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Incorporating Discrete Mode Choice of Sharing Micromobility in MATSim

A thesis presented in partial fulfilment of the requirements of the Degree of Master of Science in Transportation Systems at the Department of Civil, Geo and Environmental Engineering, Technical University of Munich.

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Abstract

In response to the constant growth of the urban transport demand and its externalities, shared micromobility (SMM) emerged as a less erosive and efficient transport alternative. However, it has been evidenced that the wrong planning of SMM could lead to increased negative externalities. Therefore, the investigation objective was to advance the simulation of SMM state of -the -art to allow better planning. Moreover, the literature review revealed a lack of discrete mode choice in SMM simulation, despite its reported importance in user adoption and use patterns. The SMM framework closed the literature gap by simulating the SMM supply, multimodality, and discrete mode choice of the users. Test scenarios were produced based on sensitivity tests to vehicle/station density, costs, and integration with PT, to validate the capacity to replicate user behavior and mode patterns of the framework. The SMM framework results showed mixed success in the sensitivities to cost, service scheme, and multimodality. Moreover, in most of the test scenarios, the results were heavily influenced by the local conditions of the study region. In conclusion, the integration of mode choice models in SMM simulation cannot depict the user patterns of mode choice and use patterns of the modes.

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1. Introduction

Due to the constant population increase in cities, the demand for urban transport grows significantly. Moreover, the externalities of urban transport are amplified due to the increasing demand. One of the most significant externalities of transportation is related to emissions. For instance, in the past twenty years, GHG emissions due to transport have been rising at a constant rate worldwide (IEA, 2021). Planning- and decision-makers are aware noticing this evident problem; thus, in the last years, transportation development has shifted to a more inclusive and less erosive realm. Consequently, there have been several different breakthroughs in the previous years, such as intelligent technologies, efficiency in vehicles, and new mobility solutions.

One of those sustainable solutions is the emergence of Shared Micromobility (SMM) into the mainstream of urban transportation. Micromobility is defined as a variety of on-demand transportation schemes using low-speed and low-weight vehicles for short trips in urban environments (Shaheen, 2019). The root of sharing micromobility can be traced to the 1960s in Amsterdam with the Provo cultural movement, which established the first communal bikesharing system in the city (Krümmel et al., 2019). However, the current stage of SMM is based on the proliferation of electric vehicle services like eScooters and electric bike-share (Krümmel et al., 2019). The current phase of micromobility is characterized by the addition of a heterogeneous realm of services such as free-floating, station-based, nonelectric and electric services. Now, in the current context, sharing micromobility has become a prominent part of the transportation puzzle up until the point of representing 136 Million trips in the U.S.A in 2019 (NACTO, 2019).

The prominent and constantly growing role of micromobility in the urban transport landscape has been causing several effects affecting how the population moves daily. For instance, there has been SMM displacing the users away from car usage. An example of this can be seen in studies such as Rodriguez et al.(2019). Consequently, reducing car usage diminishes congestion in urban environments and greenhouse emissions (Milakis et al., 2020). Finally, another positive repercussion of micromobility is increased accessibility for marginalized people and public transport (Shaheen & Cohen, 2019). However, the impacts of micromobility are not only positive for sustainability.

On the negative side, there has been contradictory information regarding the environmental impact of micromobility. For instance, in a Life Cycle Assessment (LCA) carried out in Parison free-floating e-scooter services, it was discovered that e-scooters could generate more pollution than the displaced modes such as metro and active modes.(de Bortoli & Christoforou, 2020). Additionally, most of this pollution comes from the so-called servicing part of the operation, referring to the relocation of vehicles (de Bortoli & Christoforou, 2020). On the other hand, the micromobility modes also appear to have a conflicting relationship with public transport.(Campbell et al., 2016; Rodriguez et al., 2019; Shaheen et al., 2013) Consequently, as much as micromobility can be a valuable tool in the current context, it can also have drawbacks that must be addressed.

1.1. Motivation

In light of the increasing role of shared micromobility in the current transportation landscape, the effects of negative aspects of the mode become more threatening in achieving the sustainability goals for our society. With the purpose of mitigating those negative impacts, better systems planning must be carried out. Specifically, simulation of SMM modes can help predict and quantify the effects of such measures. Nonetheless, the SMM modes are complex to model, and there is no definitive tool to simulate them cohesively and comprehensively. In the following thesis, the author aims to explore the possibilities of creating a comprehensive simulation framework for sharing micromobility. To develop the framework, the author hopes to take advantage of the mesoscopic transport simulation MATSim and its extensions. After the thesis work is finalized, the author wishes to contribute a framework that builds on the available supply and multimodality of SMM simulation while implementing the explicit mode choice of the user.

1.2. Objective

During the thesis's development, the author's objective is to advance the state of the art of agent-based micromobility simulation. Moreover, the thesis hopes to advance the state of the art of the MATSim agent-based simulation framework to accurately represent the different dimensions of micromobility services, their users, and the relationship in a multimodal urban environment. To achieve said objective, the thesis work needs to resolve the research question:

- Can discrete mode choice models in the MATSim framework represent the different sensitivities of the demand side of shared micromobility?

Further, the research question was subdivided into three subquestions:

- Can the resulting framework accurately depict the interactions between service cost and user mode choice?
- Can the resulting framework accurately depict the interactions between different service schemes and user mode choice?
- Can the framework capture the relationship between shared micromobility and other modes?

1.3. Structure of the Thesis

To provide a logical structure to the body of work, the thesis will be structured in the following chapters:

- Chapter 2 will introduce shared micromobility and the different factors. Moreover, the chapter introduces the reader to the context of micromobillity simulation frameworks. Afterward, the different micromobility frameworks will be contrasted and assessed regarding their ability to represent micromobility. Finally, the chapter will introduce SMM mode choice and mode choice models in MATSim.

- Chapter 3 will present the agent-based simulation framework created in terms of logic and inner workings. Furthermore, the chapter will provide an instruction section to implement the framework in other scenarios.

- Chapter 4 will introduce the simulation test bed of Corsica and the different test scenarios developed.

- Chapter 5 will present the results of the test scenarios in Corsica.

- Chapter 6 will discuss the validity of the patterns observed in Chapter 5 and contrast them with the literature knowledge.

- Chapter 7 will wrap up the thesis's investigation work and summarize the achievements. Moreover, it will outline the framework's shortcomings and future directions for work.

2. Literature Review

2.1. What is Micromobility?

2.1.1. Introduction to Micromobilty

Although the term micromobility started being mentioned in scientific literature around 2017 (Liao & Correia, 2020), the phenomenon of sharing low-speed vehicles have been around long enough. The first reported instance of sharing micromobility was in 1966 in Amsterdam by the PROVO collective, which established the first system of communally shared bicycles (Krümmel et al., 2019). However, the shared micromobility that the PROVO collective conceived in 1969 has constantly been evolving until it reached the actual state of the term.

According to Krümmel et al., the evolution of shared micromobility can be traced back to three different technological advancements (2019). The first technological break-through was rack locking technology, which allowed the apparition of station-based services (Krümmel et al., 2019). In these station-based or docked services, the user has specific locations to pick up or return the shared vehicles (Arias-Molinares et al., 2021). Eventually, in 2014-2017, the emergence of GPS technologies completely changed t.he landscape of shared micromobility, making space in the market for dock-less/free-floating SMM (Krümmel et al., 2019). These services differentiated from station-based ones since they were not confined to specific locations of pick up or return (Arias-Molinares et al., 2021; Shaheen et al., 2021). The free-floating services are flexible services in which the vehicles can be used, picked up, and returned inside a delimited geographic area (Arias-Molinares et al., 2021; Shaheen et al., 2021). Finally, the last technological development was one of the better vehicles equipped with electrical motors (Krümmel et al., 2019). These services introduced different vehicles such as electric-powered scooters (eScooters) and electric-powered bikes (e-Bikes). Nowadays, the sharing micromobility is a heterogeneous mode of transport composed of different types of vehicles and service schemes.

Perhaps the most accurate definition for shared micromobility is presented by Shaheen and Cohen as *“an innovative strategy that enables users to have a short-term access to a mode of transportation on an as-needed basis”* (2019, p.3). Moreover, micromobility gives its users access to low-speed, low-weight modes such as bicycles, e-scooters, and e-bikes (Shaheen & Cohen, 2019). Finally, shared micromobility is characterized by different service schemes such as station-based services, free-floating/dockless services, and a combination of them called hybrids.

With the concept of micromobility clear, it is time to contextualize it in the urban transport landscape. Since 2017, the shared micromobility realm has acquired a more significant role in the way people travel in urban environments. The phenomenon of shared micromobility is present in 350 countries (Rose et al., 2020). Moreover, shared micromobility seems to be a constantly growing trend. In places such as the US, the number of SMM trips per year has increased from 321.000 trips to 136 Million shared micromobility in the last decade (NACTO, 2019). Meanwhile, in other markets like Europe, there reportedly are 20 million eScooter users as of 2020 (Twisse, 2020). Further, the role of SMM in Europe is expected to have a continuous growth estimating a 300-500 billion market by 2030 (Heineke et al., 2020). Based on the evidence, it is clear that shared micromobility is a growing mode in urban transport now and in the future. Therefore, it is essential to critically assess which impacts SMM would have on the present and future of transportation.

2.1.2. Impact of shared micromobility in our world

The growing role of SMM and micromobility, in general, has been pushed to the forefront the scientific research in the decade between 2011-2021(Abduljabbar et al., 2021; Elmashhara et al., 2022; Marques & Coelho, 2022). Moreover, one of the main aspects the researchers have shifted their focus to is estimating the impact of micromobility (Liao & Correia, 2020). Therefore, although the impacts of SMM have been studied in detail and are extensive, this section will try to summarize the main effects, both positive and negative.

One of the main topics researchers have discussed regarding SMM is the impact on people's mobility behavior. For instance, Rodriguez et al.(2019) state that e-bikes and e-scooters have the potential to attract 40% of their trips from private cars. Moreover, Liao & Correia (2020) established that in the UK and Germany, almost half of the passenger trips in urban areas could be replaced by shared micromobility. In contrast to the positive impact of car reduction usage, Campbell et al. (2016); Rodriguez et al.

(2019), and Shaheen et al.(2013) argue that shared micromobility has a strong pull from environmental friendly modes such as walking, public transport, and conventional biking. Specifically, evidence in North America proves a strong pull from the rail, with close to 40% of trips of bikesharing trips coming from this mode (Shaheen et al., 2013). Finally, the last impact regarding mobility behavior is the evidence of micromobility positively impacting access to public transportation (Shaheen & Chan, 2016; Shaheen & Cohen, 2019). The impact of SMM on travel behavior can be positive in reducing car sharing usage, yet it has side effects that must be analyzed and addressed, such as the competence with public transport.

The impact of SMM on pollution and emissions is also a critical impact that the literature has investigated. In the first instance, the assessment seems positive due to the modal shift away from car transport, reducing direct emissions, and replacing electric or human-powered vehicles (Milakis et al., 2020). The positive impact can be realized by lowering two gigatons of CO_2 per year if trips using bikes or e-bikes reach 14% of urban trips worldwide (Mason et al., 2015). Although the outlook seems positive, some authors agree that SMM can be more pollutant than the modes it replaces (Hollingsworth et al., 2019; Moreau et al., 2020; Severengiz et al., 2020). Moreover, the emissions of e-scooter can be mainly attributed to the manufacturing and redistribution procedures (Hollingsworth et al., 2019; Severengiz et al., 2020). In detail, Hollingsworth et al.(2019) and Moreau et al. (2020) established using LCA that by shifting trips to e-scooters, the life cycle emissions would rise to between 30 and 60% of the emissions generated using the original mode of travel. Although the impact of SMM on emissions is highly researched, it is still uncertain if the effect of SMM is positive or detrimental. Furthermore, it can be influenced by non-trip-related factors such as relocation procedures and manufacturing.

The prominence of shared micromobility and its influence in the foreseeable future, however, the complexity of such modes carries a reasonable amount of uncertainty on how it will impact everyday life in urban environments. On the one hand, SMM micromobility has the potential to provide significant accessibility to PT, encouraging mode shift away from car dependency, reducing congestion, and reducing GHG emissions (Shaheen & Cohen, 2019). However, there has also been evidence of conflicting impacts, such as augmenting GHG emissions due to the Life cycle of vehicles (Hollingsworth et al., 2019; Moreau et al., 2020; Severengiz et al., 2020) and the cannibalization of public transport (Campbell et al., 2016; Rodriguez et al., 2021; Shaheen et al., 2013). Planning is crucial to foster the SMM and the positive impacts while minimizing the adverse effects. Moreover, quantifying an SMM service's impact before its implementation is critical in the SMM phenomenon.

2.2. Simulation of Shared Micromobility

One of the main functions of transport planning is understanding the impacts a planned measure will have on the context. To achieve that, planners try to represent a simplifying abstraction of reality; this process is called transport modeling (Heyns & Van Jaarsveld, 2017). Furthermore, transport modeling provides a framework for evaluating transport measures or policies, called simulation. In the context of transport planning, simulation helps quantify the impacts of planning decisions on the different city stakeholders and in metrics such as traffic flow and congestion (Grignard et al., 2018). When contrasting the complex nature of SMM and its impacts, it is clear that transport simulation plays a crucial role in planning and establishing sustainable and prosperous micromobility services.

Although simulation is a valuable tool to evaluate the impacts of SMM, the simulation of shared micromobility is not a straightforward task. As was established beforehand, SMM is a fast-changing transport phenomenon. Moreover, the current generation of shared micromobility is rather complex since the base mechanism of the bikesharing, and e-scooter sharing is to respond dynamically to the variation of demand needs throughout the day (Tzouras et al., 2022). The base mechanism of SMM limits the traditional aggregated transport modeling and simulation approaches (e.g., Four-step models). The state of the art of the SMM modeling and simulation tends to focus on disaggregated approaches; more specifically, they are based on the Agen-Based Model(ABM) framework (Liu et al., 2022; Tzouras et al., 2022)

Some instances of agent-based simulation for SMM have been presented by authors such as Coretti Sanchez et al. (2022), Fernández et al. (2020), McLean et al.(2021), and Soriguera et al., 2018). For instance, Soriguera et al. (2018) developed a Matlab-based simulation that generated demand based on OD relations and different integrated behaviors such as rebalancing, the influence of battery duration, and user interaction and information via information apps. Similarly, Fernández et al. (2020) generated a microscopic agent model for station-based bikeshare to evaluate different service schemes before a real-life implementation occurs. Again, Coretti Sanchez et al. (2022) developed a discrete event-based framework for an autonomous bike that implemented a simulation of routing, changing, demand generation, and rebalancing. Finally, (Balac & Hörl, 2021; Becker et al., 2020; Hebenstreit & Fellendorf, 2018; Khalil et al., 2021) expanded the basic MATSim framework to simulate bikeshare.

On the other hand, there have been documented instances of simulation of SMM outside the realm of ABM. One of the most popular ones is the simulation using distributions for demand generation, such as Poisson processes. Furthermore, the methodology was used to evaluate bikesharing and its service aspects, such as rebalancing (Jin et al., 2022) and the simulation of eScooter services (Mclean, 2021). Finally, the last type of simulation framework reported is using Montecarlo simulation. This latter methodology has been implemented to estimate the energy consumption by eScooter trips (Peng et al., 2021; Wang et al., 2020).

Although the simulation of SMM has been a prominent topic in the academic field, as shown by the variety of simulation frameworks, only one study has evaluated the necessary aspects of an SMM simulation framework. In 2021, Tzouras et al. conducted a literature review and qualitative assessment of the different simulation frameworks for eScooter sharing services (2021). In this review, the author compared several Agent-based models such as TRANSIMS, Netlogo, MATSim, SimMobility, AnyLogic, POLARIS, and Sarl. Moreover, the author established using literature review the following core characteristics needed in eScooter simulation:

1) The framework must be an open-source code.

2) The framework must have been used to simulate shared mobility services and their impacts.

3) The framework must be able to model large-scale transport networks.

4) The framework must describe precisely the spatiotemporal demand variations.

5) The framework must allow the modeling of bicycle traffic in cycle lanes.

6) The framework must have been used to simulate pedestrian traffic.

7) The framework must simulate mixed traffic conditions.

8) Allows the introduction of discrete mode choice models.

9) The framework must consider the socio-demographic characteristics of agents to model travel behavior.

10) The framework can simulate multimodal trips. (Tzouras, 2021).

After assessing the different ABM models contrasted with the core characteristics, Tzouras et al. point to MATSim and SimMobility as the most promising models for escooter sharing services due to them fulfilling nine out of ten core criteria (2021). All in all, MATSim is perhaps the most promising solution to simulating SMM due to it being open-source, having been used to model sharing services, being mesoscopic, describing the temporospatial variation of the demand, being able to model the bicycle traffic, allowing the implementation of discrete mode choice models, accounting for sociodemographics attribute agents and able to simulate multimodal trips.

2.3. MATSim and SMM Simulation

2.3.1. MATSim fundamentals

In 1999 Kai Nagel left his position as a research assistant in the Los Alamos National Laboratory, working with TRANSIM (A cellular automata traffic modeling framework) for ETH Zürich (Nagel & Axhausen, 2016). Moreover, Nagel found it hard to translate his work since TRANSIM was not an open-source due to US Technology restrictions (Nagel & Axhausen, 2016). Due to that, Nagel started the MATSim project as a light-weight modeling framework (Nagel and Axhausen, 2016). Posteriorly the framework would go through serval iterations with the help of several institutions until arriving at the current definition of “an activity-based, extendable, multi-agent simulation framework implemented in Java” (Horni et al., 2016,p.4). Currently, the MATSim framework is continuously developing; the most current version is MATSim 13.0.

Regarding the inner simulation mechanism in MATSim, Figure 1 represents the typical execution loop. The first stage in the loop is the input of the initial demand. In MATSim, there are typically three basic inputs the config file, the network file, and the population files (Horni et al., 2016). The population file describes the agents by giving information about the sociodemographic agents’ attributes and their daily commute trips. Finally, the description of those commute diaries is represented in the form of plans.

On the other hand, the network file consists of the links and nodes that integrate the modeled area's multimodal transport network.Finally, the Config file specifies to the simulation framework the settings under which the simulation will be carried out (Liu et al., 2022). The inputs will be parsed into the framework and initiate the MATSim simulation loop.

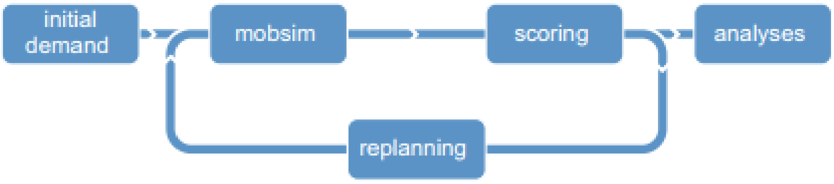

Figure 1. Source: Horni et al., 2016. MATSim Framework Loop.

