schemes.

In the next subsection, an Overview of the MATSim simulation software is provided inspired by the ODD protocol[122], followed by the Details subsection in which MaaS bundle schemes implementation is introduced. We adhere to the design that was introduced in the preceding chapter for the Design Concept subsection.

4.3.1 Overview

As explained in the previous chapter, MATSim utilizes synthetic agents to represent users, whose characteristics vary based on socio-demographic factors. These agents are uniquely defined by their initial plans, which define their activity chains [128]. MATSim tries to replicate the travel choice process driving the decisions to perform the given activities by simulating trips done with one or more modes of transport on a synthetic infrastructure defined by a network.

The users' satisfaction is represented by an experienced score (or economic/satisfaction function) [127], which is obtained by performing their daily tasks according to their plan. The performance is iterated through an iteration loop process, allowing users to experience diverse mobility services available on the network until a system equilibrium is achieved [126]. The MaaS system is introduced as a mobility option by the implementation of the MaaS scoring event which was explained in the previous chapter. The experience of diverse mobility choices is performed by the replanning process at each iteration of the simulation [138], allowing the model to capture the dynamic nature of travel behavior as agents adapt their plans in response to changing conditions, such as traffic congestion or changes in travel costs.

The replanning process is a key feature of MATSim, allowing the framework to simulate the complex interactions between agents and the transportation system over time. After several iterations a certain stochastic equilibrium state is reached, where agents are unable to improve their scores unilaterally, and a stable level of satisfaction is reached.

4.3.2 Details

This subsection aims to provide further details to understand and replicate the extension of the methodology presented in the previous chapter.

Input Data

We briefly summarise the input data used in the model and describe it in detail in the previous chapter.

Network

We employ the identical for this research [120]. While public transport in Berlin is emulated with a trip-based pricing structure, the private transport modes in the network are private vehicles, walking and cycling, which are assumed to be available to all agents. Both two-way and free-floating[1] carsharing services are modelled as time-based pricing schemes that correspond to actual city rates and offerings. In order to imitate the carsharing supply, 62 two-way stations totaling two available cars per station have been created. In contrast, a fleet of 160 automobiles for free-floating carsharing has been created and is spatially distributed within predetermined service regions based on the services that are actually offered.

Synthetic population

A synthetic population of 25560 agents with heterogeneous demand characteristics has been used, as described in the previous chapter [125].

Configuration

The simulation is configured using the input configuration file (config file), which connects the analyst and MATSim. It is made up of several software modules as well as groups of settings and tactics. Along with the randomness of single trip choice and agent satisfaction maximisation, the strategies (e.g. SubtourModeChoice, CarsharingSubtourModeChoiceStrategy) allow users to alter modes for each trip chain or single trip. To give the agents more possibilities for modifying their plans, below are extra parameters specified for the constants that represent the scoring functions (described in depth in the previous chapter). As mentioned in the previous chapter, 700 iterations are required to reach the equilibrium.

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[1] https://www.share-now.com/de/en/berlin/

Submodels

In this study, we extend the previous methodology simulating two types of bundle schemes:

1) Discounted bundle
2) Time limit bundle

The types of bundle schemes are given as input in the MaaS scoring (Event 6) which under specific constraints enables users to access the MaaS bundle. The bundle scheme parameter is kept consistent during the simulation along with the cost of ownership (TCO) per car user (explained in the previous chapter), till equilibrium is reached. In this way, it is possible to compare the impact of different bundle schemes on MaaS demand, each bundle is explained in detail below.

Discounted bundle

Discounted bundle is developed considering the scheme used in the MaaS trial developed by Hensher et al. [5] who conducted a pilot study by including a discounted cost per trip per mode within the MaaS bundle. The Discounted bundle includes a fixed discount that lowers the current cost of MaaS bundle services. It should be noted that in this scheme there are two types of services included in MaaS bundle, one using the trip-based pricing system and the other using the time-based pricing system.

Under the trip-based pricing systems, the user is charged for each trip taken, irrespective of the travel time[2]. On the other hand, the time-based pricing system charges the user based on the travel time service usage commonly used in car-sharing services[3]. In this bundle, the ticket price for the trip-based pricing system is discounted as well as the unit cost of using the time-based pricing system. The $Cost_{\text{included}}$ is calculated following equation 4.1 at iteration t:

$$Cost_{\text{included}} = \delta_{trip\_based} * C_{tickets} * \sum_{q=0}^{Q} I_{q,trip\_based} + \beta * c_T * T * \delta_{time\_based}, \tag{4.1}$$

where δ_{trip_based} represents the discounts on the ticket cost (defining by $C_{tickets}$) per trip I induced by activity q, done by using a trip_based pricing systems included in MaaS bundle. Whereas, δ_{time_based} represents the discounts on the price (defined by c_T [4]) for the time-based pricing systems. While T represents the travel time and β is the marginal utility of the time spent travelling by

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[2] https://romesite.com/transport.html

[3] https://www.share-now.com/

[4] https://berlin.stadtmobil.de/privatkunden/stationen/,https://www.share-now.com/de/en/berlin/

time_based pricing systems (previously calibrated [120, 98] and set on 1). It should be noted that the experienced score contains other factors such as the discomfort of travelling in its travel dis(utility). However, in this study, those are retained as they are calculated, because linked to the perception of the mode rather than a specific predefined cost.

Time-limit bundle

Time-limit MaaS bundle scheme is created based on a survey study done by Tsouros et al. [21], which sets a travel time limit for the usage of modes included in the bundle. As a result, users can travel for a defined amount of time (a time budget) for free within the bundle. Once they exceed the time budget, they will be charged as no MaaS subscribers.

After activating the time-limit bundle, the screening process for this scheme takes into account the time budget that users are allowed to travel within the MaaS bundle. In the case of time-based pricing systems, the screening process counts the user's total travel time and subtracts it from the time budget covered by the bundle subscription fee. On the other hand, for trip-based pricing systems, a further step is needed since their cost is based on the number of trips instead of the travel time. In this case, an additional function that makes a variable that returns the number of tickets covered $n_{ticktes}$ by the time budget ψ_{trip_based}, is implemented.

$$\begin{aligned} n_{ticktes(}\psi_{trip\_based}) &= \sum_{q=0}^{q*} I_{q,trip\_based} \\ s.t. \sum_{q=0}^{q*} I_{q,trip\_based} * TT_q &\leq \psi_{trip\_based} \end{aligned} \tag{4.2}$$

Equation 4.2 is provided to illustrate how this variable is calculated based on the number of trips (I_q) induced by the user's activities q (from 0 to q*) within their time budget. The purpose of this function is to ensure that the total travel time of those trips $\sum_{q=0}^{q*} I_{q,trip\_based} * TT_q$ does not exceed the user's time budget ψ_{trip_based}. In this way, a parameter counting the number of the tickets paid and now included in the bundle is calculated $n_{ticktes(}\psi_{trip\_based})$. Such parameter is inserted in the $Cost_{included}$ calculation for discounted bundle scheme at generic iteration t as shown in Equation 4.3:

$$Cost_{\text{included}} = n_{ticktes(}\psi_{trip\_based}) * C_{tickets} + \beta * c_T * \omega_{time\_based}, \tag{4.3}$$

where ω_{trip_based} represents the time budget for time-based pricing systems included in the MaaS bundle. As for the other discounted bundle schemes the cost linked to the discomfort of travelling is kept in the score function.

As in the previous chapter, the carsharing rates are set at 0.20 €/min for free-floating and at 0.22 €/min for two-way carsharing [5]. Regarding the subscription fee, we consider as a benchmark cost the value of the monthly price of the MaaS bundle obtained by Caiati et al. [2], in which specific price plan weights were estimated, obtaining a daily price of (7.50€) by simply dividing the estimated monthly price by 20 working days. Within the MaaS schemes, the TCO is also computed for the car mode choice with a benchmark value of 0.30 €/km following Eisenmann's study [133].

4.4 Results

This section aims to show the findings of the two parts of this study. In the first part of this section the MaaS bundle scheme demand, and the travel habits of MaaS scheme subscribers are analysed and discussed. Different discount and time limit ranges have been simulated and two scenarios revealing a similar number of MaaS members are compared. In the second part, through an experimental efficient design, 140 simulations have been performed by varying MaaS fees, TCO values, public transport discounts and carsharing time limits to understand the impact of these four types of variables on MaaS appeal, MaaS potential revenue, and the reduction of car usage that the MaaS system may induce.

4.4.1 MaaS bundle schemes

Table 4.1 shows the variants of the mobility characteristics for the two MaaS bundle schemes analysed (Discount and Time limit). A NoMaaS scenario is simulated without the implementation of MaaS as a possible mobility option. Therefore, this NoMaaS scenario represents the mobility choices for each agent before the MaaS system is embedded in the simulation and is used as a benchmark to assess the change in travel behaviour after MaaS is deployed.

We simulate three scenarios involving discounts. Discount 1 gives the same discount per trip to each transport mode included in the MaaS bundle (flat bundle scheme). We test a 50% carsharing booking discount and a 30% public transit trip discount in the Discount 2 scenario. Alternatively, we simulate a 90% discount for each public transit journey as well as a 30% discount for each carsharing booking period in scenario Discount 3. A different kind of package scheme would be examined (unlimited), which is outside of our goal, if the discount were to be increased further and resulted in unrestricted use of the public transportation system.

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[5] https://www.share-now.com/de/en/berlin/,https://www.stadtmobil.de/

Table 4.1: MaaS scheme mobility characteristics and number of MaaS members

DISCOUNT SCHEME(%)				
Mobility characteristics			**Scenario Name**	**Number of MaaS members**
Public transit	**Free floating**	**Two way**		
50	**50**	**50**	Discount 1	1302
30	**50**	**50**	Discount 2	341
90	**30**	**30**	**Discount 3**	**3197**
TIME LIMIT SCHEME (minute)				
Mobility characteristics			**Scenario Name**	**Number of MaaS members**
Public transit	**Free floating**	Two way		
102	**32**	**42**	Time limit (ave)	2530
30	**30**	**30**	Time limit 1	1553
120	**32**	**42**	Time limit 2	2605
150	**32**	**42**	Time limit 3	2660
150	**40**	**42**	Time limit 4	2900
150	**32**	**50**	Time limit 5	2670
150	**60**	**42**	**Time limit 6**	**3052**

We then simulate different Time limit schemes. The row Time limit (ave) uses the average travel time of each mode in the service observed in the NoMaaS scenario (presented in the previous chapter). We then simulate Time Limit 1 as a flat bundle scheme that gives the same time budget to all services (30 minutes). Time limit scenarios 2 and 3 are simulated by raising the public transit time budget to 2 hours while maintaining the carsharing time budgets as in Time limit. Time limit 4 simulates a higher time budget for free-floating (above average), whereas Time limit 5 does the opposite, increasing the two-way time budget while maintaining the same mobility characteristic for public transit. By extending the free-floating time budget by an hour, Time limit 6 is simulated in tandem with Time limit 4.

Looking at the last column on the right of Table 4.1 we can observe that the Discount 3 and Time limit 6 scenarios occur to have a similar number of potential MaaS members and for this reason, they have been selected as the two bundle schemes to be analysed and compared in this study. Discount 3 which from now on will be named Discount counts around 3197 members, whereas Time Limit 6 (Time from now on) occurs to have 3052 members. Findings in Table 4.1 further demonstrate how public transit mobility characteristic contributes to a significant rise in demand. In fact, when the discount cost increases from 50% to 90% in the discount scheme the MaaS subscribers double, while when a reduction of the discount is simulated, the demand drastically decreases to only 341 subscribers. Similar trend is found for the Time limit scheme in which an increase of the time budget for public transit from 100 to 150 minutes increases the demand by 20% (500 new customers). Conversely, carsharing services seem not to have such an impact on MaaS demand, suggesting how they may be seen as additional services within the bundle rather than the main services.

Focusing on the two MaaS schemes with similar potential demand, we separate the agents population by those members who subscribe to only one type of scheme and not for the other, and those members (MaaS captive or indifferent) who subscribe to both the bundle schemes indifferently (Table 4.2). In this case study, only 2% percent of the population is likely to subscribe to any of the two schemes. Instead, 12.5% chose only the Discount scheme and almost 12% subscribed only to the Time limited scheme, suggesting that offering the two variants may result in more effectively capturing the heterogeneity of the demand.

Table 4.2: Percentage of MaaS members

Scenario Name	**Members**	**%**	**MaaS Captive or Indifferent**	**%**	**Exclusive Users**	**%**
Discount	3197	12.5%	548	2%	2649	10.3%
Time	3052	11.9%	548	2%	2504	9.7%

Travel habits of MaaS bundle schemes subscribers

We first analyse the travel behaviour of the MaaS members before MaaS is implemented to try and identify the main characteristics that could drive their choice of becoming member of one and/or the other scheme.