As shown in Figure 1, a typical MATSim execution loop comprises three stages: a simulation of the agent's plans (MobSim), scoring the agent's plans, and replanning the agents. The first stage referred to as MobSim, loads all agents with a selected plan and simulates all the movements and traffic in the network, usually using a queue-based approach for traffic simulation in a network (Horni et al., 2016). After that, every agent's plan is fed into the scoring module evaluated using the Charypar-Nagel scoring function (Horni et al., 2016). This function quantifies an agent's experience with a specific plan, where traveling time means negative utility, and performing an activity apports positive utility to the plan(Horni et al., 2016). Furthermore, the Charypar-Nagel scoring function also rewards delays, on-time arrivals, and efficient activity durations (Horni et al., 2016). An example of the scoring function can be seen in Figure 2. Finally, the last step in the loop is the replanning which allows a percentage of the agents to come up with a new plan via replanning route choice, mode choice, or others.

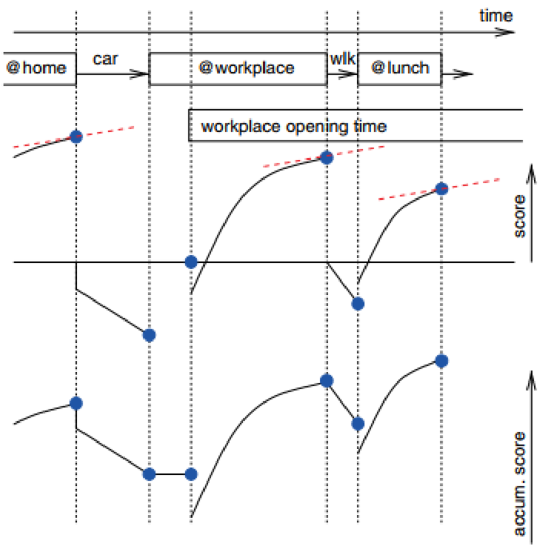

Figure 2.Source: Horni et al., 2016. Charypar-Nagel Scoring Function Representation

Finally, the cycle will repeat the number of times specified in the config file. After each iteration, every agent will select the best-scored plan in their data. This structure forces the agents to react and adapt to the different interactions between agents; this is defined as the co-evolutionary algorithm (Horni et al., 2016). At the end of the simulation, each agent would have optimized the plan score, and the population will be in equilibrium(Horni et al., 2016).

On top of providing the basic simulation, MATSim is remarkable for its ability to extend its functions. These extensions are rooted in a contribution-based modular approach; in this manner, the simulation can be modified on several points (Horni et al., 2016). In the case of SMM, it is no exception since multiple modules have been developed. Consequently, the next section will deal with MATSim and SMM simulation.

2.3.2. MATSim and SMM simulation

Although Tzouras et al. regard MATSim as a powerful framework to simulate e-scooter services (2021), it is surprising the small number of uses in which SMM has been simulated in the MATSim environment. More precisely, it has only been used in four instances, which will be presented and assessed using the criteria given in Section 2.2.

The first instance was presented by Hebenstreit and Fellendorf (2018), who developed a custom station-based bike-sharing simulation module. The module was divided into two key segments: bicycle routing and scoring and station-based framework. The bicycle and scoring routing module were based on the Dijkstra algorithm with a disutility-based bike-ability (Hebenstreit & Fellendorf, 2018). Additionally, the travel disutility for bike-sharing routes was based on the route bike friendliness, and person-type weighting proposed (Ziemke et al., 2021).On the side of plan scoring, the travel time was analogously weighted by the agent's perception of bike-friendliness (Hebenstreit & Fellendorf, 2018). Finally, the authors developed a highly detailed framework for the bike-sharing service, which simulated the supply of SMM services in detail, with charging and discharge of battery simulation, multimodality between PT and bike-sharing, and parking finding. However, one of the downsides of this simulation is that it has not been published as an open-access tool.

The following two instances were developed by Becker et al. (2020) and Khalil et al., 2021). Their first one used the Carsharing and Discrete Mode Choice (DMC) contributions to model the impact of sharing services in a Mobility as a Service (Maas) context. Similarly, Khalil et al.(2021) implemented the Carsharing contribution to simulate micromobility services in Birmingham and evaluate the impact on congestion. However, Khalil et al. (2021) focused on generating a synthetic population for the Birmingham region. The main drawback of those two simulations is the lack of a detailed sharing mobility supply due to the carsharing contribution only being allowed to simulate car vehicles. Nonetheless, Khalil et al. (2021) overcome this limitation by adjusting the simulation parameters of the e-scooter mode with a custom speed, length, width, and passenger car unit values for the mode. Moreover, the author introduced the Pass-inQueue simulation mode of MATSim, allowing overtaking between agents in the links (Khalil et al., 2021).

Finally, the latest addition to the SMM simulation on MATSim is the so-called "sharing-contrib" by Balac and Hörl (2021). Its authors developed a highly detailed and customizable module to introduce the sharing services into MATSim simulation (Balac & Hörl, 2021). It provides real-time entities such as stations, vehicles, service schemes, geofences, and real-time data sources such as the GBFS (Balac & Hörl, 2021). In addition, the sharing contrib introduces a custom routing module for the sharing micromobility services (See Figure 3). The custom sharing module modeled several stages of a typical SMM trip, such as the vehicle booking, the access egress walk from the vehicle, and the on-vehicle travel (Balac & Hörl, 2021).

However, according to the Tzouras (2021) criteria, this module lacks two crucial criteria for the simulation of SMM. In the first instance, it doesn't model the sharing vehicles but instead uses teleportation (MATSim Sharing Extension, 2021/2022). Therefore, the agent will not use the MATSim network but instead will be extracted from the simulation and located at the destination after the expected travel time between location and destination (Horni et al., 2016). On the other hand, Milos and Balac use the traditional Charypar-Nagel scoring function that fails to represent sociodemographic aspects influential in SMM simulation.

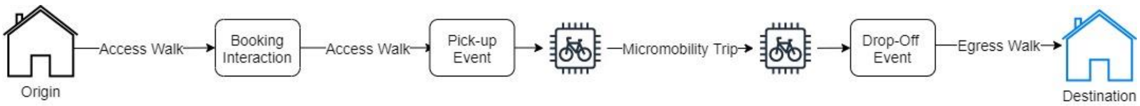

Figure 3. Sharing contrib Routing Module. Based on Balac & Hörl (2021)

As the evidence points out, MATSim complies with the criteria necessary to simulate SMM(Tzouras et al., 2022); however, when the contributions are analyzed one by one, it is clear that none comply with all requirements. For example, Hebenstreit and Fellendorf (2018) can model bike network trips and the attitudinal preferences of users, but their work is not open-source and lacks the implementation of different services. Khalil et al.(2021) model only provides the simulation of bicycle network trips and sharing services schemes but lacks in the same way as the model of Hebenstreit and Fellendorf (2018). On the other hand, Becker et al.(2020) incorporates discrete mode choice models but fail to provide a detailed service scheme representation. The most comprehensive might be the Sharing contrib, which is open-access and offers different schemes. However, it lacks the incorporation of discrete mode choice models and network simulation for services.

As the weak points of the different simulation frameworks were established, it has become clear that the most promising module is the one presented by Milos and Balac (2021). Mainly due to its open-access nature. However, implementing discrete mode choice models is a relatively new route, but still, the importance of user behavior in SMM is one of the critical aspects of the transport mode. Therefore, there is a gap between the simulation of SMM in MATSim and the discrete mode choice model.

2.4. User Behavior in SMM and Mode Choice

One of the most researched topics in SMM is who uses micromobility and why; what influences micromobility (Blazanin et al., 2022; Liao & Correia, 2020).To establish the factors, authors such as Elmashhara et al. (2022) and Liao and Correia (2020) have conducted literature reviews regarding the influential factors that make people choose micromobility. In the case of Liao and Correira, they found that age, education, gender, and income influence the choice to use micromobility (2020). However, these socio-demographic factors have been heavily contrasted by investigating their influence on a person's frequency of using SMM (Blazanin et al., 2022). On the other hand, trip-related factors such as trip length were related to choosing to use e-bike-share (Liao & Correia, 2020). This aligns with the experiments conducted in Beijing’s bikesharing systems by Campbell et al. (2016), which determine that trip length and precipitation are critical factors for an individual to shift a trip to SMM.

Although defining the factors that influence the user of SMM is an extensive task, Elmashhara et al. (2022) present a concise framework in which the user is affected by user-related factors systems related factors, and temporal, spatial, and weather factors. The first ones refer to factors such as time of day, weather conditions, distance, topography, land use, and infrastructure for SMM, among others (Elmashhara et al., 2022). Then, when referring to systems factors, it describes the relation of the user with the system with factors such as the price of the trip, the economic savings of the mode, the closeness of vehicles or stations, and service quality, among others (Elmashhara et al., 2022). Finally, the user-related factors refer to the inherent variables of the user, such as attitudes, social factors, concerns, and socio-demographic factors (Elmashhara et al., 2022).

Further from establishing which factors influence the SMM user, determining how each factor influences the choice of SMM is another required field of study, as Reck & Axhausen (2021) stated. To show the influence of individual factors, mode choice models are a common strategy for this question (Reck & Axhausen, 2021). However, the typical approach to this question is to generate mode choice models between the shared modes and the previous model for each trip, as was carried out by Campbell et al. (2016). However, authors such as Krauss et al. (2022) and Reck et al. (2022) have estimated logit models to evaluate the influence of SMM factors and their impact on mode choice for SMM and traditional modes.

In the case of Krauss et al. (2022), the author conducted surveys in different german cities to quantify the factors that make a person choose sharing services instead of traditional modes such as car and public transport. Moreover, the author considered crucial aspects of the sharing modes such as access/egress time, service characteristics, and personal attributes. Finally, Krauss et al. (2022) established several synergies between modes, such as increasing the cost of private car trips having the most potential to produce mode shifts.

All in all, SMM modes and user selection are a complex realm with several categories of factors playing a role. Additionally, the most common methodology to analyze the influence of each of the factors is discrete mode choice modeling. Consequently, incorporating the discrete mode choice models is key in representing the behavior of SMM demand.

2.5. Mode Choice and MATSim

Mode choice is a crucial aspect when simulating SMM. Thus, it is essential to contextualize mode choice in MATSim. As described in Section 2.3.1, the mode choice in MATSim is based on the Charypar-Nagel scoring function. However, this modality does not explicitly include demographic user factors. Consequently, the Discrete Mode Choice contribution was created to analyze the effects of DMC models in an iterative microsimulation framework (Hörl et al., 2018). The main structure of the contrib can be seen in Figure 4. The framework is based on three components, the alternative generator, the estimation of the choice dimensions, and the candidate selection (Hörl et al., 2019). The basic logic of the systems relies on the alternative generating a set of trips or tours based on the parsed agent plan. Posteriorly the estimator will evaluate the trips or tours based on travel time, costs, and waiting time, among others, and assign a utility for the trip or tour (Hörl et al., 2019). The last step in the model is the candidate selector, which, based on the utility of the trip/tour, will select a candidate based on multinomial logit selection or the best utility (Hörl et al., 2019).

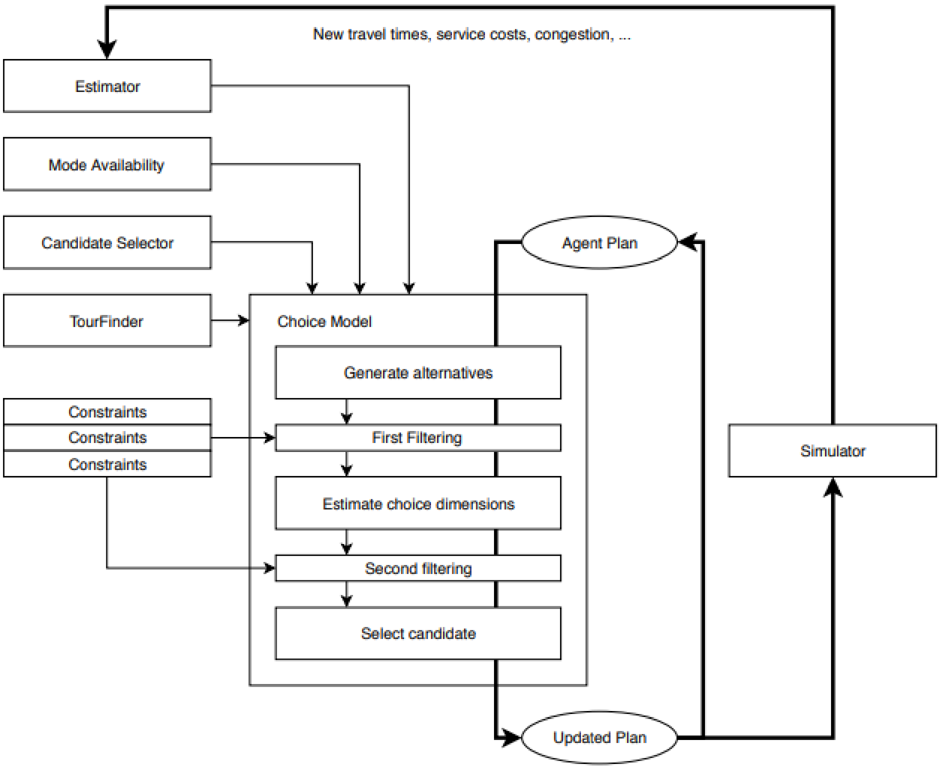

Figure 4.Source Hörl et al., 2019.Structure of DMC Model contrib.

The base DMC model uses the Charypar-Nagel function to score utilities. However, it can be expanded to use custom utility functions. (Hörl et al., 2019). Based on the extension capacities of the DMC utility, Hörl and Balac (2019) introduced the Eqasim pipeline to model different utility functions. Furthermore, Hörl and Balac extended the estimator module into the classes cost model, model parameters, variables, and predictors (2021). The modified framework can be seen in Figure 5.

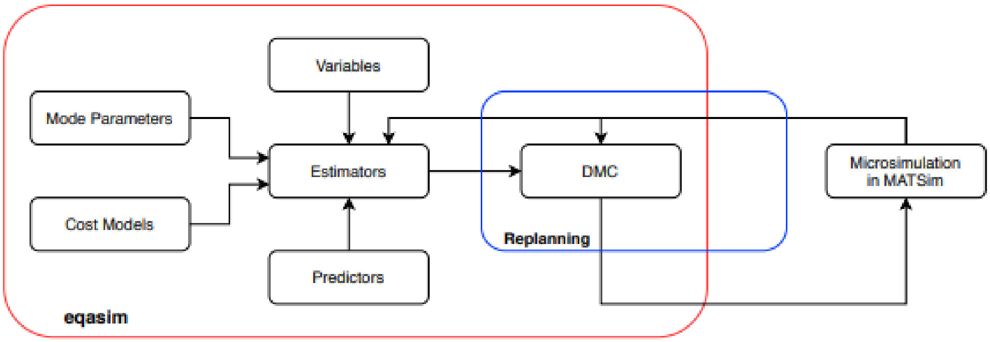

Figure 5. Source: Hörl & Balac, 2021 Eqasim Framework.

The extension's base function is based on each class's interaction. For instance, the model parameters class defines the coefficient for the utility functions. Meanwhile, the cost model describes how the cost of a trip will be calculated based on trip distance or travel distance (Hörl and Balac, 2021). Finally, the predictors are in charge of calculating the trip-related variables such as travel time, waiting time, and access/egress time, among others (Hörl and Balac, 2021). The predictor result will be stored in a variables object and simultaneously parsed into the estimator to calculate the utility based on the Mode Parameters and Variables (Hörl and Balac, 2021). The general class diagram of the procedure can be seen in Figure 6.

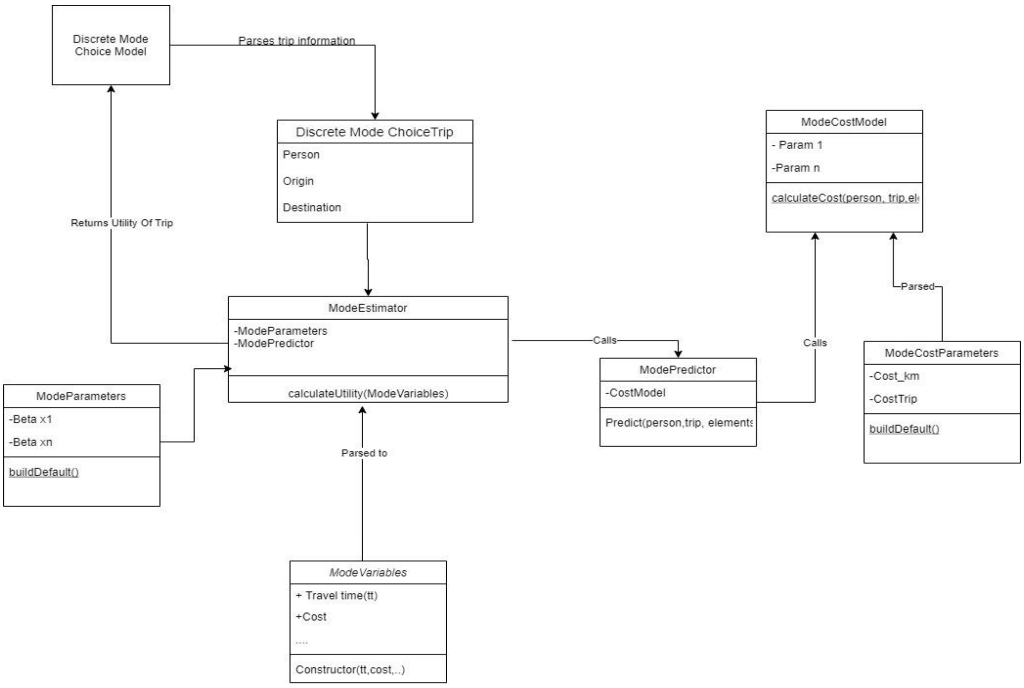

Figure 6.Class Diagram of Eqasim. Based on Hörl & Balac (2021)

In conclusion, the simulation of mode choice models in MATSim is quite advanced. It can model utility functions and multinomial logit models, making evident the research gap between the simulation of SMM and the use of the discrete mode choice model.