The top chart in Figure 4.1 presents the modal split for each type of bundle scheme in the NoMaaS scenario. The modal split is determined by dividing the number of trips for each transport mode by the total number of trips performed by all agents. The second chart depicts the average travel time, while the last chart displays the average number of trips taken by each user type across transport modes (excluding walking and cycling modes). The indifferent members, represented in red, primarily consist of private car users (over 45%) and public transit users (19%). They also frequently use their own bikes (17%). However, they do not utilize two-way carsharing, and only around 5% of trips are employed using free-floating services. Additionally, indifferent users spend over 2.5 hours traveling by public transit and almost 1 hour using a private car during their day. Furthermore, they employ

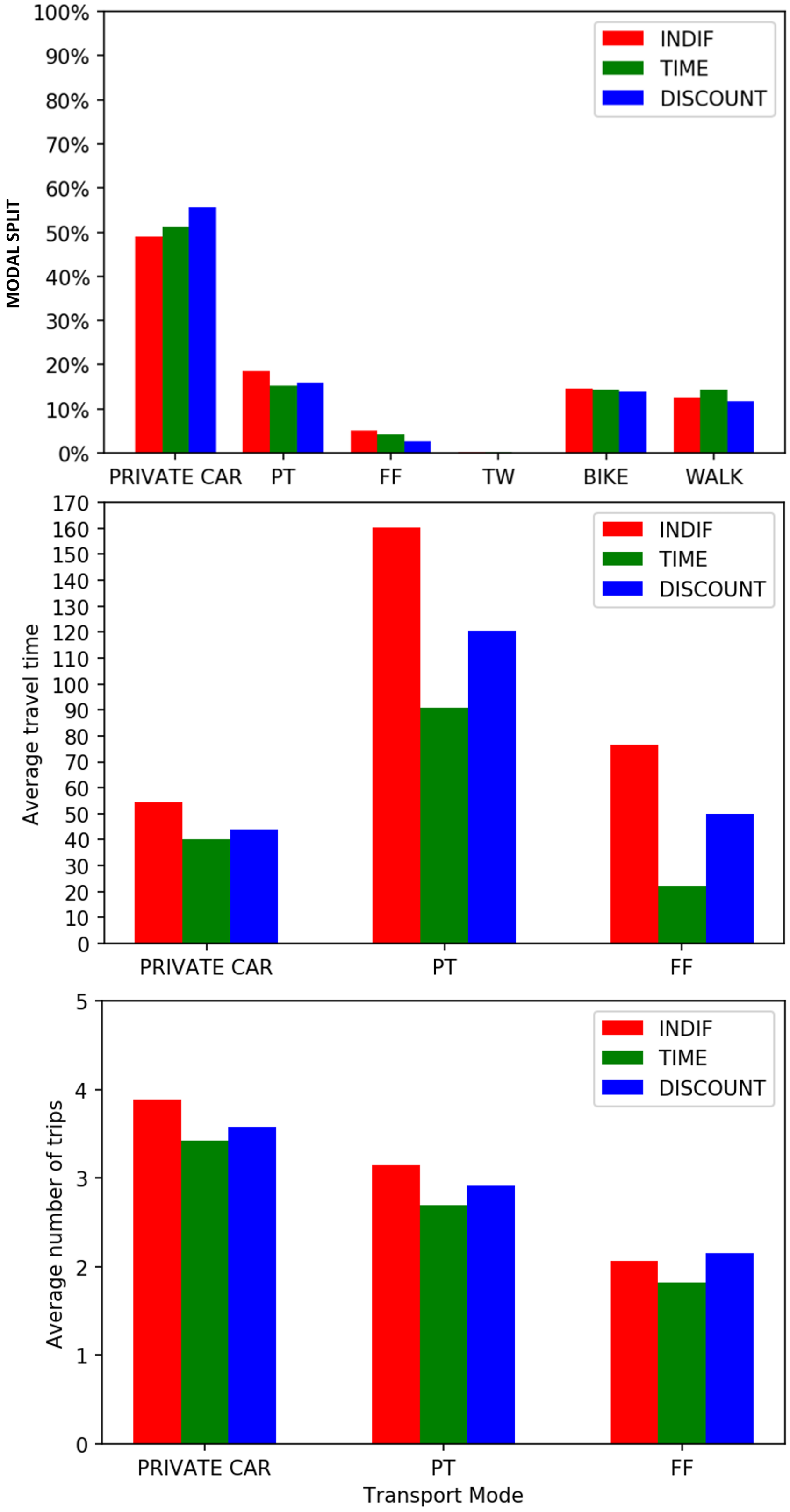

Figure 4.1: Travel characteristics of MaaS schemes subscribers

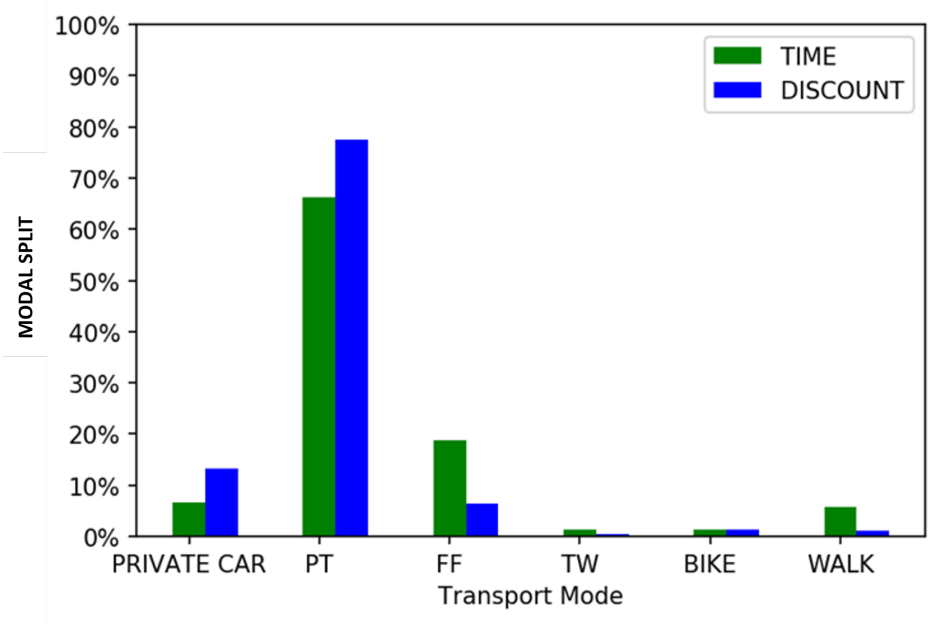

Figure 4.2: Modal split of MaaS bundle schemes after subscription

free-floating services for more than 1 hour on their daily journeys (see Figure 4.1, second chart). It is therefore evident that the indifferent users (which recall they are just 2% of the agents) are among the most frequent travellers in the system.