2.6. The Research Gap

Through the literature review, it has become clear that SMM is a more relevant prospect in urban transportation. However, the SMM modes can carry severe consequences if planning fails to address them. A way to predict the negative impacts of SMM is the simulation of those systems. Nonetheless, the SMM modes are complex to model, and there is no definitive tool to simulate them cohesively and comprehensively. Perhaps the most promising framework is the MATSim framework due to its modularity and frequent usage for SMM simulation. Yet one of the main drawbacks of SMM simulation using MATSim is that discrete mode choice models have rarely been associated with the SMM. In this order of ideas, this thesis project aims to fill the gap in the literature regarding DMC and SMM simulation in MATSim. Moreover, the objective is to build on the existing Sharing contribution, integrate the mode choice module, and evaluate the impact of this implementation.

3. Methodology

To bridge the gap between MATSim ABM models and sharing micromobility, the following section will present the custom extension framework for the simulation of SMM. Specifically, this chapter will describe in detail how the previous knowledge and contributions have been applied and how the extension of evaluating the user's choice has been adopted into the MATSim framework. Further, the inputs to configure a based simulation will also be discussed.

3.1. General SMM framework

As presented in section 2.3.1, the general framework for MATSim simulation is described in 3 stages, in which the framework receives an initial demand, simulates the traffic flow through the network, and then scores the agents' plans. Based on those, the framework will create new strategies for a percentage of the agents and choose the best strategy. Now, the SMM framework expanded the current offer of micromobility simulation in MATSim. In addition, the SMM framework uses two existing extensions to integrate Sharing contrib with the Eqasim mode choice module.

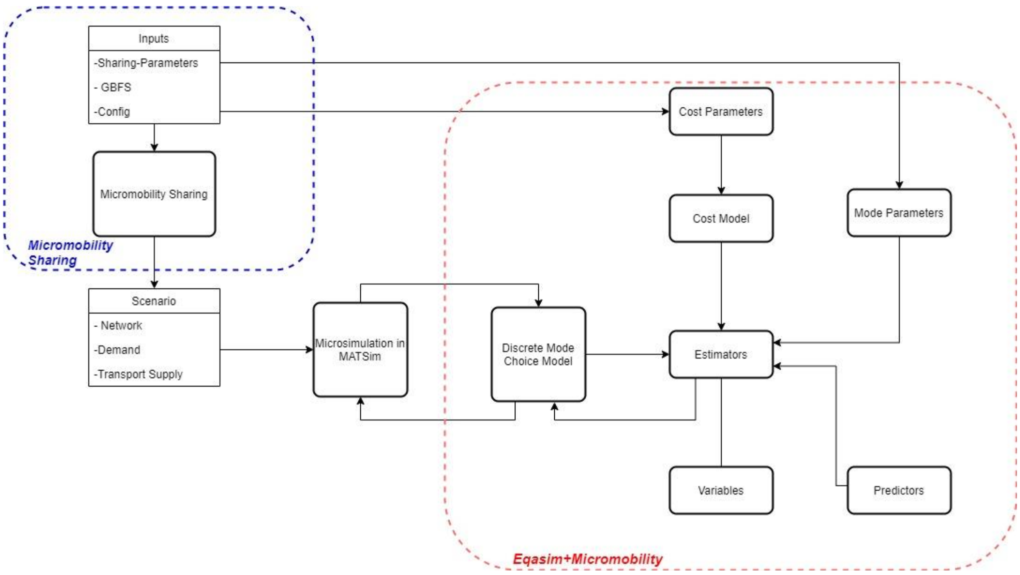

Figure 7.High-Level architecture of the SMM framework

To establish the main workflow of the SMM framework, Figure 3 presents the high-level architecture that modifies MATSim. On a high level, the SMM represents a modification of the typical MATSim loop using two existing contributions Eqasim (Hörl & Balac,

2021) and the Sharing contrib (Balac & Hörl, 2021). The sharing contrib is responsible for parsing the shared micromobility services and representing their supply and spatio-temporal variation (Section 2.3.2). On the other hand, the adaptations to the Eqasim module replace the traditional planning module in MATSim with a custom implementation of a logit mode choice model. The adaptations to the contribs and functions to tailor an extendable framework for micromobility services will be presented in detail in Section 3.3.

Now, the general flow of the SMM framework starts with three critical input data: the General Bike Sharing Feed data (GBFS), the sharing parameters, and the Config file. Those inputs provide the simulation information, the SMM services, and the configuration of the discrete mode choice model for SMM. Posterior to the parsing of the inputs, the sharing micromobility module is in charge of creating the supply of sharing micromobility, as explained by Section 3.4. Subsequently, the services will be stored in the scenario object. The scenario object is one of the main objects in MATSim since it contains a description of the network, population, and transport supply (Horni et al., 2016). At the end of this step, the model is built and is prepared for simulation of iteration 0.

The scenario is parsed into the MATSim microscopic simulator at the start of the simulation. Then all agents will be simulated in the typical MATSim queue-based simulation. After completing the simulation, each plan will be parsed into the Discrete Mode Choice Module. This module will create a tour based on the plan and will calculate the utility of each by estimating the utilities of each trip in the tour as described in the DMC and Eqasim section (See Section 2.5). Finally, the DMC will decide on the best set of trips and return it to the microscopic simulation. This process will be repeated until the Config file establishes the number of iterations.

Although the SMM framework appears relatively simple to the eye, it has many intricacies. Thus, the following sections will describe the inputs in detail, the main modifications to the existing contribs, and how the framework can be implemented with other cases.

3.2. The SMM Framework Inputs and Requirements

As Liu et al.(2022) established in the micromobility simulation review, the simulation's input data will help build the basic simulation framework and the rules that govern the simulation's behavior. Thus, the first file that will be input is the Config.xml, which is the typical MATSim config file described in Section 2.3.1. However, there are a few linked requirements to the Config.xml file. First, the Config file must be multimodal and have the modes car, pt, bike, and walk defined as modes. Additionally, the Config file must point to a population file with the following characteristic for each agent that will have the socio-demographics as in Table 1.

Moreover, Extract.1 presents the typical structure of a person in the plans.xml file. Additionally, the network.xml file must have a defined car network or multimodal in case the public transport or bike have been set as network modes. Finally, the Config.xml must also point to the Households.xml that will describe the households in the study area; the required attributes are described in Table 2. Although this implementation is not standard for MATSim, the SMM framework works within the Eqasim pipeline by Hörl and Balac (2021).

Table 1.Required Attributes in Population

Socio Demographic Variable	**Attribute Name**	**Data Type**	**Category Type**
Age	Age	Integer	Discrete
Bike Availability	bikeAvailability	String	Categorical
Car Availability	carAvailability	String	Categorical
Household ID	householdId	Long	Continous
Person ID	censusPersonId	Long	Continous
Employment Status	Employed	Boolean	Binary
Car License	hasLicense	String	Categorical
Public Transport Subscription	hasPtSubscription	Boolean	Binary
Household Income	householdIncome	Double	Continous
Gender	Sex	String	Categorical
Uses ride pool	isPassenger	Boolean	Binary

```xml
<!-- ====================================================================== -->

<person id="100066">
 <attributes>
  <attribute name="age" class="java.lang.Integer">23</attribute>
  <attribute name="bikeAvailability" class="java.lang.String">none</attribute>
  <attribute name="carAvailability" class="java.lang.String">none</attribute>
  <attribute name="censusHouseholdId" class="java.lang.Long">37365</attribute>
  <attribute name="censusPersonId" class="java.lang.Long">84917</attribute>
  <attribute name="employed" class="java.lang.String">True</attribute>
  <attribute name="hasLicense" class="java.lang.String">no</attribute>
  <attribute name="hasPtSubscription" class="java.lang.Boolean">true</attribute>
  <attribute name="householdId" class="java.lang.Integer">44732</attribute>
  <attribute name="householdIncome" class="java.lang.Double">1786.5695695078953</attribute>
  <attribute name="htsHouseholdId" class="java.lang.Long">19652</attribute>
  <attribute name="htsPersonId" class="java.lang.Long">48056</attribute>
  <attribute name="isPassenger" class="java.lang.Boolean">false</attribute>
  <attribute name="sex" class="java.lang.String">f</attribute>
 </attributes>
 <plan selected="yes">
  <activity type="home" link="56253" facility="home_44732" x="1175992.368861" y="6107760.211399" end_time="07:29:48" >
  </activity>
  <leg mode="walk" dep_time="07:29:48" trav_time="00:14:54">
   <attributes>
    <attribute name="routingMode" class="java.lang.String">pt</attribute>
   </attributes>
   <route type="generic" start_link="56253" end_link="50222" trav_time="00:14:54" distance="1073.0092361440584"></route>
  </leg>
  <activity type="work" link="50222" facility="work_44" x="1176132.91" y="6108573.55" start_time="08:24:48" end_time="15:39:48" >
  </activity>
  <leg mode="walk" dep_time="15:39:48" trav_time="00:14:54">
   <attributes>
    <attribute name="routingMode" class="java.lang.String">pt</attribute>
   </attributes>
   <route type="generic" start_link="50222" end_link="56253" trav_time="00:14:54" distance="1073.0092361440584"></route>
  </leg>
  <activity type="home" link="56253" facility="home_44732" x="1175992.368861" y="6107760.211399" start_time="16:39:48" >
  </activity>
 </plan>

</person>

<!-- ====================================================================== -->
```

Extract 1. Person plan structure

Table 2. Household attribures required

Household Variable	***Attribute name***	***Data Type***	***Category Type***
Id	censusId	Integer	Discrete
Bike Availability	bikeAvailability	String	Categorical
Car Availability	carAvailability	String	Categorical
ID Members of Houshold	members	Array of PersonId	Continous
Household Income	household_Income	Double	Continous

The second input file of the framework is the General Bike Specification (GBFS). The General Bike Specification is an open data standard that informs the real-time status of shared mobility (NABSA, 2015/2022a). The GBFS defines multiple dimensions of sharing services, such as the stations, the vehicles, their status, and the price structure of the services, among others. However, the SMM framework only focuses on three possible GBFS: *station_information.json*, *station_status.json*, *and free_bike_status.json.* When referring to station-based micromobility service, the framework must be provided with the *station_information.json* and *station_status.json files*. Conversely, the Free-floating scheme is implemented using only the free_bike_status.json file. Finally, the description of each file and mandatory fields are as follows:

- *Station_information.json*: this file is the collection of parking stations of the service and their characteristics (NABSA, 2015/2022b). The SMM framework is crucial in providing identification for each station, the stations' coordinates, and each station's parking capacity. To provide that information, the JSON file provided must contain the fields “capacity,” "lat”, lon”, and “station_id”.

- *Station_status.json*: The station status file informs the number of vehicles available in the station (NABSA, 2015/2022b). In the context of the SMM framework, this file informs the sharing module of the number of vehicles per station at the beginning of the simulation day. Further, the JSON file must contain the fields “num_bikes_available” and “station_id”.

- *Free_bike_status.json:* The free vehicle file defines which vehicles are not being used at the current time the GBFS was generated and their location (NABSA, 2015/2022b).In the SMM framework context, this file informs of the location and the id of the service vehicles. Therefore, the JSON file must contain the values “bike_id,” lat,” and “lon”.

Finally, the last set of inputs refers to the sharing simulation, which helps configure the modules of the SMM framework. These inputs can be divided into three subcategories according to their function in the model. The first category refers to the configuring factors of sharing services. The inputs of this category define the factors related to modeling the supplied setting, the service scheme type, the access – egress distance, and the mode. The second category refers to the configuration of the discrete mode choice model, specifically its utility. This set is called the "mode parameters set" and will be described in more detail in the following sections. Finally, the last parameters are called “cost parameters” since they define the cost structures of the sharing services. This cluster will be discussed in the following section with the model parameters.

After describing the primary inputs of the SMM framework and their usage, requirements, and categorization, the next section will present the inner mechanism of the two modules within the SMM framework.

3.3. The SMM Framework Module

3.3.1. The Eqasim+Micromobility Module

As described in Section 2.5, Eqasim is a novel framework based on MATSim for mesoscopic simulation and the inclusion of a discrete mode choice model. Nonetheless, the available use cases haven’t been used for cases in micromobility. Consequently, the Eqasim+micromobility module is a custom extension using the micromobility mode choice model, as explained by Krauss et al. (2022). This subsection will deal with the adaptations made to the Krauss et al. (2022) mode choice model, and posteriorly it will dwell into the detailed implementations for estimating mode choice variables in micromobility trips.

As established in Section 2.4, mode choice models that include micromobility options and traditional transport modes are rare. Furthermore, there are only two instances in which micromobility provides such a specific framework. Krauss et al. (2022) were selected for the SMM framework since it contained several essential variables that determine the micromobility used behavior, as presented in Section2.4. Further, the Krauss et al. Model is modeled after the users' behavior in Germany; several simplifications were carried out.

The first simplification is regarding the type of the mode choice model. Krauss et al. (2022) describe their model as a mixed logit model. According to the literature, the mixed logit models can represent the individual's tastes (Krueger et al., 2021). Random user taste may be interesting to use in the context of SMM because the user is influenced by several attitudinal perceptions, such as green thinking and environmental awareness (Blazanin et al., 2022; Elmashhara et al., 2022; Liao & Correia, 2020). Nonetheless, the current state of the Eqasim DMC framework does not implement the mixed logit model. Instead, the choice probability was estimated based on the multinomial logit model (see Equation 1). Here represented the utility of a trip being made in the mode i.

$$P(i) = \frac{e^{u_i}}{\sum_i e^{u_i}} \tag{1}$$

Now, regarding the utility calculation, the mode choice model proposed by Krauss et al. was divided into four sections: time-related attributes, cost attributes, supply characteristics, vehicle characteristics, and personal attributes. However,the SMM framework implementation ignored several vehicle attributes such as battery range and occupation level in public transport vehicles since MATSim does not explicitly model these aspects of transport supply. On the other hand, the supply characteristics were also ignored due to availability. The mode scheme was explicitly simulated using the Sharing contrib as explained in Section 2.3.2. Thus, Table 3 depicts the variables and coefficients used in the model.

Table 3. Mode parameters adapted for SMM.Based on Krauss et al.,2021

	Variable	*eScooter Sharing*	*Bikesharing*	*Walking*	*Private Car*	*PT*
Time	Travel time [min]	-0.116	-0.09	-0.212	-0.057	-0.065
	Access time [min]	-0.04	-0.04	-	-0.034	-0.04
	Egress time [min]	-0.03	-0.03	-	-0.042	-0.03
	Parking search time [min]	-0.04	-0.04	-	-0.04	-
Cost	Cost [EUR/trip]	-1.886	-1.886	-	-1.886	-1.886
	σcost	-1.414	-1.414	-	-1.414	-1.414
Supply	Transfers	-	-	-	-	-0.081
Personal	Constant	-1.574	-1.199	4.551	-	-1.205
	Age	-0.051	-0.041	0.02	-	0.013
	Bike accessibility	1.811	2.345	0.495	-	0.9
	Car accessibility −	-0.858	-1.026	-1.216	-	-1.556
	Public transit pass	1.621	1.799	1.64	-	3.651
	MaaS subscription	1.377	1.172	-0.228	-	1.241
	σj	1.315	1.587	-2.933	3.498	1.792
	ζpool	-	-	-	0.776	-

$$U_{ES} = \beta_{ES} + \beta_{timeES} * time_{ES} + \beta_{accessshared} * access_{ES} + \beta_{egressshared} * egress_{ES} + \beta_{parking} * parking_{ES} + \beta_{cost} * cost_{ES} \quad (2)$$

$$\beta_{ES} = \beta_{ES_0} + \beta_{ageES} * age + \beta_{carES} * hhcar + \beta_{bikeES} * hhbike + \beta_{ptpassES} * ptpass + \beta_{maasES} * maas + \sigma_{ES} * \zeta 2 \quad (3)$$

$$\beta_{cost} = -e^{\beta\_cost0} + \sigma cost * \zeta 1 \quad (4)$$

Finally, the last adaptation to the original mode choice model concerns the utility equations. To illustrate the modifications, the original equations by Krauss et al. (2022) for the eScooter Sharing utility will be presented. Equation 4 represents the cost coefficient for all modes, according to Krauss et al. (2022). Meanwhile, Equation 2 depicts the personal utility of an eScooter trip. In the framework of Mixed logit models, the error parameter represents the mean vector $(\zeta 1)$ and is directly related to the taste variable of the model (Krueger et al., 2021).

Consequently, in the adaptation for the SMM framework, this factor was assumed as 0. Therefore, it is congruent with the implementation of an MNL model. Finally, the example equations were the following.

$$U_{ES} = \beta_{ES} + \beta_{timeES} * time_{ES} + \beta_{accessshared} * access_{ES} + \beta_{egressshared} * egress_{ES} + \beta_{parking} * parking_{ES} + \beta_{cost} * cost_{ES} \quad (5)$$

$$\beta_{ES} = \beta_{ES_0} + \beta_{ageES} * age + \beta_{carES} * hhcar + \beta_{bikeES} * hhbike + \beta_{ptpassES} * ptpass \quad (6)$$

$$\beta_{cost} = -e^{\beta\_cost0} \quad (7)$$

Now, with the modifications and assumptions related to the mode choice model selected, the next logical step was implementing the mode choice model inside the Eqasim framework. Although in Section 2.5, the structure of the Eqasim was presented with the estimators, cost models, predictors, cost parameters, model parameters, and variables. In this research, the main focus is SMM. Therefore, the modes like PT, car, bike, and walk will be obviated since they derive heavily from the core Eqasim framework (See Appendix A). Instead, the elements of the SMM Eqasim will be presented for the case of eScooter since their programmatic approach is identical to the ones of bike share. Figure 8 depicts the class relationships in the implementation of eScooter in the SMM framework.