This behavior highlights the inclination of Time users to subscribe since it allows them to stay within their time budget without incurring additional ticket costs. Discount users, on the other hand, mostly rely on cars (58% of their trips) and undertake multiple trips using public transit, resulting in longer travel times compared to Time users. These characteristics make discount users more suitable for the Discount scheme, as they may exceed their time budget and incur additional pay-as-you-go costs throughout the day. None of the user types employ two-way services, indicating that this type of service could be an additional option within a bundle rather than a standalone attractive choice.

Potential shift toward multimodality of MaaS bundle schemes

After analyzing the customer profiles of bundle schemes, we investigate the modal split of MaaS users after the implementation of the MaaS bundle schemes.

Figure 4.2 illustrates the modal split of users after subscribing to both the Discount (shown in blue) and Time (shown in green) schemes. A noticeable shift from private cars to public transit for both schemes is observed when comparing to the top chart in Figure 4.1 with Figure 4.2. However, looking at Figure 4.2 a significant difference in the modal split between the two bundle schemes is evident when it comes to free-floating usage rates. Approximately 20% of Time limit scheme subscribers utilize free-floating services, whereas only 5% of them employ private cars. Interestingly, the opposite trend is observed for the discount scheme, with over 10% of customers still using their private cars after subscribing, while only 5% utilize free- floating services. The majority of discount scheme customers (80%) rely on public transit.

These results may suggest that the discount scheme could strongly encourage the use of public transit. Conversely, the Time scheme appears to have a more positive impact on free-floating usage and a stronger reduction in private car usage (over 45%). It should also be pointed out that active modes such as walking and cycling are impacted by the introduction of MaaS services in both bundle schemes scenarios. These findings may be further attributed to the characteristics of the schemes. The Discount scheme, which offers a discount on carsharing travel time but does not provide a time budget limit like in the Time limit scheme, may not be sufficient to motivate users to shift from private cars to free-floating. In the Discount scheme, users incur costs for each travel mode within the bundle, in addition to the subscription fee. The cost savings from shifting to public transit may be higher than the cost savings from shifting to free-floating. It is important to note that the public transit discount is at its highest possible value of 90%, meaning users only pay 10% of the actual ticket cost. On the other hand, Time scheme users may perceive all services included in the bundle as free as long as they stay within the time budget.

These findings may imply that a hybrid bundle scheme that combines subsidized public transit costs with a time-based budget for carsharing services will encourage customers to use both forms of transportation while maximizing the benefits provided by the MaaS system.

4.4.2 Experimental efficient design

In the previous section, we presented the travel characteristics of users in the MaaS bundle schemes, while keeping the total cost of ownership (TCO) and subscription fee parameters constant. In this section, we vary all parameter schemes such the subscription fee, TCO, discounted cost for public transit, and time budget for carsharing usage. The aim of this part of the study is to examine how specific key performance indicators (KPIs) are affected by these parameters, and to identify bundles that can be more effective in pursuing different goals.The KPIs considered are potential business profitability (MaaS revenue), the potential MaaS attractiveness in the market (Maas Users satisfaction), and the possible reduction of private car usage for MaaS subscribers (Car Reduction).

Due to the large number of potential parameter combinations and the time required for performing MATSim simulations, we have chosen to use the efficient experimental design proposed by Rose and Bliemer [136]. This approach allows us to explore the effects of different parameter values effectively while using limited computational resources. It also aims to provide statistically reliable and precise results with the fewest possible experiments (therefore parameters). With the goal to guarantee that the experiment's parameters are statistically independent, the efficient experimental design prior to the parameters assumption creates and minimises the variance-covariance matrix [136, 139].

To begin, we establish a value range for each parameter. For example, we vary the TCO by increments of 0.05 €/km from 0.00 €/km to 0.60 €/km, and the subscription fee ranges from 0 to 15 € per day (increasing by 1 € increments). Building on the findings from the previous section, we decided to focus on bundles where carsharing services are offered using a time limited budget ranging from 30 minutes to 90 minutes, with 15-minute increments, while public transit is offered with discounted costs ranging from 0% to 100%, increasing by 10% increments. This approach allows us to efficiently investigate the impact of these parameters on KPIs that evaluate the MaaS system. Using this efficient experimental design, we obtained 140 scenarios from a total of 14,440 combinations of all MaaS scheme parameters. Thus, we have a representative sample that consists of 1% of the entire solution space. The 140 scenarios and the combination of parameters are displayed in the appendix.

Analysis of Key Performance Indicators

Figure 4.3 shows the correlation between Demand (MaaS users) and its increment (on average) of daily satisfaction after subscribing (Potential gain) among the 140 scenarios. The trend shows an increasing relationship between the number of MaaS members and the increase in MaaS score (satisfaction) if compared to the NoMaaS scenario. Hence, through the goal of increasing the number of MaaS members, an overall satisfaction growth of MaaS potential subscribers is also obtained.

Figure 4.4 shows how the KPIs vary within the parameters discounted cost of public transit (y-axis) and carsharing time budget (x-axis) through a 2-dimensional heat map visualisation. The primary feature that influences the increase in Car Reduction and Potential gain is the discounted cost for public transit, while carsharing does not appear to have a significant impact on these KPIs. Therefore, giving a bundle scheme with a highly discounted cost per public transit would facilitate the shift

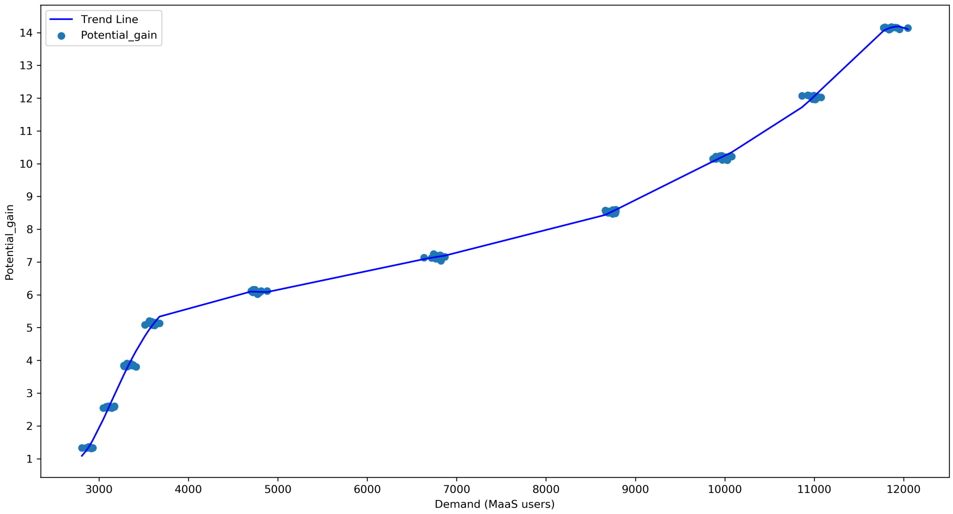

Figure 4.3: The correlation between Demand (MaaS users) and its increment of satisfaction (Potential gain)

from car to MaaS services and make users more satisfied with their travel choice while increasing the MaaS appeal. Furthermore, the combination of high public transit discounted costs along with a high time budget for carsharing, resulted in increased revenue for the MaaS system (last chart of Figure 4.4). This output suggests that offering extended time availability for carsharing services, combined with affordable public transit costs, could incentivize users to shift from stand-alone mobility costs to a fixed subscription cost that grants them nearly unlimited access to various mobility services. This bundle offer would allow users to meet their daily travel requirements while potentially generating significant revenue for the MaaS broker and reducing the number of car trips taken by MaaS subscribers.

Figure 4.5 illustrates the trend of (KPIs) with respect to the variation in MaaS subscription fee. The graph shows that Car Reduction (in red) and the satisfaction of users (Potential gain in blue) are not influenced by the subscription fee. This implies that these KPIs are not directly related to the fee of the bundle, and potential MaaS subscribers may decide to subscribe based on the services offered rather than the cost to acquire them. On the other hand, the graph indicates that the Revenue for the MaaS Broker increases with an increase in the subscription fee. This result, combined with the earlier findings displayed in Figure 4.4, suggests that offering the MaaS bundle scheme for a higher subscription fee, which includes heavily discounted public transit costs and a high time budget for

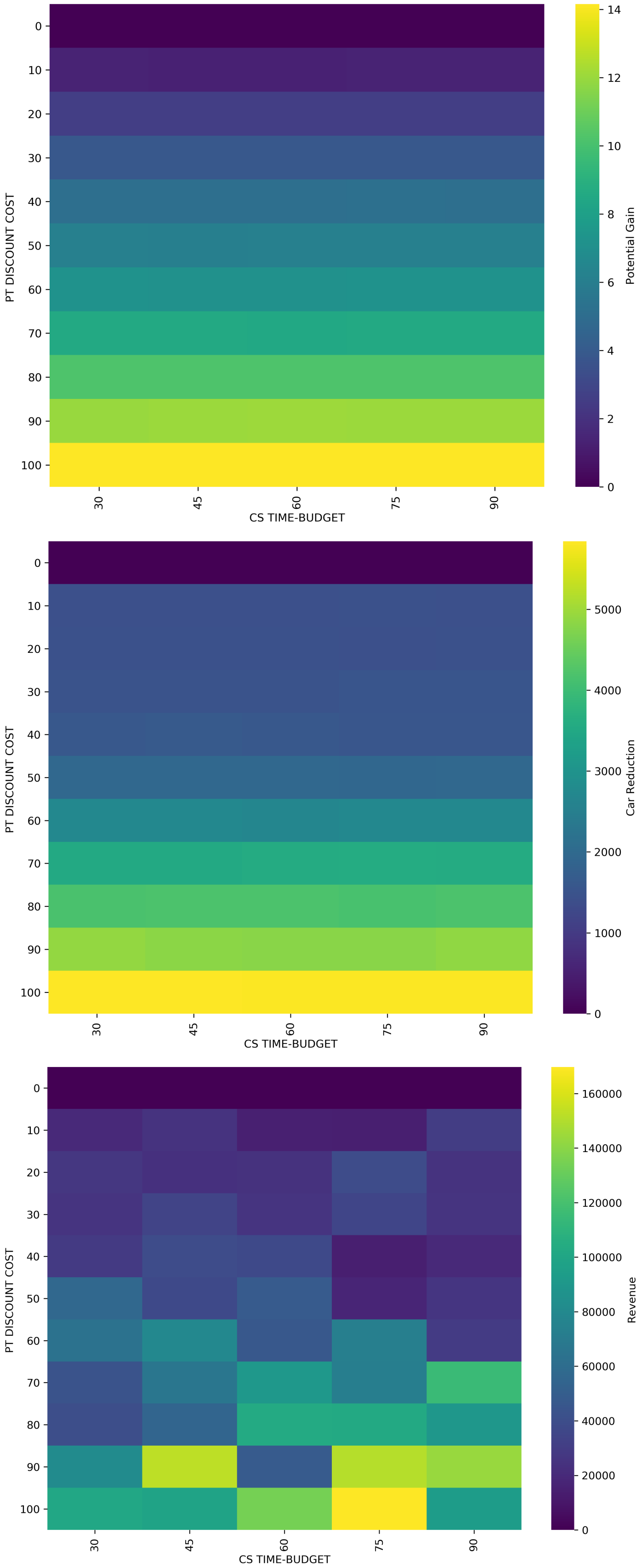

Figure 4.4: Heatmap chart for Potential Gain, Car Reduction, and Revenue KPIs across PT and carsharing variation