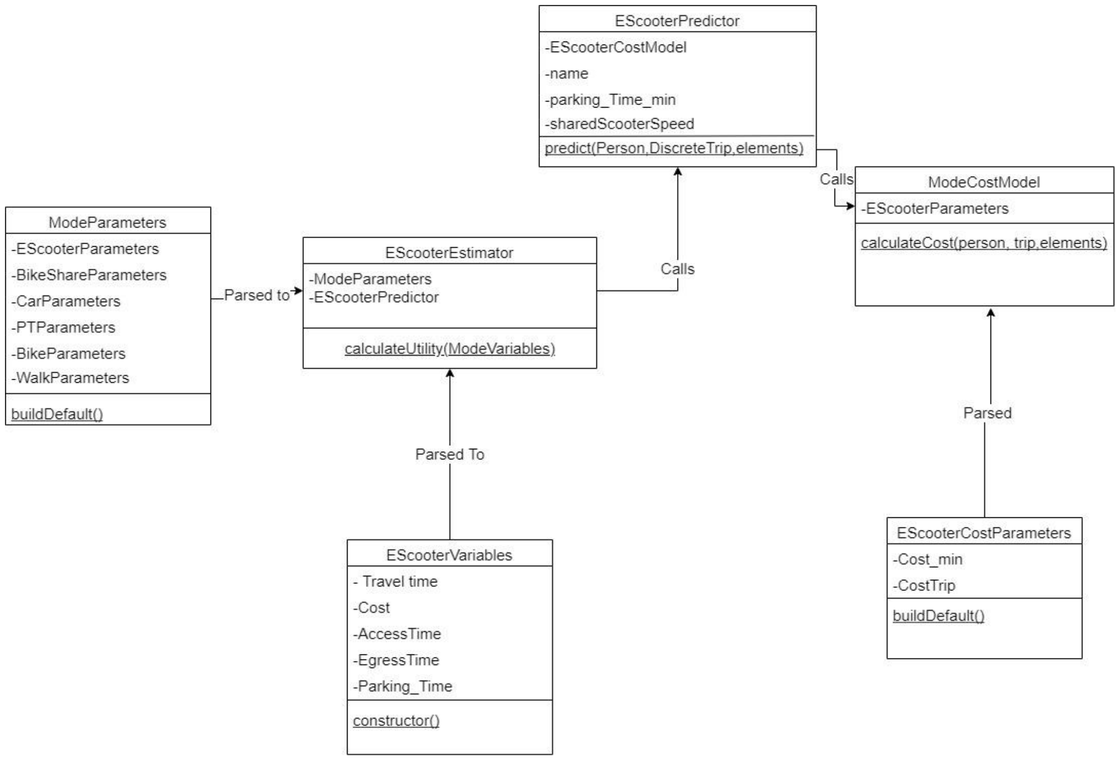

Figure 8.Class Relation Diagram for eScooter Sharing in the SMM Framework

In contrast to the basic Eqasim framework, the SMM adapted the functionalities of the basic classes of cost model, predictor, and cost variables. The first modification regards the cost model and cost parameters. Generally, micromobility has different payment schemes, such as subscription-based, km-based, and minute-based, among others. However, in the current SMM configuration, the model was minute based, in which the cost of a shared micromobility trip is defined by Equation 8. Thus, the cost parameters class is determined by the unlocking price of the mode (CostTrip) and the cost per minute (Cost_min).

$$Cost = CostTrip + TravelTime * Cost\_min \quad (8)$$

On the other hand, the predictor class is the engine of the implementation; it bridges the gap between the simulation data of the MATSim simulation and the utility needed for the discrete mode choice model. Further, the Predictor class (See Figure 5) has an input of the simulation elements of the eScooter trip (as discussed in Section 2.3.2). Based on the trip elements, the method will iterate and classify the travel times according to their previous or next activities and modes: travel time, access time, or egress time. Finally, the travel time is parsed into the cost model, and the trip cost is calculated. Finally, the method stores the trip variables in an EScooterVariables object and feeds it to the estimator class.

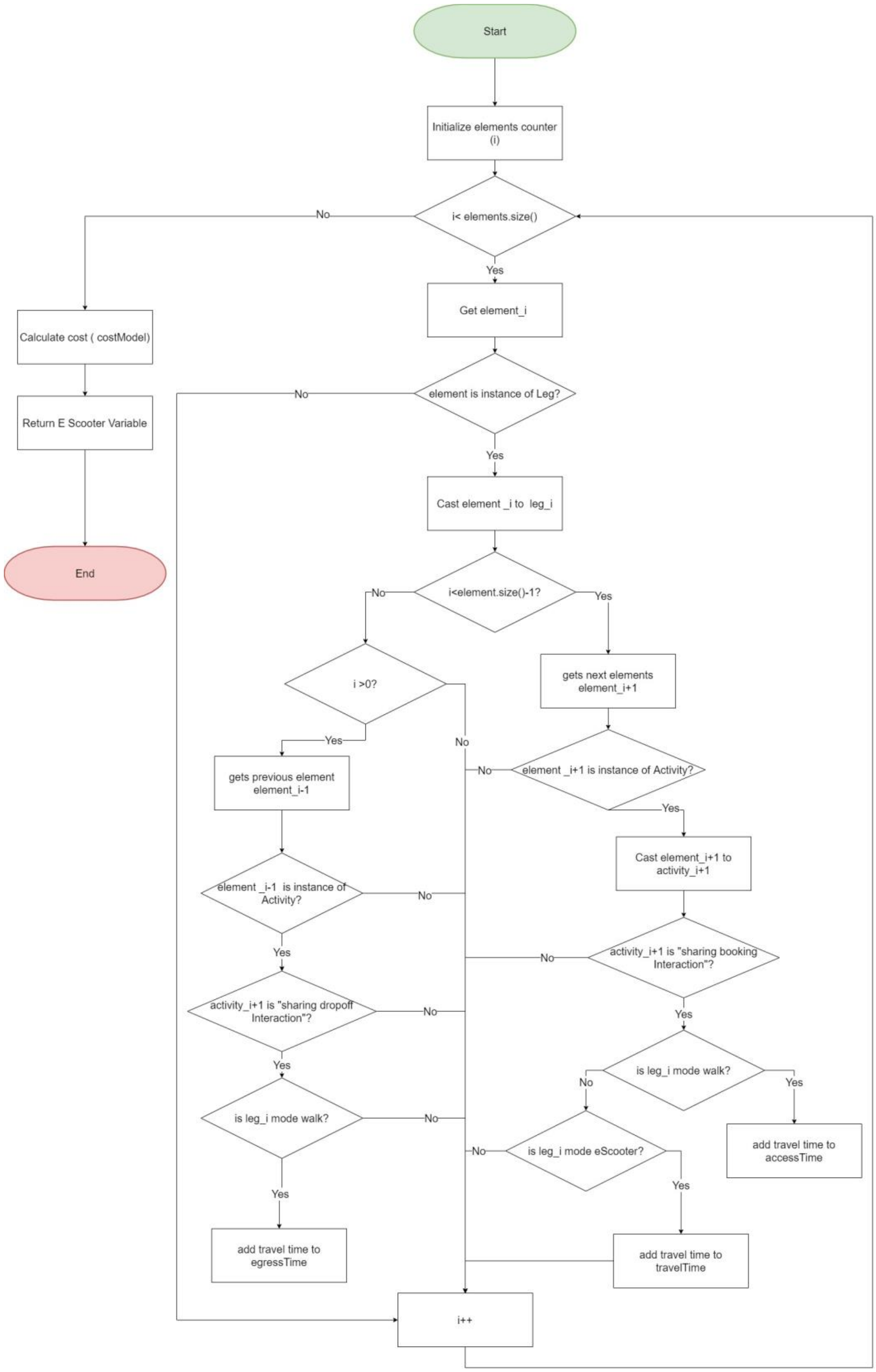

Figure 9. Flowchart of Predict Method for the eScooter Implementation

3.3.2. Multimodality (Sharing-PT) and Eqasim in the SMM Framework

One of the most concerning side effects of SMM is the relationship between the PT and SMM modes. Further, the existing simulation frameworks were equipped with multi-modal interaction between PT and SMM. However, the introduction of Eqasim into the SMM framework presented a compatibility issue with Multimodality between PT and SMM. Consequently, the SMM framework was extended with two extra modules, the Sharing-PT Routing module and the Sharing-PT Eqasim module. These modules are rudimentary routing modules for SMM-PT trips And an extension to the base Eqasim SMM model.

3.3.2.1. The Sharing-PT Routing Module:

Traditionally, in the MATSim framework, the access and egress modes can be set up using the Swiss Rail Raptor (*MATSim-Extensions by SBB*, 2018/2022). due to the in-compatibilities with Eqasim, the approach taken in the SMM framework was the creation of three different modes for each PT-SMM service as the following:

- Case (1): SMM as an access mode (Sharing-PT)
- Case (2): SMM as an egress mode (PT-Sharing)
- Case (3): SMM as access and egress mode (Sharing-PT-Sharing)

Regarding routing modules, the implementation was a rudimentary interpolation between the SMM routing module and the PT default routing module. Figure 11 depicts in detail the procedure of the Sharing-PT routing module. The implementation of the routing module was based on the class StationFinder, which given the coordinates of a Facility or Activity, finds the closest PT station by euclidean distance. The main algorithm of the trip router was based on finding the closest PT stops to origin and destination. Then, the trip would be divided into two trips, in the case (1) and case (2), or three trips in case (3). Those trips would be routed to the corresponding SMM or PT Routing modules. Finally, the Sharing-PT routing module will aggregate them into a complete Sharing-PT trip (See Extract 2).

Finally, Figure 10 describes the internal structure of a Sharing-PT trip. In this structure, the Activity Types Sharing_PT Interaction and Sharing Interaction were introduced into the trip to represent the transfer time between the drop-off activity of the SMM vehicle and the arrival at the PT station. By default, a conservative value of five minutes was assumed based on the studies of bikesharing and metro transfers in Beijing by Ma et al.(2022)

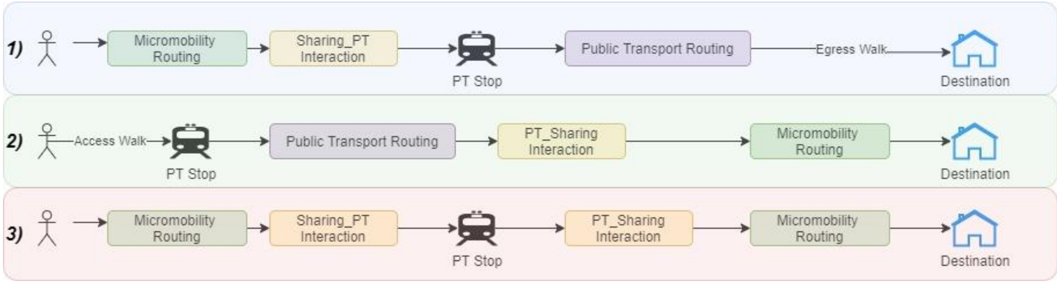

Figure 10.Sharing-PT Module Cases

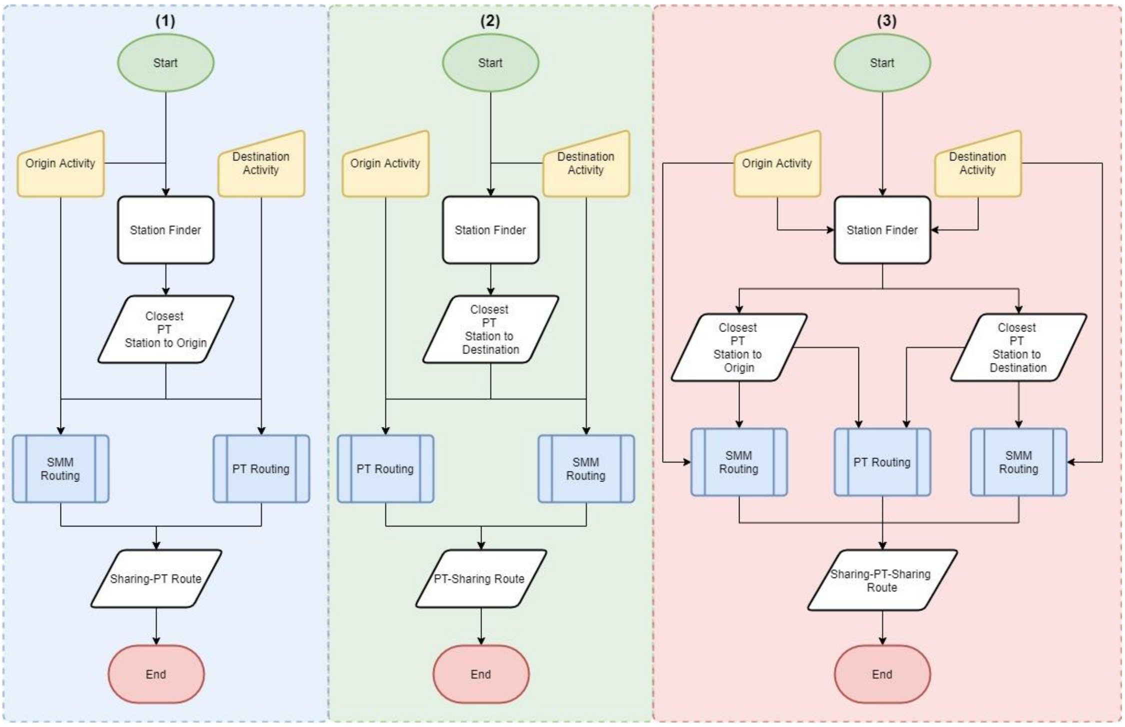

Figure 11. Sharing_PT routing modules

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  </leg>
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    </attributes>
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  </leg>
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  </activity>
  <leg mode="pt" dep_time="15:30:00" trav_time="03:40:00">
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    </attributes>
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  </leg>
  <activity type="pt interaction" link="2332" x="1224757.406095624" y="6075399.770370662" max_dur="00:00:00" >
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      <attribute name="routingMode" class="java.lang.String">PT_standardeScooter</attribute>
    </attributes>
    <route type="generic" start_link="2332" end_link="2332" trav_time="00:00:00" distance="0.0"></route>
  </leg>
  <activity type="PTSharing_Interaction" link="33956" x="1224757.406095624" y="6075399.770370662" max_dur="00:05:00" >
  </activity>
  <leg mode="walk" dep_time="19:11:00" trav_time="00:00:00">
    <attributes>
      <attribute name="routingMode" class="java.lang.String">PT_standardeScooter</attribute>
    </attributes>
    <route type="generic" start_link="2332" end_link="2332" trav_time="00:00:00" distance="0.0"></route>
  </leg>
  <activity type="sharing booking interaction" link="2332" start_time="19:11:00" max_dur="00:01:00" >
    <attributes>
      <attribute name="sharing:service" class="java.lang.String">standardeScooter</attribute>
    </attributes>
  </activity>
  <leg mode="walk" dep_time="19:11:00" trav_time="00:00:00">
    <attributes>
      <attribute name="routingMode" class="java.lang.String">PT_standardeScooter</attribute>
    </attributes>
    <route type="generic" start_link="2332" end_link="2332" trav_time="00:00:00" distance="0.0"></route>
  </leg>
```