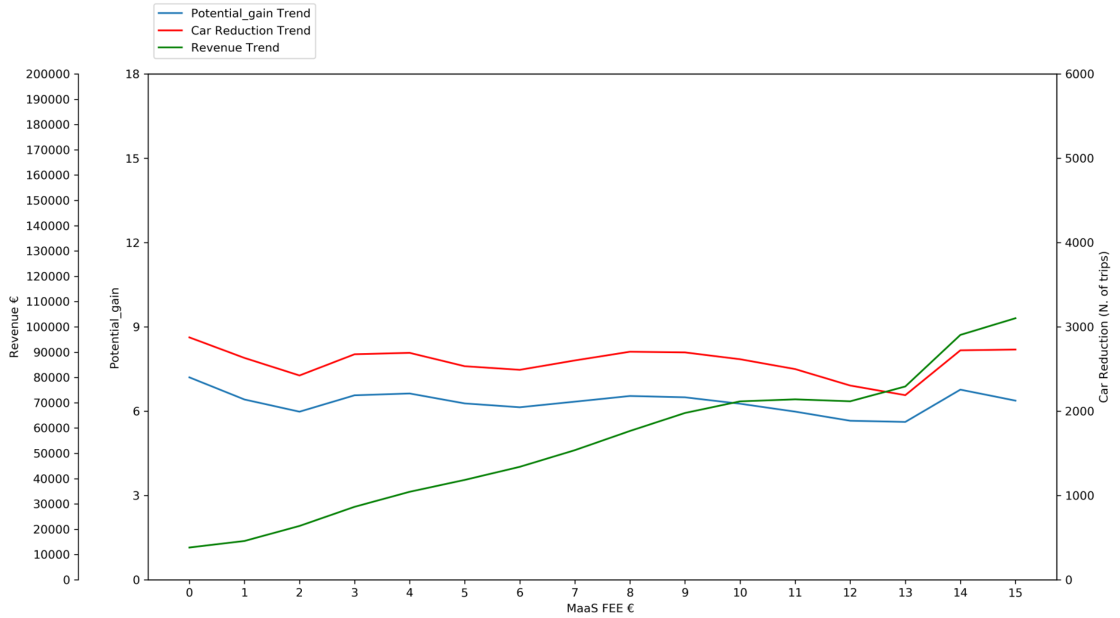

Figure 4.5: KPIs trend for MaaS subscription fee variation

carsharing, may increase MaaS demand and revenue while at the same time resulting in a decrease in private car trips in the network. Regarding the TCO analysis, which might be related to a prospective car policy involved in the MaaS development (e.g. increased taxations), it appears that no KPIs are significantly impacted by a change in TCO values. No particular trend was identified in the investigation, indicating that this metric alone might not be enough to work toward MaaS development. These results may indicate that users are more interested in the mobility alternatives that are put forth to them as a replacement for their private vehicle than they are in a price rise for what they presently possess.

4.5 Discussion

This study aimed to endogenize the MaaS mobility choice within the users' set of mobility travel possibilities by simulating different MaaS bundle scheme features in an agent-based simulator.

Firstly, we simulated two types of MaaS bundle schemes, drawing inspiration from existing literature pilots [134, 21]. These schemes were designed to have distinct mobility characteristics. During our analysis, we focused on the schemes that had a similar number of subscribers.

First, three different types of members have been identified and analysed: the MaaS captive are users, who are willing to become members indistinctly of the MaaS bundle schemes offered. Such users are characterized by long trip chains within a long daily travel time. Whereas the members that subscribe for having a specific time limit within the bundle (Time scheme) substitute the car traveling by public transit to exhaustively use the time-budge included in their membership. Such subscribers also book free-floating carsharing services to fulfill their daily activities. Instead, the members of the MaaS discount scheme they mainly substitute all the modes by public transit after subscribing. Discount members use the car as a main mode, which is not substituted by free-floating service making this carsharing mode a no-appealing service for potential MaaS discount bundle scheme subscribers.

The discount scheme may be seen as a stand-alone service bundle that does not promote multimodality, while the Time bundle may be more adapted to induce such a shift in MaaS potential members. The discount scheme strongly encourages the use of public transit, while little evidence exists for the positive effects of free-floating use. Conversely, the Time scheme may have a positive impact on repacking mobility services and altering subscribers' mobility habits. On the other hand, both MaaS schemes replace active modes, which may be viewed as a drawback of MaaS adoption. In addition, the total MaaS market appeal, in a context in which both bundles are offered, arises to 20% of the whole population suggesting how differing mobility characteristics of services within the MaaS bundle may help to increase the MaaS subscription appeal.

The second part of this study utilized an efficient experimental design to examine how various features of MaaS bundle schemes can impact MaaS demand, subscribers' daily satisfaction, MaaS Broker's revenue, and the potential decrease in private car usage.

Findings indicate that the higher the number of MaaS subscribers, the more satisfied they will be with their new choice. Users who are willing to subscribe are more influenced by the services offered within the bundle and the way they are offered, rather than the price of accessing them (subscription fee). Additionally, to increase MaaS demand and subsequently enhance satisfaction, the central focus of the MaaS scheme should be on public transit with a significant cost reduction. A similar trend is observed for reducing the number of car trips in the network, which can be a desirable goal for Government or public administrations when developing a MaaS system [10, 18]. In other words, potential subscribers are more interested in the mobility alternatives presented within the bundle as a substitute for their private vehicle, rather than an increase in price for what they currently own. From the perspective of the MaaS Broker, an optimal scheme to increase revenue would involve selling a bundle with low costs for public transit and a generous allocation of time for carsharing, while maintaining a higher subscription fee. In conclusion, the core aspect of the MaaS bundle scheme should revolve around public transit with a significant cost reduction, while the subscription fee only affects the MaaS Broker's revenue.

4.6 Conclusion

The objective of this chapter was to simulate a MaaS system using an agent-based model in order to analyze how bundle features impact the potential development of the MaaS system. To begin, we simulated two different bundle schemes from existing literature while keeping the membership fee and cost of car ownership parameters constant for car users. In the second part, we varied all MaaS features simulated in the model to observe the trend of specific KPIs that could represent the development of the MaaS system.

As with any study, there are limitations to consider. For example, we only simulated three types of services while MaaS can encompass a wide range of services such as bike sharing, one-way carsharing, carpooling, and taxis. Additionally, we did not conduct a cost-benefit analysis of suppliers involved in the MaaS system. Our calculations focused solely on the revenue from the perspective of the MaaS broker, without considering the costs incurred by the supply side.

In this context, a possible future outlook is to expand the supply capacity by including other public services such as bike sharing, one-way carsharing, carpooling, and taxis/ride-sharing services to attract a broader range of potential MaaS members. Furthermore, the second generation of the MaaS system, known as Mobility-as-a-feature (MaaF), will not only encompass mobility services but also a diverse range of features that cater to household needs rather than individual user preferences [134]. Therefore, future studies should incorporate not only diverse product offerings but also consider membership options for groups of users such as family members or employees [140, 25]. Despite these considerations, the current study has already provided valuable insights into understanding the influence of MaaS bundle parameters on key performance indicators of the MaaS system. We offer recommendations for MaaS scheme planning to achieve the diverse goals of various MaaS actors.

Chapter 5

Discussion and Perspectives

The primary objective of the thesis was to gain a comprehensive understanding of membership and bundle choices within the context of a Mobility-as-a-Service (MaaS) system. In the subsequent section of the thesis, a detailed answer is provided to the research question, providing in-depth insights into the findings and conclusions derived from the study along with future outlooks.

5.1 Answer to research questions

The research question has been also broken drown into three ancillary problems which have been answered through the manuscript.