```
      <activity type="sharing pickup interaction" link="2332" start_time="19:11:00" max_dur="00:01:00" >
        <attributes>
          <attribute name="sharing:service" class="java.lang.String">standardeScooter</attribute>
        </attributes>
      </activity>
      <leg mode="eScooter" dep_time="19:12:00" trav_time="00:03:47">
        <attributes>
          <attribute name="routingMode" class="java.lang.String">PT_standardeScooter</attribute>
        </attributes>
        <route type="generic" start_link="2332" end_link="1957" trav_time="00:03:47" distance="631.4747100684116"></route>
      </leg>
      <activity type="sharing dropoff interaction" link="1957" start_time="19:12:00" max_dur="00:01:00" >
        <attributes>
          <attribute name="sharing:service" class="java.lang.String">standardeScooter</attribute>
        </attributes>
      </activity>
      <leg mode="walk" dep_time="19:13:00" trav_time="00:00:00">
        <attributes>
          <attribute name="routingMode" class="java.lang.String">PT_standardeScooter</attribute>
        </attributes>
        <route type="generic" start_link="1957" end_link="1957" trav_time="00:00:00" distance="0.0"></route>
      </leg>
      <activity type="work" link="1957" facility="work_1994" x="1224283.75" y="6075360.43" start_time="14:59:21" end_time="17:59:21" >
      </activity>
```

Extract 2. Plan representation of Sharing-PT trip

3.3.2.2. Sharing-PT Eqasim Module

As described in Section 2.5, for each mode in the Eqasim discrete mode choice module, there must be an Estimator, a Variables object, and a Predictor. Specifically, Figure 7 presents the class relationship for the multimodal case (2). In this section, the adaptations to the base Eqasim model will be presented by discussing the implementation of eScooter-PT. Like the Eqasim base features, the eScooter-PT mode possesses the estimator class, predictor class, variable class, and cost model class.

The predictor would incorporate the Cost Model for a PT and the SMM modes to calculate the Sharing-PT variables. Moreover, it would also know the predictor for both the PT and SMM mode. Based on that information, the Predictor class's functionality is to split the Sharing-PT trip into access and PT trips in the first instance. Then, based on those, the Predictor calls the corresponding predictor and stores the values in the Sharing-PT Variables object (See Figure 12).

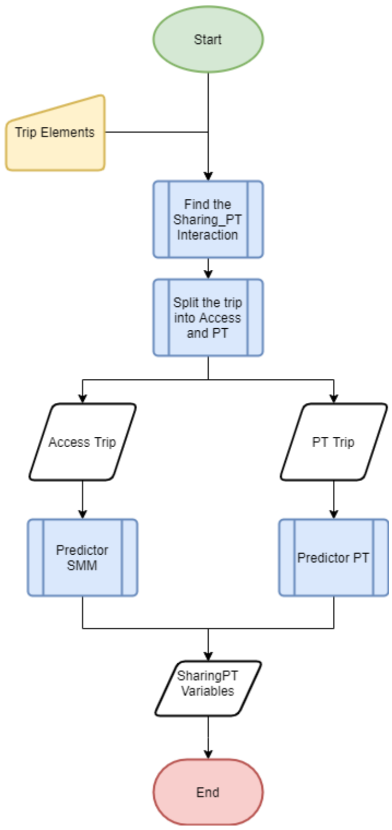

Figure 12.Predictor method for Sharing-PT Trip

As the Predictor class of Sharing PT returns the variables for the different segments of the trips, the Estimator class follows the same approach. In detail, the calculation mechanism of the utility would consider it as two different trips. Moreover, the estimator class would calculate the utility of the SMM access or egress to PT and the utility of the base PT trip (Equation 9).

$$U_{eScooter-PT} = U_{eScooter_{Access}} + U_{PT} \quad (9)$$

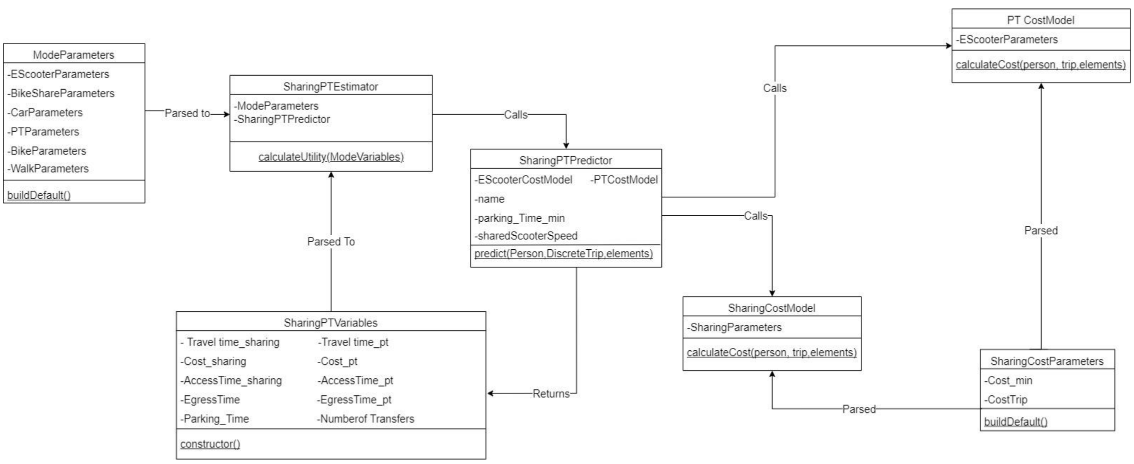

Figure 13.Sharing_PT Class Relationship

3.4. Configuration of the SMM Framework

One of the main objectives of the research was to integrate the simulation into a cohesive configurable SMM module. The past subsections described the main modifications made in the MATSim environment and the primary inputs to achieve the latter. In addition, that section described the framework and its structure; however, they did not discuss the implementation of the framework and the configurable aspect. Consequently, this subsection will introduce the main architecture of the framework implementation and, subsequently, how it can be configured.

Perhaps the first starting point to understanding the SMM structure is its high-level architecture, meaning how the different contributions are integrated into MATSIM. Figure 1 represents the high-level architecture of the main class, RunSMMSimulation, which is the main class to run the SMM framework. This class takes the parameters presented in Section 3.2 and builds the basic configuration of a MATSim simulation. Afterward, the DMC module is installed with the Krauss et al. coefficients described in Section 3.3.1. In this manner, the simulation would be equipped with a discrete mode choice model that can be extended with SMM modes in the next step. The method, addSharingServices, is perhaps the connector element between the discrete mode choice model and micromobility. This method is the one in charge of configuring the parameters for SMM modes in both the simulation and the mode choice model. However, this will be discussed in the next paragraph in more detail. Finally, the simulation will be run in the SMM framework loop (See Figure 7).

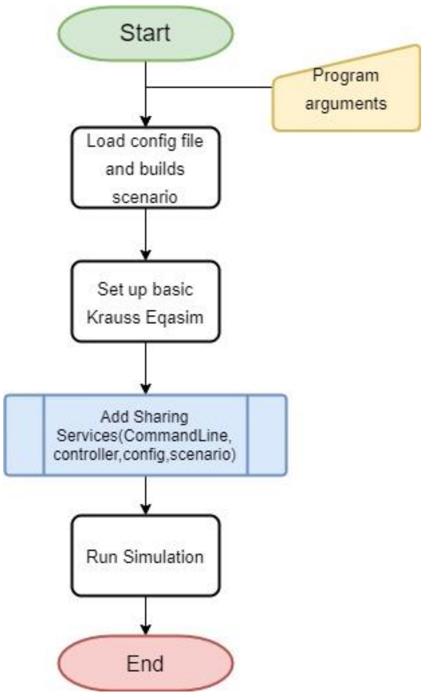

Figure 14.SMM Implementation High-Level architecture

Now, the method AddSharingServices pertains to the class MicromobilityUtils. The class comprises all the ways needed to set up the SMM modes in both the simulation framework and the discrete mode choice model. The main architecture of the method is presented in Figure 15; this method is based on the inputs given by command line arguments. Based on these inputs, it applies the command line, using the method ApplyCommand LineServices, which generates a service set of parameters, including the name, the access egress distance, the cost structure, the mode, and the GBFS files. Subsequently, the parameters are parsed into the generateServiceFile method, which translates the GBFS data into the sharing contrib information scheme. After this stage, the method has a map with the number of services and their characteristics. Then, those services will be iterated into the addSharingServices method, Figure 16. In this step, the services will be introduced in both the Sharing contrib and the Eqasim discrete mode choice module. Finally, the Sharing contrib and Sharing-PT modules will be added to the controller and returned to the main class to run the simulation.

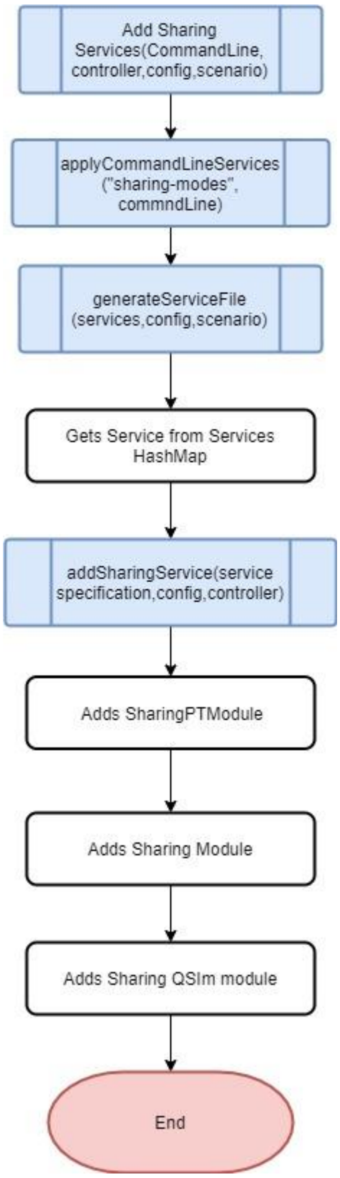

Figure 15. "AddSharingServices" method

As mentioned before, the addSharingService method is one of the keys to the framework's functioning since it configures both the DMC and simulation modules. First, the addSharingService gets a service specification for an SMM mode. Then, based on the service specification, the method will add the base mode for eScooter sharing as "eScooter" with a speed of 10 km/h and as "Shared-Bike" with a speed of 12.38 km/h, an approximation based on Almannaa et al. (2020). Afterward, the method identifies if the service is station-based or not and implements it as the corresponding scheme using the Sharing contrib. At this moment, the method starts to set up the SMM mode in the Eqasim DMC framework. Thus, based on the service specification, the Cost Model, Predictor, and Estimator classes for the mode will be set up according to the implementation presented in Section 3.3.1. Finally, the method establishes if the SMM mode can be a multimodal access mode for PT. In case it is multimodal, the Sharing - PT modes will be implemented in the simulation and the DMC module.

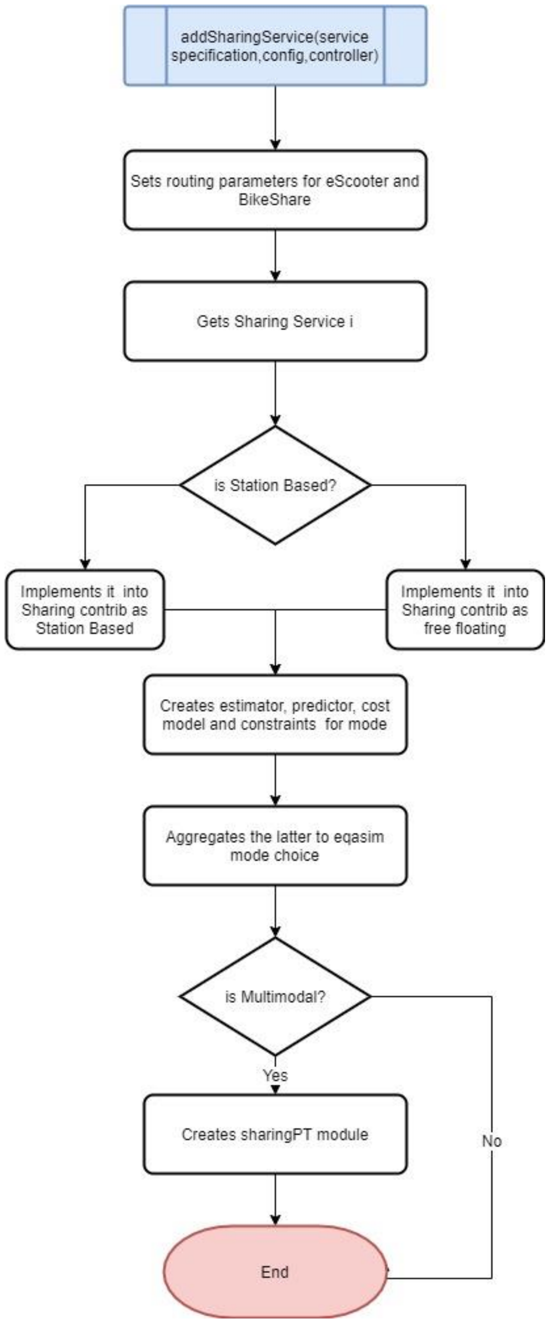

Figure 16. AddSharingService method

Now, with the general structure of the simulation module explained, the next step is to introduce its configurable aspect. To make it as simple as possible, the configuration of the SMM framework takes the typical structure of Eqasim. In this manner, the configuration values will be taken as program arguments of the RunSMMSimulation class. Table 4. Input parameters specification for SMM Framework Table 4 presents the values that can be configurated.

To provide clarity, the parameters can be described as the following:

- Config Path: Provides the file path to the config file as a String. It is a mandatory input.

- Station Information: If the desired service is an SB service, it provides the *Station_information.json file path as a String.*

- Station Status: If the desired service is an SB service, it provides the *Station_status.json* path as a String.

- Free Vehicles: If the desired service is a FF service, it provides the *Free_bike_status.json path as a String.*

- Access / Egress Distance: The maximum access/egress distance the agents can walk to an SMM station or vehicle. It must be a Double value and is a mandatory parameter for the SMM framework.

- Service Name: Describes the service name allocated to the service. It is a mandatory parameter for the SMM framework.

- Mode: Provides the mode which will route the trips made using this mode. The possible values are the Strings “eScooter” and “Shared-Bike”. It’s a mandatory parameter for the SMM framework.

- Service Area: If the desired service is a Free-floating service, it provides the path to the service area shapefile as a String. This parameter is optional for FF services.

- Multimodal: Establish if the desired service can be used as an access/egress mode to public transport. The parameter must be entered as a String with possible values "Yes" or “No”. It is a mandatory parameter for the SMM framework.

- Service Scheme: Determines which service scheme the service will have, either a FF or SB scheme. The parameter must be entered as a String with possible values "Station-Based" or “Free Floating”. It’s a mandatory parameter for the SMM framework.

- Sharing Trip Unlock Fee: Describes the cost of unlocking a SMM vehicle of the service. This parameter must be a Double and is mandatory for the SMM framework.

- Sharing Trip per Min Cost: Describes the cost of using a SMM vehicle of the service per minute. This parameter must be a Double and is mandatory for the SMM framework.

- Cost Parameters: Defines the cost in Euro/min for the different modes such as PT, car, bike, among others. The parameter must be a Double and is optional since the SMM includes pre-defined values (Appendix C).

- Mode parameters: Defines the parameters for the utility function of the modes such as PT, car, bike, among others The parameter must be a Double and is optional since the SMM includes pre-defined values (Appendix C).

Finally, to introduce the parameters of the SMM framework. They must be using prefixes as established in Table 4.Moreover, the service name needs to be replaced with the service file. To illustrate the implementation, Extract 3. presents the program arguments to configure a SB bikesharing service named "standardBikeShare".