RQ 1: Which modelling approach can assess the INTERACTIONS between POTENTIAL CUSTOMERS and THEIR heterogeneous MOBILITY NEEDS and COSTS?

The first research question has been addressed in the second Chapter of this thesis.
By conducting a descriptive and critical analysis of the existing literature, we developed a comprehensive MaaS ecosystems framework. Our primary focus was on understanding the decision-making process of customers, enabling us to determine the most suitable model for assessing potential MaaS subscribers and their bundle choices. This thesis highlights the agent-based model (ABM) as a promising approach for evaluating the interaction between mobility needs and potential MaaS customers. ABM proves to be advantageous over traditional models in representing the complexities of the MaaS system. It offers a microscopic view of users' mobility habits and captures the temporal and spatial distribution of the various mobility services that are part of the MaaS bundle. By incorporating the MaaS system within the decision-making process of users, as modeled by ABM, this study marks a comprehensive model that configures and supports the MaaS system.

RQ 2: How is the CUSTOMERS' WILLINGNESS-TO-SUBSCRIBE impacted by the MAAS SUBSCRIPTION FEE? And how much does this impact depend on OWNERSHIP COST?

In Chapter 3 of this study, we examined the impact of MaaS subscription fees on potential MaaS adoption using an ABM simulation. The simulation incorporated vehicle ownership costs and MaaS subscription costs, allowing users to experience the trade-off between MaaS fees and costs of using private modes of transport. Overall, the willingness to subscribe to Maas decreases with the rise of the subscription cost. Users with long-distance travel and multimodal trip chains prefer higher fees in order to utilize all available transportation options in the MaaS bundle and reduce car usage. However, this group represents a niche profile compared to the average population's travel habits. While users relying on cars and public transport for short distances, prefer cheaper fees and utilize carsharing as an opportunistic mode for last-mile trips after subscribing to MaaS. To promote sustainable mobility and MaaS adoption, offering medium-low fees may be more effective for this user segment. Our findings indicated that, in the long run, a MaaS system has the potential to be financially viable and competitive compared to ownership costs. We also discovered that providing subsidies to the MaaS system could further incentivize the reduction of car users and lead to lower subscription fees for users. On the other hand, implementing a car policy that increases the total cost of ownership (TCO) could result in even more users shifting away from car ownership and towards the MaaS system. In such cases, it may be necessary to consider increasing subscription fees to boost revenues. Interestingly, this approach would also mean that users would have to bear a higher membership fee.

RQ 3: Which features of MAAS BUNDLES SCHEMES affect PRIVATE CAR USE, the number of MAAS MEMBERS and REVENUE for the MaaS system?

In Chapter 4 of this study, we focused on varying features related to the implementation of the MaaS bundle scheme within the ABM simulation. Our findings revealed several important insights. Firstly, we observed that offering MaaS bundle services at a discounted cost strongly encourages the use of public transit. We found little evidence, however, to support the positive effects of free-floating services on MaaS adoption. Instead, providing a time budget for using the services showed a positive impact on reshaping mobility habits and the utilization of different mobility services within the bundle. Overall, our study highlighted that potential MaaS subscribers are more interested in the mobility alternatives offered within the bundle as substitutes for their private vehicles, rather than an increase in price for what they already own (e.g., private cars). In conclusion, the core aspect of the MaaS bundling scheme should prioritize public transit with a significant cost reduction. The subscription fee primarily impacts the revenue of the MaaS Broker. To stimulate MaaS demand, increase MaaS broker revenue, and achieve a reduction in private car usage, the most effective bundle scheme should include a high availability of carsharing services, a substantial discount for public transit, and a higher subscription fee.

5.2 Main Findings

The main findings of this thesis can be separated into three aspects. The first one is related to building a customer's decision-making process framework based on a critical and descriptive review of the current literature. Through the review was possible to develop the other two aspects that are methodological.

MaaS ecosystem modelling framework:

The current state-of-the-art MaaS system was extensively analyzed. Based on this analysis, a novel framework was proposed to assess the interrelationships among various actors in the MaaS ecosystem and identify potential areas for further development. We focused on implementing a decision-making process for MaaS customers by developing a detailed pattern that captured users' specific mobility requirements and the associated trade-off costs. This framework took into account the inclusion of MaaS bundles as part of users' mobility choices, facilitating the evaluation of MaaS demand and bundle options. Additionally, we individualize ABM as are suitable method to represent the decision-making process for MaaS customers.

MaaS Membership model:

Following the recommendation of the first part, the second part concerns the development of ABM for MaaS system. The model incorporated various parameters of the MaaS ecosystem, enabling analysts to investigate the impact of modifying these parameters on MaaS membership. In this second part, the perimeters embedded are subscription fees and ownership costs. Through the model is possible to conduct diverse experimental setups to evaluate MaaS demand under different parameter ranges while keeping the bundle offering constant. Due to the model's adaptability, it is possible to assess the travel habits of MaaS members both before and after they purchase the MaaS system. The model allows also analysts to explore diverse policies aimed at achieving MaaS objectives, such as MaaS Broker revenue and minimizing private car usage.

Maas bundle choice:

The third part of the thesis builds upon the model proposed in the second part by introducing variations to all the features embedded in the ABM for the MaaS bundle offer. This expansion allows for a more comprehensive analysis of the MaaS system and its functionality. In the final part of the thesis, we refined the ABM model by exploring different types of simulated bundles and adjusting the mobility characteristics of the services included in them. This enables the examination of the impact of these variations on MaaS adoption and usage patterns. The model is capable of determining the most suitable bundle offer to meet the diverse goals of various MaaS actors, with a specific focus on the satisfaction and preferences of customers.

5.3 Future Research

As with every thesis some limitations are faced. The main limitations stem from the limited number of mobility services included in the MaaS bundle modeled during the simulation. Specifically, only two-way and free-floating carsharing services were incorporated, along with fixed public transit supply and an emphasis on investing in the demand side. As a result, it is important to recognize that the findings may differ when additional services are introduced into the simulation. Additionally, we did not conduct a cost-benefit analysis of suppliers involved in the MaaS system. Our calculations focused solely on the revenue from the perspective of the MaaS Broker, without considering the costs incurred by the supply side. We must not overlook the fact that the model presented lacks validation due to a shortage of MaaS system data. In fact, the model lies on the synthetic population of the city of Berlin in turn based on a survey [125], and on a calibrated scenario for only a two-way carsharing system [120]. Thus, in order to evaluate the validity of the model that is being presented, it is crucial to recognise that there may be differences in the outputs when a possible calibration using a data set is possible. Despite these limitations, we believe that this thesis provides valuable insights and perspectives regarding membership and bundle choices in the MaaS ecosystem. It also opens up opportunities for future research and exploration in this field.

Considering the advancement of the second generation of MaaS, referred to as MaaF (Mobility-as-a-Feature) [141], the current methodology necessitates an additional step. The concept of this new MaaS (MaaF) generation is to expand bundled subscriptions beyond transportation services to include various non-transport services. It proposes a shift from a multi-service to a multi-modal transportation system, aiming to overcome the limitations of previous generations and offer financial benefits to users through a wider range of included services. In this way, changing the type of services included in the bundle may increase the market appeal of the MaaF system and grow the profit for the MaaS Broker. Being in the second generation of MaaS, future research should consider expanding the presented model by simulating a range of mobility services and incorporating more nuanced no-transport-related services to achieve a more comprehensive understanding of MaaS dynamics. While the focus of this thesis primarily revolves around the city of Berlin as a case study, it is imperative to acknowledge the potential of MaaS in rural areas. Consequently, there is an opportunity to expand the model to assess the appeal of MaaS in rural settings [142].

Another aspect worth exploring is the recalibration of ownership costs. In the current thesis, these costs are combined as a daily additional expense; however, a more realistic approach would involve breaking them down into marginal costs (e.g., repairs, maintenance, financing, and insurance) and daily costs (e.g., parking, tolls on roads or bridges, and tunnels). This would lead to a more accurate prediction of MaaS demand. Furthermore, it is noteworthy that the thesis does not account for the implementation of MaaS platform usage in the simulation. This gap provides room for incorporating additional parameters to simulate and evaluate MaaS membership and bundle choices.

Lastly, a promising direction for future research would entail integrating the methodology with synthetic population data derived from a MaaS stated-preference survey. This approach could involve not only individual users but also households, enabling the calibration of scenarios and facilitating the implementation of policies or experimental designs among potential MaaS users as both independent customers and households. This would guarantee replicability in following MaaS ecosystem research by enabling the model to be validated and leading to the creation of a more dependable and flexible approach.

Chapter 6

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Appendix A

Appendix

Table A.1: The 140 scenarios through efficient experimental design

Scenario Numb.	MAAS FEE €	TOTAL COST OF OWNERSHIP €/KM	PT DISCOUNT COST (%)	CARSHARING TIME-BUDGET (min)
1	13	0.35	50	30
2	10	0	10	60
3	0	0.5	10	75
4	10	0.3	100	30
5	9	0.6	100	75
6	6	0.6	10	45
7	10	0.15	70	45
8	9	0.05	40	30
9	13	0.1	80	90
10	11	0.05	100	90
11	3	0.35	0	90
12	10	0.1	30	90
13	7	0.6	60	45
14	9	0.5	80	75
15	14	0.1	20	75
16	0	0.2	90	60
17	4	0.25	50	75
18	1	0.5	100	30
19	11	0.4	10	45
20	11	0.55	40	30
21	1	0.25	40	30
22	4	0.55	100	90
23	12	0.55	10	75
24	5	0.5	60	60
25	2	0.4	60	30
26	9	0.3	70	60
27	6	0.05	80	75
28	14	0.25	60	30
29	12	0.35	90	90
30	14	0.2	0	45
31	15	0.3	0	30

32	7	0.3	10	90
33	11	0.35	30	60
34	12	0.15	60	75
35	14	0.3	40	45
36	1	0.6	80	90
37	1	0.3	30	60
38	11	0.45	0	30
39	12	0.2	70	90
40	3	0.1	60	75
41	9	0	60	45
42	3	0.25	100	45
43	7	0.15	40	90
44	7	0.35	20	75
45	9	0.1	50	30
46	15	0.05	60	45
47	8	0.25	30	90
48	13	0.05	30	75
49	1	0.55	20	45
50	6	0.1	70	30
51	5	0.55	30	30
52	8	0	20	60
53	14	0.4	100	75
54	13	0.2	20	30
55	0	0.05	70	30
56	0	0	80	30
57	8	0.55	70	75
58	8	0.45	90	75
59	14	0.55	90	90
60	0	0.45	100	90
61	4	0.4	0	90
62	8	0.2	60	90
63	12	0.1	40	45
64	15	0.35	100	60
65	15	0.45	10	90
66	6	0	100	30
67	1	0.45	60	90
68	10	0.05	90	45
69	10	0.6	50	30
70	15	0.25	80	60
71	6	0.55	60	60
72	7	0.45	80	60
73	13	0	0	45
74	3	0	30	90
75	7	0	70	45
76	5	0.05	50	90
77	1	0	50	75
78	6	0.5	90	90
79	13	0.3	60	75
80	1	0.1	10	60
81	3	0.4	80	60
82	9	0.45	20	45

83	2	0.6	30	30
84	5	0.15	0	60
85	0	0.55	0	45
86	15	0.15	20	75
87	11	0.25	70	90
88	2	0	40	90
89	3	0.45	70	60
90	5	0.35	40	75
91	2	0.35	80	45
92	3	0.15	90	30
93	9	0.4	30	60
94	14	0.45	30	30
95	5	0.6	20	90
96	10	0.2	80	75
97	0	0.15	50	45
98	0	0.6	40	75
99	14	0.6	70	60
100	8	0.35	10	30
101	10	0.4	20	90
102	13	0.25	90	45
103	7	0.2	0	75
104	0	0.35	60	90
105	4	0.1	90	60
106	11	0.2	50	60
107	5	0.2	10	30
108	11	0.3	90	75
109	4	0.5	70	30
110	2	0.05	20	60
111	5	0.3	80	45
112	8	0.6	0	60
113	12	0.25	20	60
114	13	0.5	40	60
115	8	0.4	50	45
116	4	0.15	80	30
117	6	0.15	30	75
118	9	0.15	10	90
119	6	0.4	40	60
120	7	0.55	50	60
121	4	0.45	40	75
122	4	0.2	30	45
123	15	0.5	30	45
124	2	0.5	50	90
125	8	0.1	100	45
126	1	0.35	70	45
127	6	0.3	50	90
128	11	0.5	20	45
129	15	0	90	75
130	12	0.05	0	30
131	2	0.25	10	75
132	4	0.05	10	60
133	3	0.2	40	45
134	5	0.4	70	75
135	3	0.3	20	30

136	2	0.15	100	60
137	10	0.25	0	60
138	12	0.45	50	45
139	7	0.4	90	30
140	2	0.1	0	75