```
--sharing-mode-name:Service_Name.standardBikeShare
standardBikeShare
--sharing-mode-name:StationsGBFS.standardBikeShare
.\eqasimMicromobility\StationInformation_SD_30_VD_16.json
--sharing-mode-name:StationsStatusGBFS.standardBikeShare
.\eqasimMicromobility\StationStatus_SD_30_VD_16.json
--sharing-mode-name:Scheme.standardBikeShare
Station-Based
--sharing-mode-name:Mode.standardBikeShare
Shared-Bike
--sharing-mode-name:Multimodal.standardBikeShare
Yes
--sharing-mode-name:AccessEgress_Distance.standardBikeShare
250
--cost-parameter:sharingBookingCosts.standardBikeShare
1
--cost-parameter:sharingMinCosts.standardBikeShare
0.20
--mode-parameter:car.betaTravelTime_u_min
-0.8
```

Extract 3. Program arguments for SMM Framework

Table 4. Input parameters specification for SMM Framework

Parameter Type	***Parameter***	***Prefix***	***Data Type***	***Possible Values***
Input File	Config Path	--config-path	String	-
GBFS	Station Information	--sharing-mode-name:StationInformationGBFS.ServiceName	String	-
	Station Status	-- sharing-mode-name:StationStatusGBFS.ServiceName	String	-
	Free Vehicles	-- sharing-mode-name:FreeVehiclesGBFS.ServiceName	String	-
Sharing Input	Access / Egress Distance	-- sharing-mode-name:AccessEgress_Distance.ServiceName	Integer	-
	Service Name	-- sharing-mode-name:´Service_Name.ServiceName	String	-
	Mode	-- sharing-mode-name:Mode.ServiceName	String	"eScooter" - "Shared-Bike"
	Service Area	-- sharing-mode-name:Service_Area.ServiceName	String	-
	Multimodal	-- sharing-mode-name:Scheme.ServiceName	String	"Yes" - "No"
	Service Scheme	-- sharing-mode-name:Multimodal.ServiceName	String	"Station-Based" - "Free-floating"
	Sharing Trip Unlock Fee	-- sharing-mode-name:Access.ServiceName	Double	-
	Sharing Trip per Min Cost	-- sharing-mode-name :Access.ServiceName	Double	-
	Cost Parameters	--cost-parameter:Mode_i.Parameter_i	Double	-
	Mode parameters	--mode-parameter:Mode_i.Parameter_i	Double	-

4. Validation and Test Scenarios

With the description of the methodology, general functions of the SMM, and parameter configuration, the SMM framework must be tested to answer the research questions introduced in 1.2. Consequently, the following section will briefly describe the Corsica MATSim scenario. Later, it will discuss the test scenarios used to evaluate the sensibility of the choice model to SMM cost and accessibility, and finally, the representation of multimodality.

4.1. Corsica Scenario MATSim

A relatively small MATSim scenario with detailed sociodemographic variables was needed to test the SMM framework. Moreover, the Eqasim base repository is equipped with several scenarios, such as Sao Paulo, Paris, Los Angeles, and Corsica. Corsica was selected among all the choices available because it is the smallest scenario available. Now, Corsica is one of the largest islands in the Mediterranean, with an area of 8,600 km^2 and a population of 339,000 inhabitants (Tamm et al., 2019). Moreover, it is a low population density region of France with 38.9 inhabitants per km^2Error! Bookmark not defined. (Inseee, 2022)

In the realm of MATSim, the Corsica scenario is scaled to 1%, which is reflected in an agent population of 3162. On the other hand, the scenario contains a multimodal network for cars and PT. This network is made of 62178 Links and 29778 Nodes (see Figure 17) whose capacity was scaled to 1% to simulate realistic traffic congestion. Finally, the model can simulate bike and walk modes using the teleportation mechanism of MATSim.

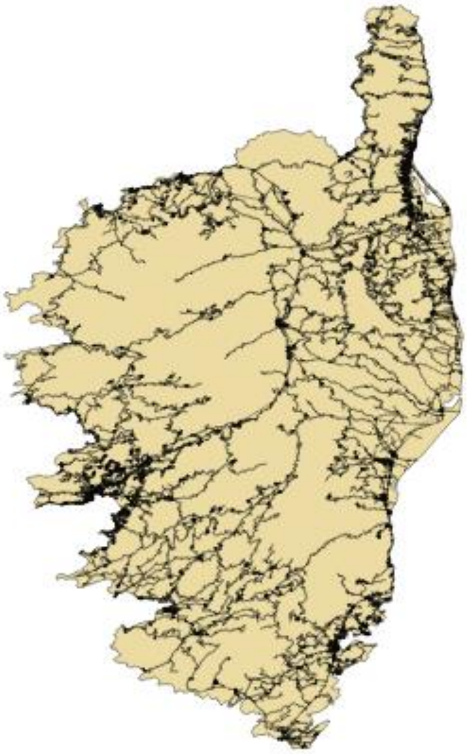

Figure 17. Corsica MATSim Network

Even though Corsica provided an adequate test scenario for the SMM framework, two obstacles must be addressed. In the first place, Krauss et al. (2022) developed their mode choice module in the context of Germany. Thus, it was clear that the model calibration would need to be carried out. The approach to calibrate the scenario was based on the reported mode shares of the region. In the first run of the Eqasim mode choice module, the mode shares were as Table 5 shows. It depicted a stark difference between the real Corsica share of walking (27%) (BACCI, 2021).

Consequently, the approach of Becker et al. (2020) in which the author calibrated the walking mode share by introducing a constant to the utility equation. In this case, an iterative process was carried out until the utility equation was calibrated, as presented in Equation 10. The final shares can be seen in the last row of Table 5

$$U_{WA} = \beta_{WA} + \beta_{time_{WA}} * time_{WA} - 2.933 \quad (10)$$

Table 5. Corsica mode shares

Scenario	Mode Share (%)				
	Bike	**Car**	**PT**	**Walk**	**Others**
Corsica Report	0.5	66	3.2	27.2	3.1
MATSim Uncalibrated	0.03	61.19	4.64	34.15	0
SMM Calibrated	0.07	77.27	4.66	18	0

With the calibration carried out, the second issue was the lack of sharing micromobility services in the region. Thus, random services must be generated to provide a test case scenario. To generate the services and test the SMM framework, random services were based on the guidelines for bike-sharing planning (Yanocha et al., 2018).In the guide, the author specifies that most bikesharing services must have a specified vehicle density of 4-10 vehicles per 1000 inhabitants, while there must be 4-10 stations per km^2 to provide good coverage. With those parameters, a random generator of GBFS services based on station and vehicle density was created. The generator was based on a one km^2 grid of the region, the population home locations from the Corsica MATSim scenario.Finally, the process of generating the stations is described in Figure 18.

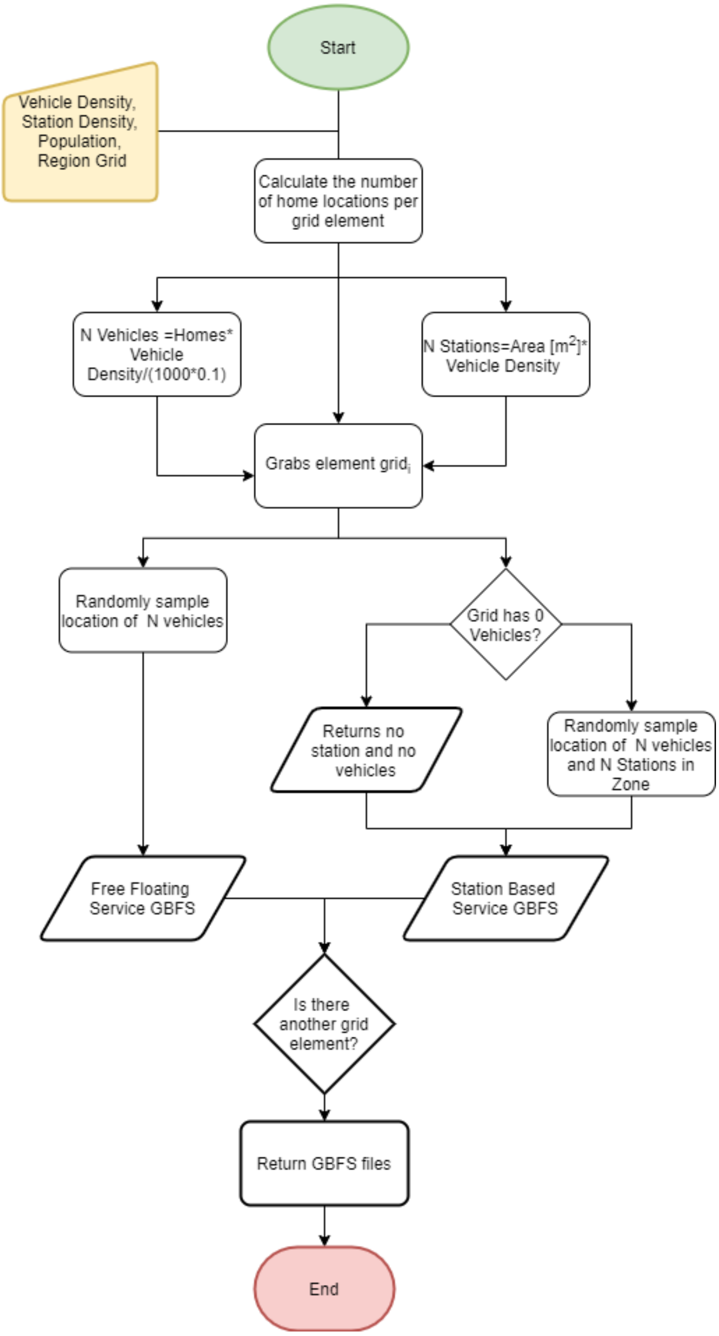

Figure 18. Randomized GBFS creation algorithm

4.2. The Test Scenarios

This thesis has formulated three fundamental questions: Can DMC models represent the different factors that influence SMM user behavior? What is the impact of the DMC modeling on the multimodality of SMM PT? As a manner to prove the capacities of the SMM 3 test scenarios. The following subsection will discuss the specifications of each test and the scenarios used for each one.

4.2.1. Sensitivity of Policies Test

Two policies were evaluated to test the SMM simulation framework's accuracy in representing user behavior. The first one was to evaluate the several cost structure variations for a free-floating eScooter service and a station-based service, as depicted in Table 6. The cost structures were modified by changing the unlocking fee, and fee per min traveled. The summary of the cost structures can be seen in

Table 6. Services simulated specifications

Service	*Mode*	*Service Scheme*	*Station Density [1/km^2]*	*Vehicle Density [Veh/1000 inhabitants]*	*Multi modal [-]*	*Unlocking Fee [Euro]*	*Per min Cost [Euro/Min]*	*Access Egress Distance [m]*
A	Bikesharing	Station Based	10	10	No	1	0.2	250
B	eScooter	Free Floating	-	10	No	1	0.15	210

Table 7. Cost structure test scenarios

Scenario	***Service***	***Unlocking Fee [Euro]***	***Per min Cost [Euro/min]***	***Scenario***	***Service***	***Unlocking Fee [Euro]***	***Per min Cost [Euro/min]***
1	A	0	0.2	1	B	0	0.2
2	A	0.25	0.2	2	B	0.25	0.2
3	A	0.5	0.2	3	B	0.5	0.2
4	A	0.75	0.2	4	B	0.75	0.2
5	A	1	0.2	5	B	1	0.2
6	A	1.25	0.2	6	B	1.25	0.2
7	A	1.5	0.2	7	B	1.5	0.2
8	A	1.75	0.2	8	B	1.75	0.2
9	A	2	0.2	9	B	2	0.2
10	A	1	0	10	B	1	0
11	A	1	0.05	11	B	1	0.05
12	A	1	0.1	12	B	1	0.1
13	A	1	0.15	13	B	1	0.15
14	A	1	0.2	14	B	1	0.2
15	A	1	0.25	15	B	1	0.25
16	A	1	0.3	16	B	1	0.3
17	A	1	0.35	17	B	1	0.35
18	A	1	0.4	18	B	1	0.4

The second sensitivity test was based on how accessible the services were to the agents. To evaluate the service accessibility, the station and vehicle density were simulated as in Table 8.

Table 8. Station and vehicle density test scenarios

Scenario	***Service***	***Station Density [1/km^2]***	***Vehicle Density [Veh/1000 inhabitants]***
1	A	4	4
2	A	6	4
3	A	8	4
4	A	10	4
5	A	4	6
6	A	6	6
7	A	8	6
8	A	10	6
9	A	4	8
10	A	6	8
11	A	8	8
12	A	10	8
13	A	4	10
14	A	6	10
15	A	8	10
16	A	10	10
17	B	-	4
18	B	-	6
19	B	-	8
20	B	-	10

4.2.2. Sharing-PT Scenario

Finally, the multimodality test was created to evaluate how SMM-PT multimodality would influence the mode choice of users and how those trips would look. The GBFS were used with the maximum vehicle and station density to implement a best-case scenario(10 vehicles per 1000 inhabitants ;and 10 stations per km^2). Furthermore, the cost structure was the default cost structure in the SMM Framework. The summary of the implemented scenarios can be seen in Table 9.

Table 9. Scenario specification for multimodality tests

Scenario	***Mode***	***Service Scheme***	***Station Density [1/km^2]***	***Vehicle Density [Veh/1000 inhabitants]***	***Multi modal [-]***	***Unlocking Fee [Euro]***	***Per min Cost [Euro/Min]***	***Access Egress Distance [m]***
1	Bikesharing	Station Based	10	10	Yes	1	0.2	250
2	eScooter	Free Floating	-	10	Yes	1	0.15	210
3	Bikesharing	Station Based	10	10	Yes	1	0.2	250
	eScooter	Free Floating	-	10	Yes	1	0.15	210

5. Results

5.1. Sensitivity Tests

5.1.1. Price Structures Sensitivity

In order to evaluate the sensitivities of the SMM framework and the different micromobility modes in the Corsica case, different scenarios were run as described in section 4.2.2. The scenarios were run in 25 iterations of the MATSim cycle. In each scenario, the price of unlocking or cost per minute was modified. Since the objective of the Test scenario is to represent the effects of SMM cost in user mode choice in Corsica, the primary measure to quantify the change was to decide the variation of the mode share by mode concerning the base scenarios (Equation 11). Specifically, the base price structure was Scenarios 5A, Scenario 14A for eScooter services, and Scenario 5B and Scenario 14B for the station base bikesharing service. In the following section, the processed mode share variations will be presented.

$$Variation\ SMM\ Share_i = \frac{SMM\ Share_{Scenario_i} - SMM\ Share_{Scenario_{Base}}}{SMM\ Share_{Scenario_{Base}}} * 100 \qquad (11)$$

The first case is the eScooter sharing service for Corsica; Figure 20 presents the variation of eScooter mode share based on the variation of the elements of the price structure. The first assessment to extract from the results was the clear, strong relationship between the unlocking fee and the mode share for eScooter trips. In this case, the mode share would increase by 102% if the cost of unlocking were reduced to 0 Euro against 1 Euro. In this manner, the eScooter share in the region would increase from 5.5% (Base scenario) to 11.7% for the no-cost unlocking scenario (See Table 10). Moreover, the relationship seems similar on the other side of the spectrum. Specifically, an increase of 100% of the unlocking fee (2 Euros) generated a decrease of 43 %, specifically to 3.12% of the total trips in the study region

Table 10. Mode shares for eScooter cost scenarios

Scenario	***Mode Share (%)***						
	Bike	Car	Car passenger	PT	eScooter	Walk	Independent Variable
1A	0.03	64.34	8.14	4.50	6.22	16.77	Price per Minute
2A	0.03	64.34	8.14	4.50	6.22	16.77	Price per Minute
3A	0.03	64.69	8.14	4.51	5.88	16.75	Price per Minute
4A	0.03	64.81	8.14	4.52	5.72	16.79	Price per Minute
5A	0.03	65.01	8.14	4.52	5.50	16.80	Price per Minute
6A	0.03	65.16	8.14	4.52	5.36	16.79	Price per Minute
7A	0.03	65.39	8.14	4.54	5.16	16.75	Price per Minute
8A	0.03	65.45	8.14	4.54	5.01	16.83	Price per Minute
9A	0.03	65.61	8.14	4.54	4.84	16.85	Price per Minute
10A	0.03	59.71	8.14	4.14	11.17	16.80	Price of Unlock-ing
11A	0.03	61.64	8.14	4.31	9.14	16.73	Price of Unlock-ing
3A	0.03	62.97	8.14	4.42	7.65	16.80	Price of Unlock-ing
13A	0.03	64.09	8.14	4.48	6.44	16.82	Price of Unlock-ing
14A	0.03	65.01	8.14	4.52	5.50	16.80	Price of Unlock-ing
15A	0.03	65.76	8.14	4.57	4.70	16.80	Price of Unlock-ing
16A	0.04	66.33	8.14	4.58	4.09	16.82	Price of Unlock-ing
17A	0.04	66.78	8.14	4.59	3.52	16.92	Price of Unlock-ing
18A	0.04	67.16	8.14	4.61	3.12	16.93	Price of Unlock-ing

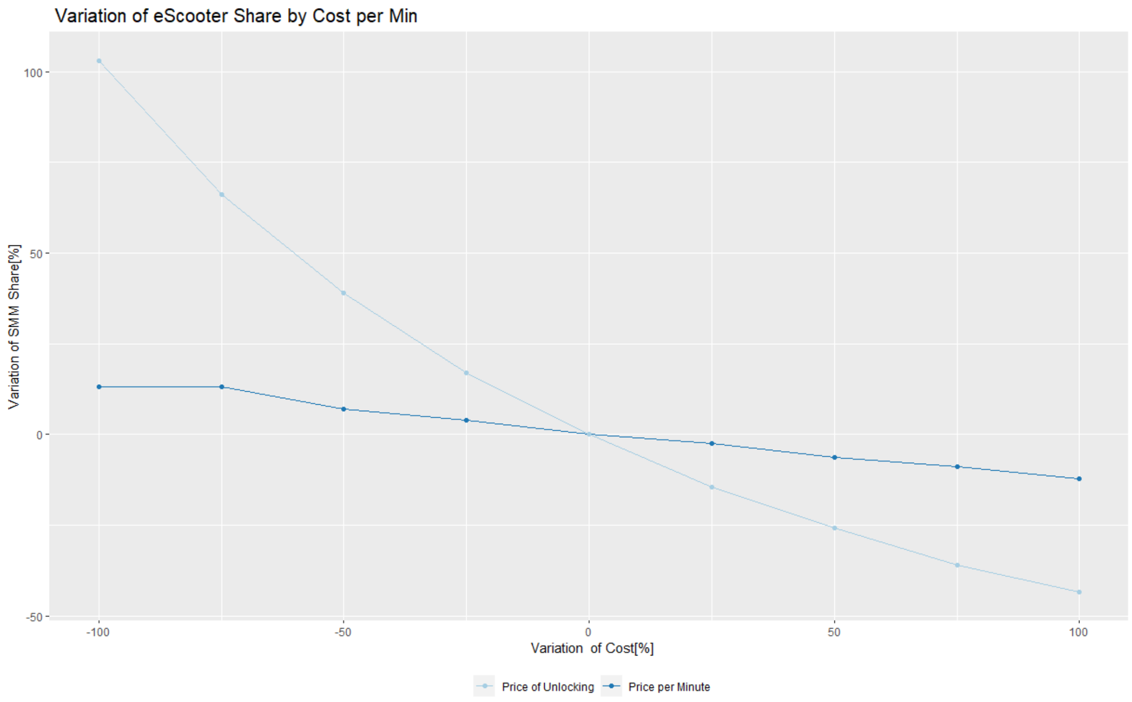

Figure 19 . eScooter share variation by price structure

On the other hand, the relationship between eScooter ridership and cost per minute can also be seen in Figure 19. Similar to the cost of unlocking, in the study case, the diminution of using an eScooter per minute will reflect a more significant ridership of the mode. However, the relationship is undoubtedly weaker than the one of unlocking cost. The eScooter share variation will vary between + 13% and -12% from the base scenario, based on the decrease or increase of cost per minute. Moreover, it appears that the reduction of the per-minute cost only benefits until a reduction of the cost of 75% (Scenario 2A) since the variation between the reduction of 100% and 75% of eScooter per minute cost is insignificant. Overall, it appears that decreasing the cost of unlocking fees in an eScooter service for Corsica would result in a more powerful tool to promote the mode shift to sharing eScooter.

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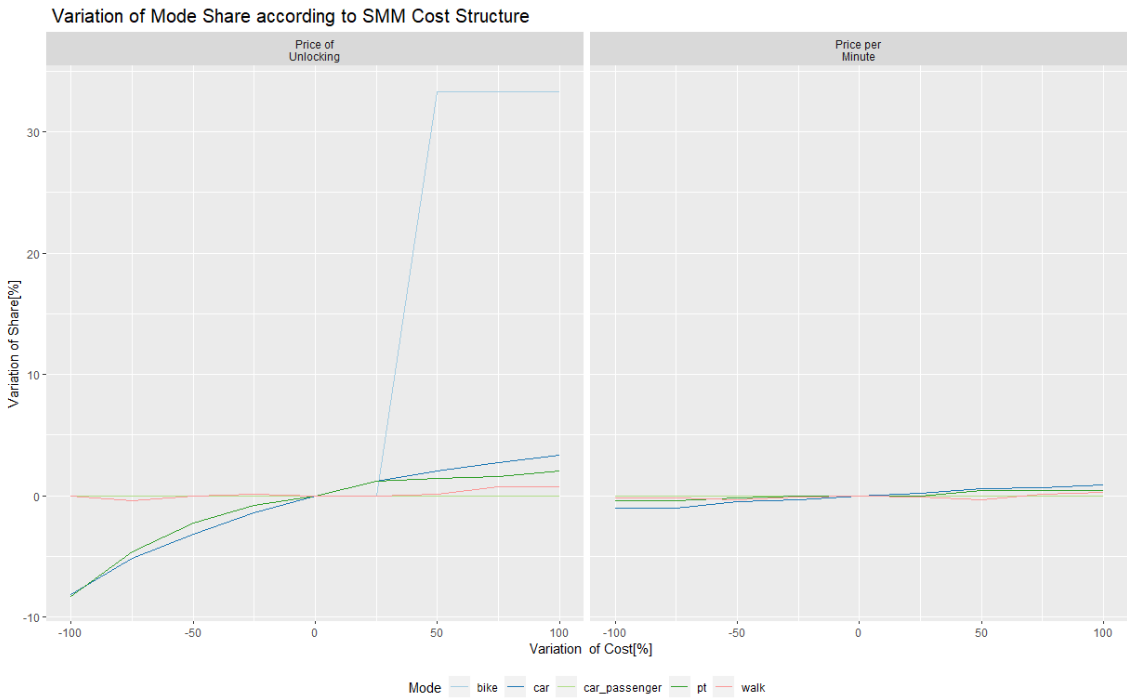

Figure 20. Other modes share variation based on eScooter price structures.

Another interesting analysis is how the cost structure changes influence the mode shares of the remaining mode shares in Corsica. The first assessment is the similarity in the pattern of mode replacement, in which the cost of unlocking is significantly more influential on mode choice than cost per minute. Moreover, the unlocking cost graph presents interesting insights into the mode replacement caused by the cost variation. It can be observed that the curves for car and PT trips variation are remarkably similar. These curves have a similar variation when the cost of unlocking is reduced, with a reduction of 8.26 % of PT ridership and 8.14% of car ridership. However, on the other side of the curve, the increase in unlocking cost increase ridership by 3.32% for car and 2% for PT. Another interesting result of the simulation runs is the relationship between bike and eScooter. Figure 21 shows that at an increase of 25% of the unlocking fee, the bike share augments by 33%. This observation can lead to understanding that eScooter sharing in Corsica draws a significant amount of ridership from the bike trip pools.

When contrasting the variation based on the per-minute cost of eScooter sharing, it can be seen that the variations are significantly lower, with the maximum variation being a reduction of 1.02% of car ridership when the cost per minute of the service is zero. On the other end of the curve, a similar pattern is in place in which the increase of cost per minute to 0.40 Euros will increase 0.92 % for car trips. This pattern is relatively similar for the rest of the modes, confirming the theory that cost per minute of service is not a barrier for the mode shift to eScooter.

Now, the analysis of cost sensitivity was also carried out for the bikesharing service in Corsica. Figure 21 and Figure 22 present the variation of bikesharing ridership and the remaining modes' variation of ridership, respectively. Meanwhile, Table 11 presents the global mode shares for the scenarios. Conversely, the results of cost structure for bikesharing in Corsica are strikingly different from the eScooter cost effect. In the case of bikesharing, it appears that neither the cost of unlocking nor the cost of driving per minute is a barrier to the adoption of bikesharing. The non-influence of the cost in this mode can be correlated to it being a station-based service. The users in Corsica would probably be more constricted to the locations of the bikesharing stations rather than the cost. However, these factors and results will be discussed in the next section.

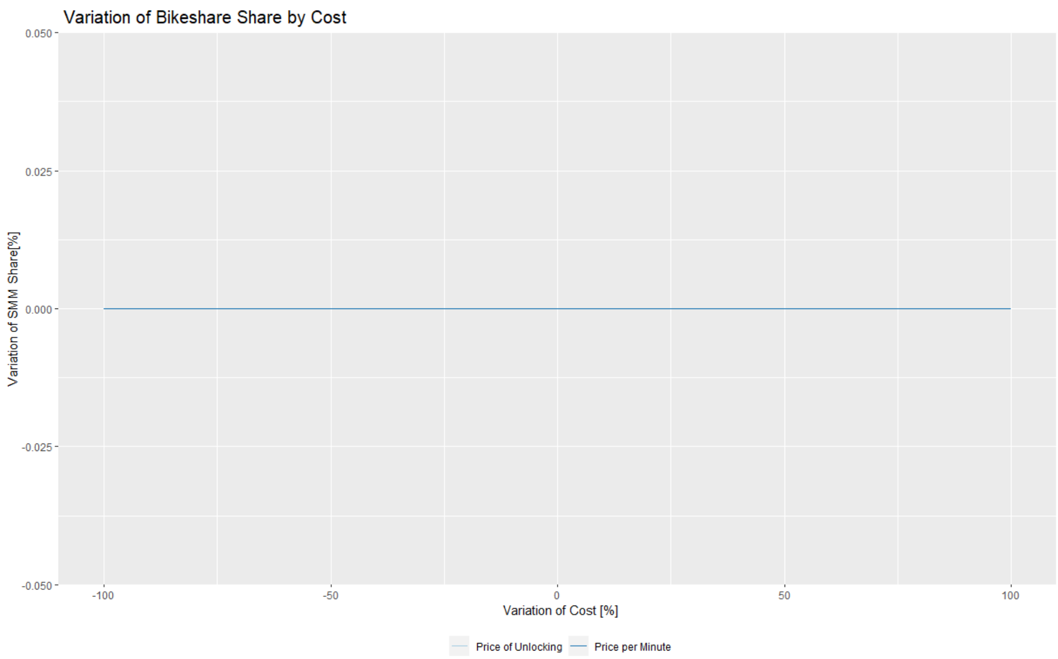

Figure 21.Bikesharing share variation by price structure

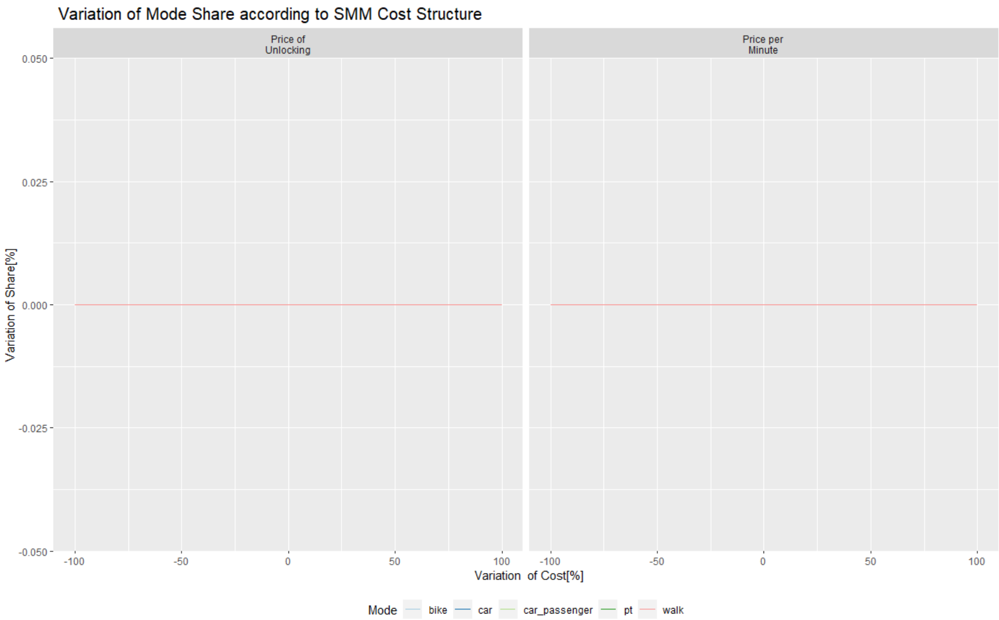

Figure 22.Other modes share variation based on bikesharing price structures.

Table 11.Mode shares for bikesharing cost scenarios

Scenario	***Mode Share (%)***						
	Bike	Car	Car passenger	PT	BikeSharing	Walk	Independent Variable
1B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
2B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
3B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
4B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
5B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
6B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
7B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
8B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
9B	0.07	69.35	8.14	4.66	0.57	17.20	Price per Minute
10B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
11B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
3B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
13B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
14B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
15B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
16B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
17B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking
18B	0.07	69.35	8.14	4.66	0.57	17.20	Price of Unlocking

Al, All in all, the analysis of price structures in the Corsica case provided some interesting results on the mode choice of the user. In the first place, it is evident that the cost of unlocking is a far more significant barrier to adopting the eScooter services compared to the cost of driving the vehicle per minute. Further, the results present a strong relationship between the replacement of bike trips for eScooter trips, especially when the prices of eScooter increase by 25%. Furthermore, results of PT and car trips present a similar replacement relationship with eScooter trips. Finally, the results for station-based bikesharing services evidence that the cost of the service is not a significant barrier to the adoption of the model.

5.1.2. Station Density and Vehicle Density Sensitivity Test

Similar to the cost sensitivity scenarios analysis, several scenarios were run in 50 iterations of MATSim as described to analyze the effect of vehicle density and station density on mode choice. However, since there is no base scenario for vehicle and station density, the measure taken to evaluate the sensitivity of the framework was the mode share of the SMM mode by their vehicle density or station density. That being said, the scenarios for station-based bikesharing service were analyzed from the point of view of station and vehicle density. Meanwhile, the free-floating eScooter service was analyzed using only vehicle density.

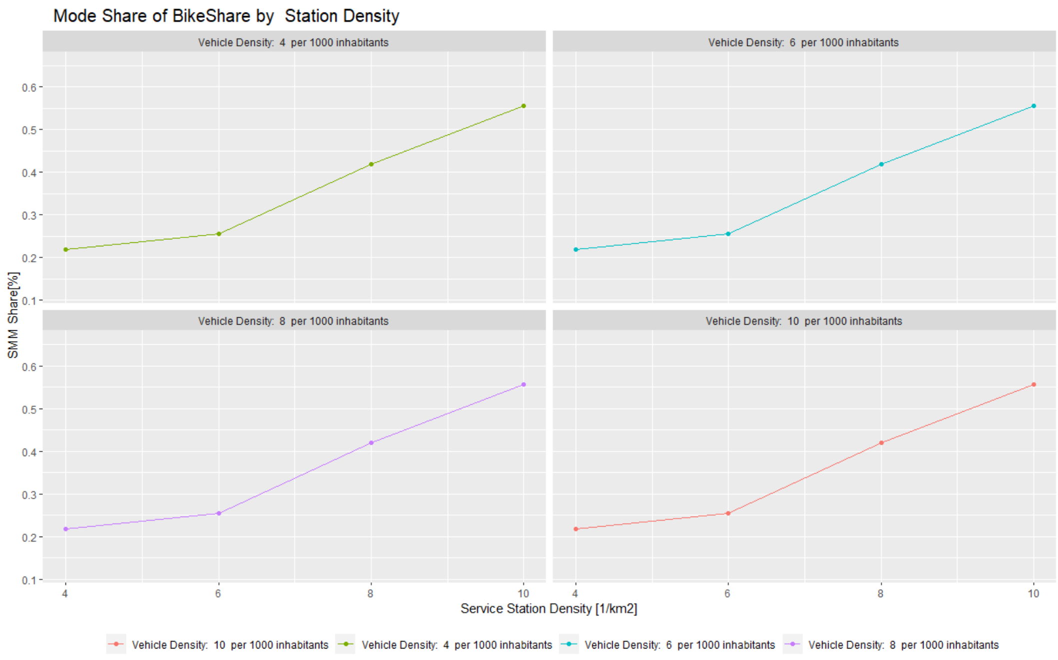

Figure 23. Mode share of bikesharing service by station density.

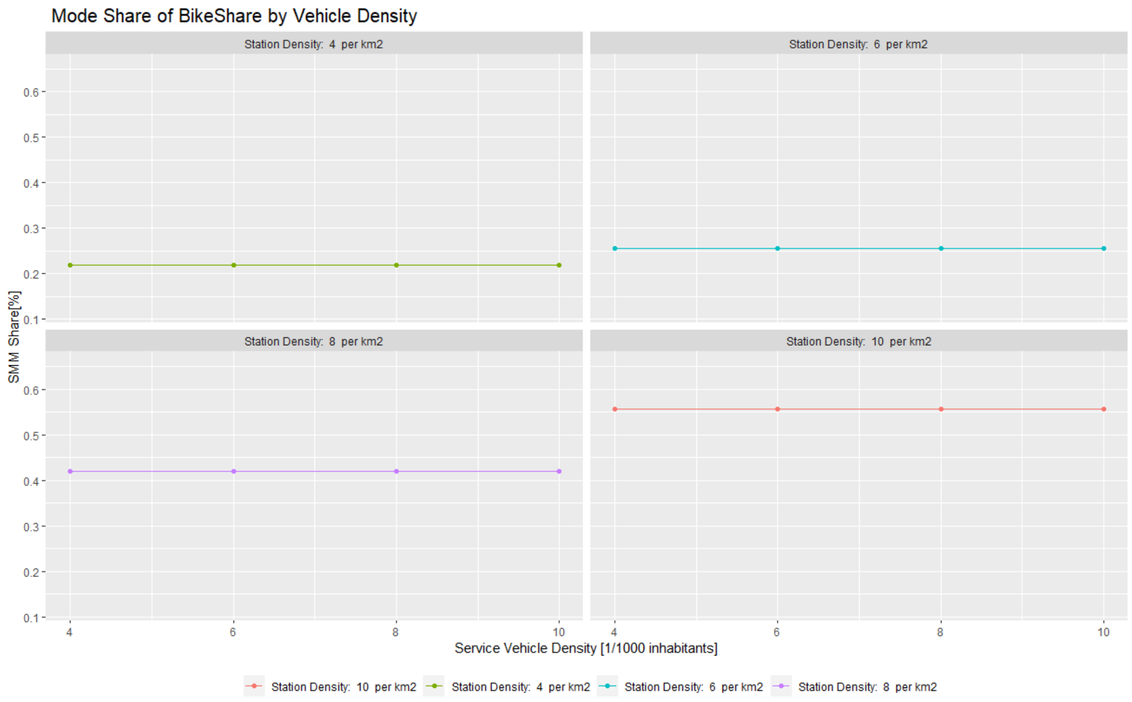

Figure 24. Mode share of bikesharing by vehicle density

As was established, the bikesharing service for Corsica was evaluated based on vehicle and station density. Thus, Figure 23 depicts the variation of the bikesharing ridership by station density; meanwhile, Figure 24 depicts the variation of the bikesharing ridership by vehicle density. Based on Figure 23, it can be established that there is a correlation between the station density of the service and the mode share of bikesharing. Moreover, the pattern is identical when analyzing different vehicle densities, in which the bikesharing ridership increases significantly when the density exceeds the threshold of 6 stations per km^2 for all vehicle densities analyzed. Moreover, the maximum bikesharing ridership appears to be correlated to 10 stations per, near 0.55% of the mode share in Corsica.

Conversely, Figure 24 illustrates the zero correlation between the bikesharing ridership and the vehicle population density. However, the station and vehicle density results clearly show this variable's correlation for a station-based bikesharing service in Corsica. Higher station densities are correlated to a significant increase in ridership; meanwhile, the vehicle density appears not to correlate with ridership in the specific Corsica case.

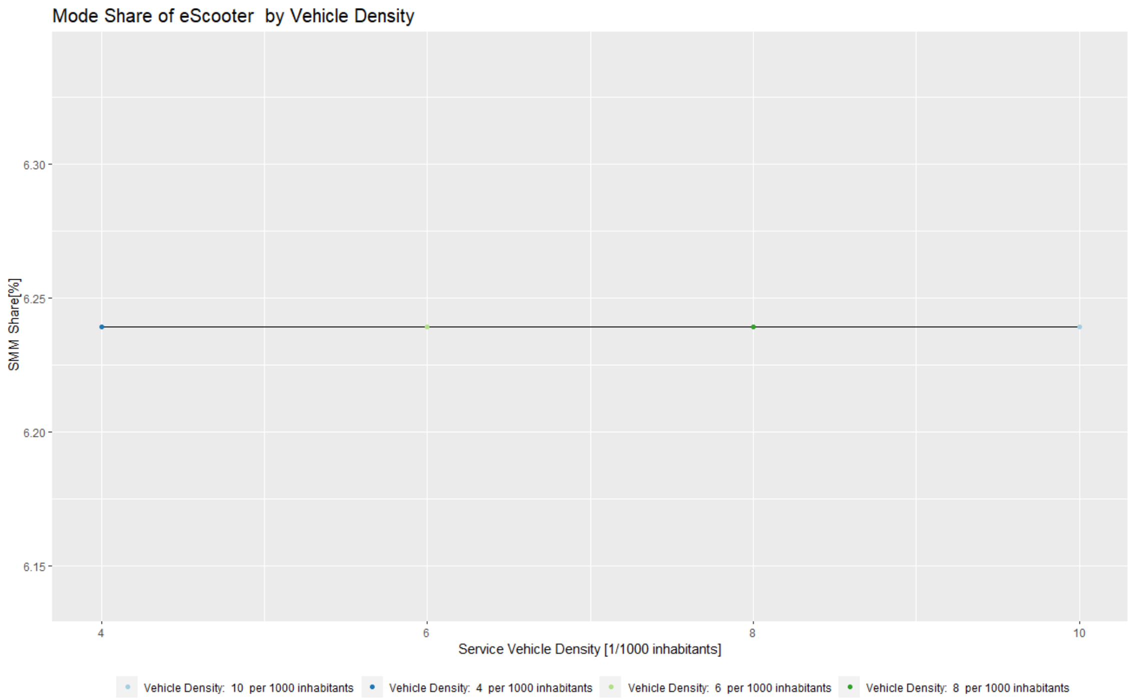

Figure 25. Mode share of eScooter by vehicle density.

In the case of eScooter sharing, Figure 26 represents the modal share in function of the vehicle distance. Similar to the station-based bikesharing service case in section 5.1.1, the vehicle density in the Corsica case appears not to be correlated with the ridership of eScooter. In-depth, the results point to service in Corsica with low vehicle density (4 vehicles per inhabitant) as optimal service for promoting SMM. Moreover, the results indicate that the increase in eScooter vehicle density would not reflect an increase in eScooter trips.

5.2. Multimodality Tests

As established in Section 4.2, the multimodality test would be run in three scenarios where different modes were evaluated for the relationship between SMM and PT. Moreover, to describe the results, two-measure instruments were taken. The first instrument was the mode share of the Corsica region to understand how much SMM would increment the ridership of PT by expanding the accessibility radius. On the other hand, the travel time of access and egress legs for PT transport will also be evaluated to quantify the impacts of accessibility in PT using SMM.

5.2.1. Multimodality Mode Choice Impact

Regarding the effect of SMM multimodality in PT ridership, the mode share in Corsica was taken as a measure. For instance, Figure 26 depicts the change in the mode shares for the user scenarios. The first modified scenario correlates bikesharing as a connecting mode for PT, increasing 0.42% of the mode share in PT compared to the base calibrated scenario. On the other hand, implementing the eScooter multimodal causes an increase in the PT ridership by 3.85%. Finally, the increase of PT by allowing both SMM modes as multimodal connectors is 1.99%. Another insight the test scenarios provide is the region's change in car mode share. In all the cases, the reduction in car usage is evident. The decrease ranges from 5% to 0.46% of the total mode share. Thus, the result of the test scenarios signal that the availability of SMM modes in Corsica would improve the ridership of PT transport meanwhile producing a moderate shift away from car usage.

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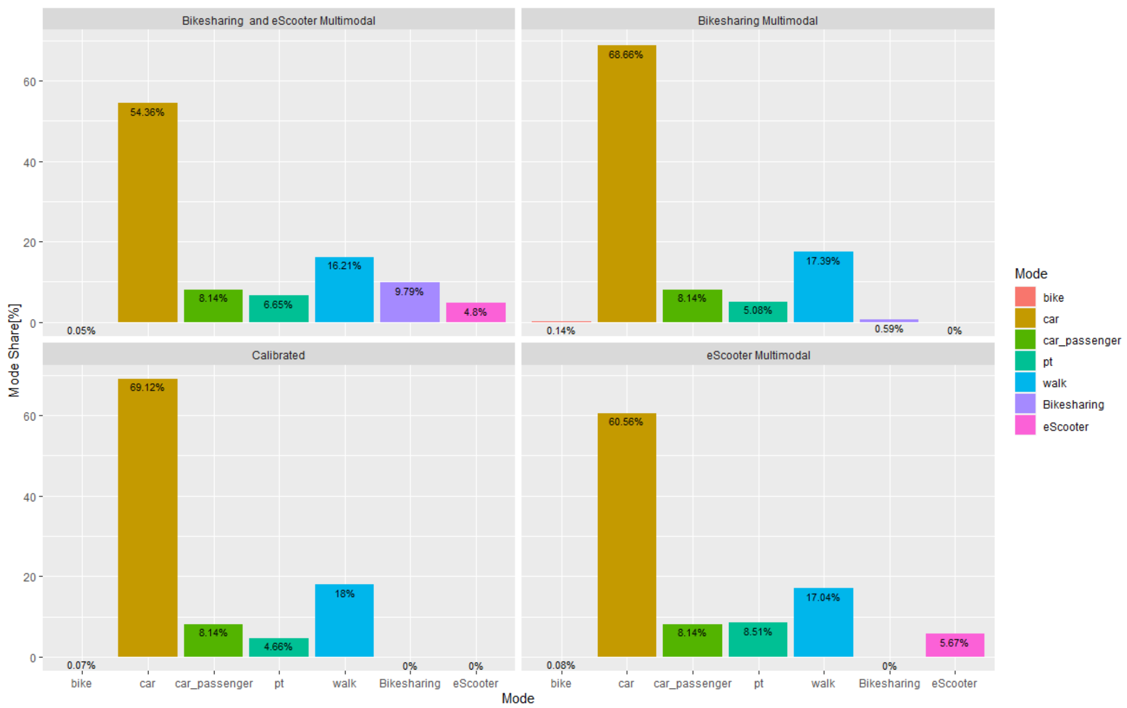

Figure 26. Mode Shares of Scenarios

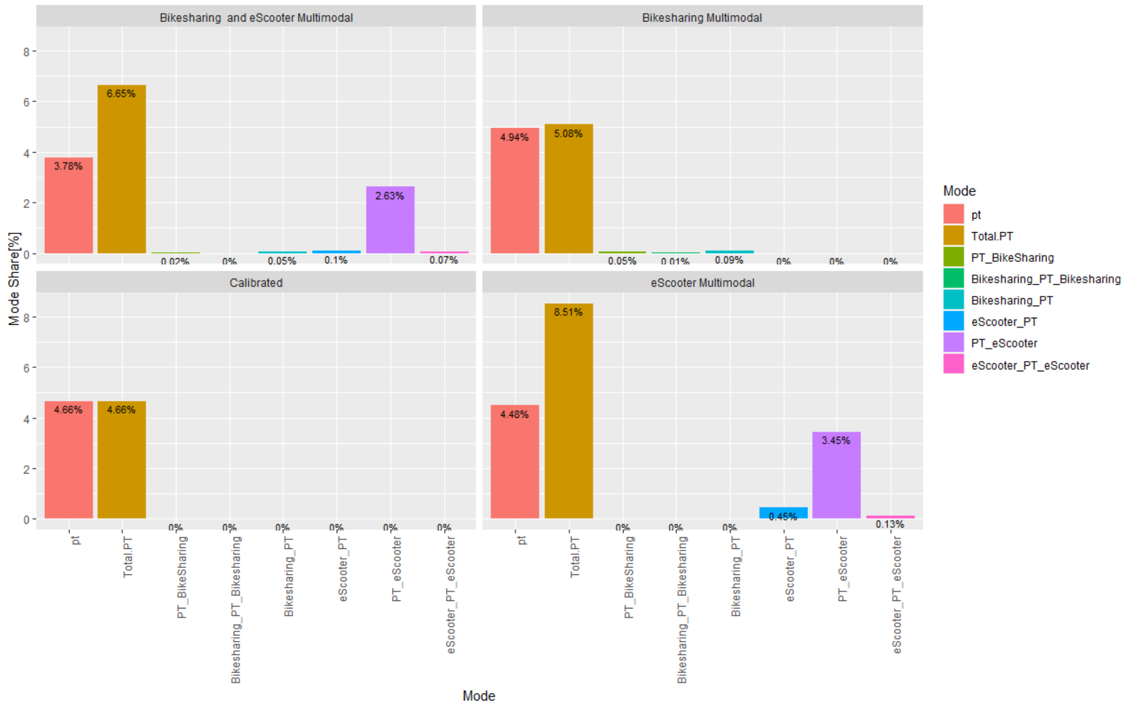

Figure 27. Mode Shares of Multimodal PT

Another interesting question about SMM-PT multimodality is how the users employ SMM and PT. Figure 27 depicts the mode share of the mode chain of a trip (Eg. Bikesharing_PT). As seen in the Bikesharing Multimodal scenario, the impact of bikesharing on PT is relatively minuscule, with a total increase of 0.1% of the total modal share, which corresponds to 16 trips. Moreover, the users in Corsica would be more likely to use bikesharing as an egress mode from PT (0.09% mode share) rather than using it as access or access and egress (0.05 and 0.01% mode share).

Regarding the multimodal eScooter scenario, the pattern is similar to the one presented by the bikesharing scenario. Further, in the case of eScooter, users tend to use the mode as an egress mode from PT since 3.45% of the trips in Corsica use the mode chain PT-eScooter.On the other hand, using eScooter as access or access and egress mode is somewhat unusual for the Corsica region, with only 0.45% and 0.13% done with those mode chains.

Finally, the bikesharing and eScooter multimodal scenario depict the competence of the SMM modes. In this scenario, there is evident competition between the SMM modes for PT access and egress. The competition can be reflected in the fact that the bikesharing-PT mode shares diminish by 0.026% on average. Meanwhile, the eScooter-PT mode shares diminish by 0.41% on average. However, the mode share of PT transport increased to 6.65% of the total trips in the region. When the increase of the PT share in the region is contrasted with the one in the eScooter multimodal scenario, it is evident that the competence is damaging to the SMM-PT multimodality since the total mode share of PT decreases by 2% of the Corsica modal share.

5.2.2. Characterization of Multimodal SMM-PT trips

Finally, the last relevant aspect of SMM and PT multimodality refers to the characteristics of the trips. Specifically, the distance and travel time using SMM in conjunction with PT are interesting factors. Thus, Figure 28 and Figure 29 present the travel distance distribution of SMM-PT trips according to SMM usage in the mode chain. In the case of the bikesharing access trips, the travel distribution is fairly concentrated in the region between 980 mts and 2000 mts. Further, more than 50% of the trips belong to these distances. Moreover, most bikesharing access trips fall in the range of 10 minutes to 13 minutes, with an average travel time of 11.72 minutes.

Regarding the egress trips using bikesharing, 75% of the trips do not exceed the distance of 1138 mts, with an average length of 1041 mts. Thus, the travel distance for egress using bikesharing is relatively homogeneous in the Corsica region. The homogeneity of this measure is well reflected in the travel time for bikesharing egress, which is less than 10 minutes on 75% of the trips; meanwhile, it has an average travel time of 8.72 minutes.

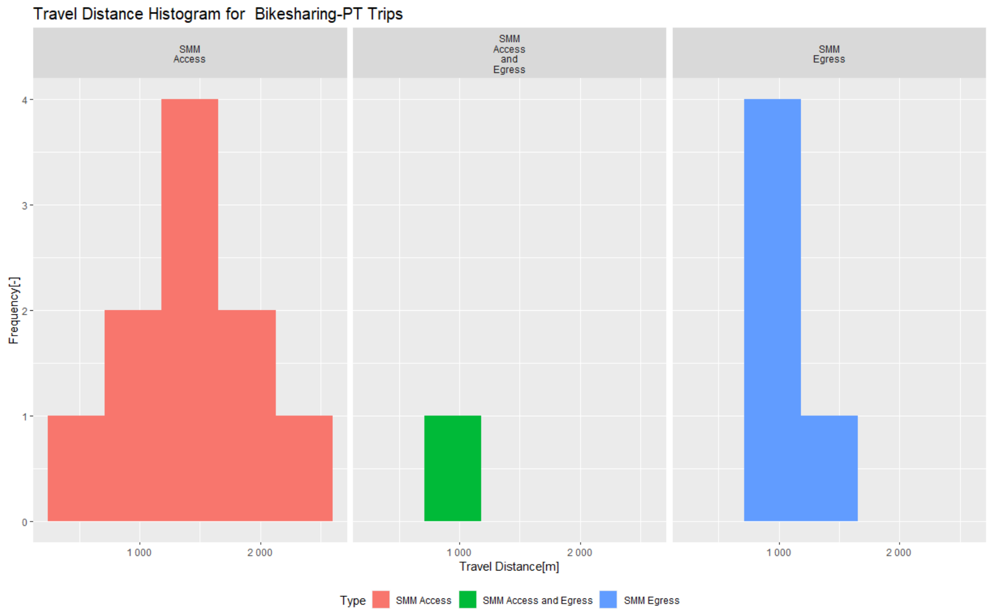

Figure 28. Travel distance histogram using bikesharing as access and egrees for PT.

Table 12. Descriptive statistics for distance of multimodal bikesharing trips

Multimodal Bikesharing Distance [m]						
Type	**Min**	**Q1**	**Median**	**Mean**	**Q3**	**Max**
SMM Access	321.10	986.53	1411.77	1379.19	1694.35	2211.81
SMM Access and Egress	1058.61	1058.61	1058.61	1058.61	1058.61	1058.61
SMM Egress	852.49	858.52	1071.41	1041.08	1138.82	1284.19

Table 13.Descriptive statistics for travel time of multimodal bikesharing trips

Multimodal Bikesharing Time [min]						
Type	**Min**	**Q1**	**Median**	**Mean**	**Q3**	**Max**
SMM Access	7.25	10.39	9.48	11.72	13.50	13.50
SMM Access and Egress	7.88	7.88	7.88	7.88	7.88	7.88
SMM Egress	6.75	7.10	8.05	8.72	9.98	11.73

Besides the bikesharing service, the multimodality test was also tested for an eScooter service in Corsica (Section 4.2). Figure 29 presents the travel distance distribution of eScooter legs in eScooter-PT trips. The eScooter mode is not usually used for access or access and egress of PT. Thus, there is not a consistent distribution of travel distances. On the other hand, the trips using eScooter as egress mode from PT are characterized by having a heterogeneous distribution of distances, ranging from 270 mts to 2316 mts. However, they present an average travel distance of 842 mts.

Regarding the travel time of eScooter as the egress mode of PT, the mean average travel time is 6.04 min. While it exhibits the same heterogeneity as travel distance since the travel time can vary from 1 min to 13 min. Based on the results of the Corsica case, the eScooter data for access and access/ egress of eScooter does not provide meaningful insights due to the low volume of trips. Meanwhile, the distribution of travel times and travel distances for eScooter as an egress mode have a heterogeneous distribution.

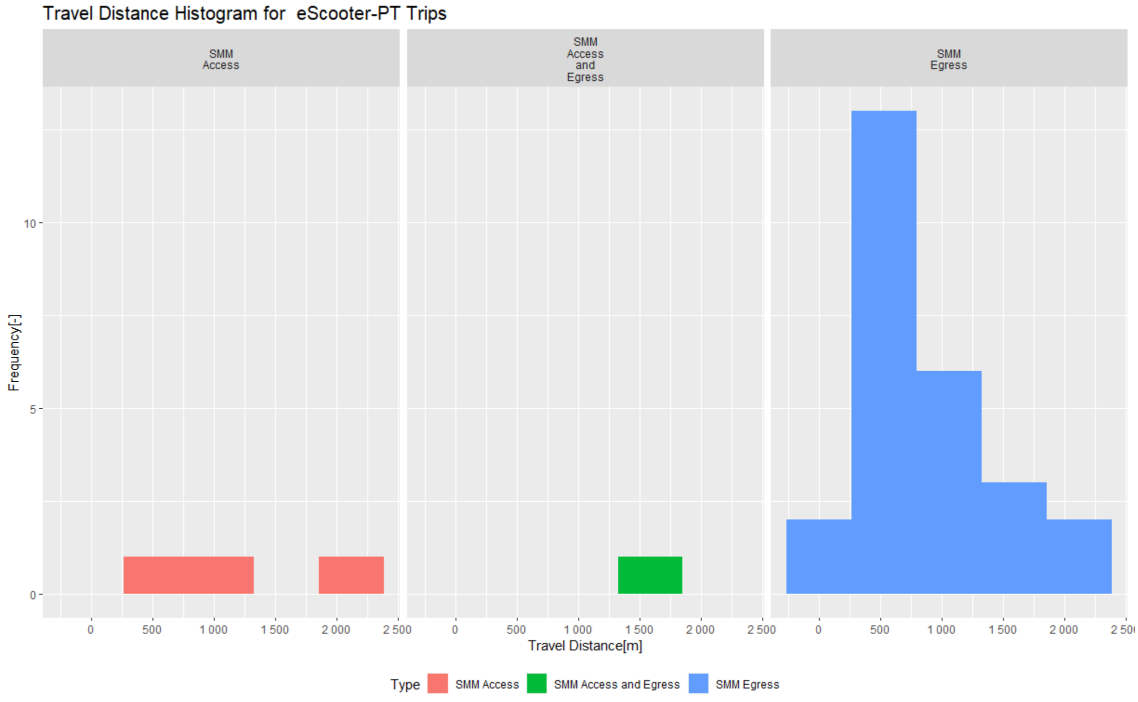

Figure 29.Travel distance histogram using eScooter as access and egrees for PT.

Table 14.Descriptive statistics for distance of multimodal eScooter trips

Multimodal eScooter Distance [m]						
Type	**Min**	**Q1**	**Median**	**Mean**	**Q3**	**Max**
SMM Access	269.27	734.24	1199.21	1261.58	1757.74	2316.27
SMM Access and Egress	1475.47	1475.47	1475.47	1475.47	1475.47	1475.47
SMM Egress	198.02	450.43	656.80	842.65	1090.28	2173.89

Table 15.Descriptive statistics for travel time of multimodal eScooter trips

Multimodal eScooter Time [min]						
Type	**Min**	**Q1**	**Median**	**Mean**	**Q3**	**Max**
SMM Access	2.17	5.74	9.32	9.14	12.63	15.93
SMM Access and Egress	10.30	10.30	10.30	10.30	10.30	10.30
SMM Egress	1.18	3.46	5.33	6.04	7.32	13.07

6. Discussion

6.1. Sensitivity Test

6.1.1. Price Structure Sensitivity

The first results presented for the scenarios refer to the price structure sensitivity. On the side of eScooter sharing, the results showed that the cost of unlocking would be much more effective in increasing the mode's ridership compared to the variation of per-minute cost. Although the goal of the SMM framework and test scenario is not to predict accurate data, the pattern can be critically assessed based on logical and literature knowledge. Thus, considering the nature of eScooter sharing, authors such as Liao and Correia (2020) state that the mean trip distance for eScooter trips is near 1.8 km. Furthermore, the author also states that the free-floating eScooter trips are mainly used for short distances such as 3 km. Considering the latter and the average speed of eScooter as 2.78 m/s(Almannaa et al., 2020), an average eScooter trip would report a 2 Euro cost. Thus, it indicates that the trips in Corsica would need to be shorter than the average reported in the literature, so the 1 Euro unlocking fee would be more significant than the driving cost. Evidence of this can be seen in the eScooter-PT scenario, where the mean distance is less than 1 km. Consequently, it is logical to assume that the pattern in cost of unlocking is significantly more important in increasing the eScooter ridership in Corsica.

Now, to compare it with similar models in the literature, Krauss et al.(2022) and Reck et al. (2022) analyzed the change in the cost of sharing modes in a multimodal context. Krauss et al. determined that by decreasing the eScooter sharing price, the car mode share would fluctuate between +0.3% and -0.3% in Germany (2022). On the other hand, Reck et al. evaluated the substitution rate of trips in the function of the traveled distances of the eScooter trip (2021). The authors concluded a positive relationship between the replacement of the car, pt, and bike trips with eScooter trips and the trip distance. In the context of the Corsica, the pattern seems to fit the literature patterns since the car and pt are the most heavily substituted trips when the eScooter trip cost diminishes.

Furthermore, in the Krauss et al. model, the cost of traveling for eScooter trips represents 40% of the mode utility (2022). Therefore, contextualizing the idea in Corsica, it is clear that the cost reduction will allow eScooter trips to be longer, which would lead to the mode share replacement of bike, car, and PT. In conclusion, the patterns illustrated by the Corsica case match the reported literature patterns for eScooter price sensitivity.

On the other hand, the case of bikesharing and cost variation illustrates a non-influence of cost. Compared to the Krauss et al. model, it was estimated that the variation of bikesharing mode share due to cost ranges between +1% and -1.5% (2022). In Corsica's case, the pattern's divergence can be explained by the location of the bikesharing stations. It is known that the Corsica region is quite extensive and has a low population density. Thus, the station density might need to be high to provide close access to bikesharing for users all around the region. Further, this pattern overpowers the effect of cost in station-based services. Moreover, the station density and distance to bikesharing are critical to the ridership of station-based services (Guo et al., 2017; Reck et al., 2022; Yanocha et al., 2018).

After discussing the price sensitivities results, a few conclusions can be drawn. First, the SMM framework can represent the relationship between the cost structure and eScooter ridership. Additionally, the mode replacement patterns seem to fit the literature relationship between eScooter travel cost and multimodal replacement. Conversely, the case of bikesharing in Corsica establishes that the cost of bikesharing is not influential in mode choice. Finally, although the literature indicates a moderate cost impact in bikesharing ridership, the local conditions of Corsica may indicate that the station density overshadows the cost effect. Overall, the patterns generated by the SMM framework in Corsica for cost and ridership of SMM modes are reasonable for the case study and consistent with the literature.

6.1.2. Station and Vehicle Density Structure

Regarding the station density influence on mode choice, the results illustrated that the station density of bikesharing was highly influential in the ridership of the mode. Moreover, the results for vehicle density illustrated that the vehicle density of bikesharing services was not influential for Corsica. When compared with the values in the literature, Yanocha et al. (2018) argue that the relationship between stations of bikesharing service density stations correlates positively to the bikesharing ridership. Conversely, the author also established a weak correlation between vehicle density and bikesharing ridership. On the other hand, Lazarus et al. (2020) stated that the bikesharing parking and station density in San Francisco positively impacted the ridership of JUMP, a hybrid bikesharing service. Based on the evidence, it can be assumed that the SMM framework depicts the accurate sensitivity for station-based bikesharing.

Regarding the vehicle density sensitivity, it was established by the bikesharing and eScooter scenarios that there was no influence on the mode choice of users for SMM users. However, authors such as Elmashhara et al. (2022) and Reck et al. (2022) established that the vehicle density of SMM was correlated to a positive ridership increase. Moreover, Reck et al. (2022) established that the vehicle density increase would more heavily influence the free-floating modes. Additionally, Reck et al. (2022) established that the probability of a user choosing station-based bikesharing varies insignificantly in terms of vehicle density. In that order of ideas, the SMM framework adequately simulates vehicle density's influence on users' mode choice.

Conversely, the eScooter vehicle density sensitive for the Corsica case does not align with the reported literature. A plausible explanation for this deviation relates to the GBFS file generation, in which a vehicle density was based on the number of inhabitants in a squared kilometer polygon. Specifically, the algorithm faulters in the zones with low population density since the vehicles will always be zero for this zone. Thus, these users would never be allowed to use eScooters. Meanwhile, the dense areas of the regions would be saturated with vehicles. Consequently, it would be safe to assume that the population density of Corsica explains the non-influence of vehicle density in eScooter ridership. In the future, the framework must be tested against densely populated areas to acquire a more comprehensive relationship between ridership and vehicle density.

6.2. Multimodality Test

The results of the multimodality mode choice scenario depicted a clear picture of the potential of SMM as an access egress mode of PT in the Corsica region. The potential can be illustrated in the increase in the global share of PT, ranging from +4%- to +1% of the mode share in Corsica. Moreover, when compared with the service type, it was evidenced that eScooter sharing was the most powerful connector to PT since it augmented the mode share by 3% more than bikesharing. Finally, the implementation of both modes simultaneously evidences a competence between bikesharing and eScoter for the access of PT.

In order to evaluate the validity of the results, the literature presents great insight into the influence of the SMM service schemes and the integration of PTT. Regarding station-based services, the location of parking stations near PT stations is a crucial factor in the SMM-PT integration(Oeschger et al., 2020; Tavassoli & Tamannaei, 2020). Moreover, the maximum walking distance between the bikesharing stations and PT is around 200-210 mts (Oeschger et al., 2020). To compare the values described with the Corsica case, Figure 30 and Figure 31 present the spatial distribution of bikesharing stations around the 200 mts radius of both train and bus stations in Corsica. As seen in the figures aforementioned, it is evident that the current distribution of bike-sharing stations for bikesharing in most cases is not close enough to the PT stations. Therefore, the low integration of the bikesharing mode with PT seems to be linked to the lack of strategic location of bikesharing stations for the test scenario. Finally, the e Scooter free-floating approach is reported to be more efficient in bridging last and first-mile solutions due to the user's ability to access and egress the vehicles in any place they desire in the service area (Grosshuesch, 2020). Finally, the literature appears to validate the results of eScooter being a more efficient connector of PT due to the flexibility of service compared to the station-based bikesharing service.

Figure 30. Station based bikesharing and PT stations detail 1

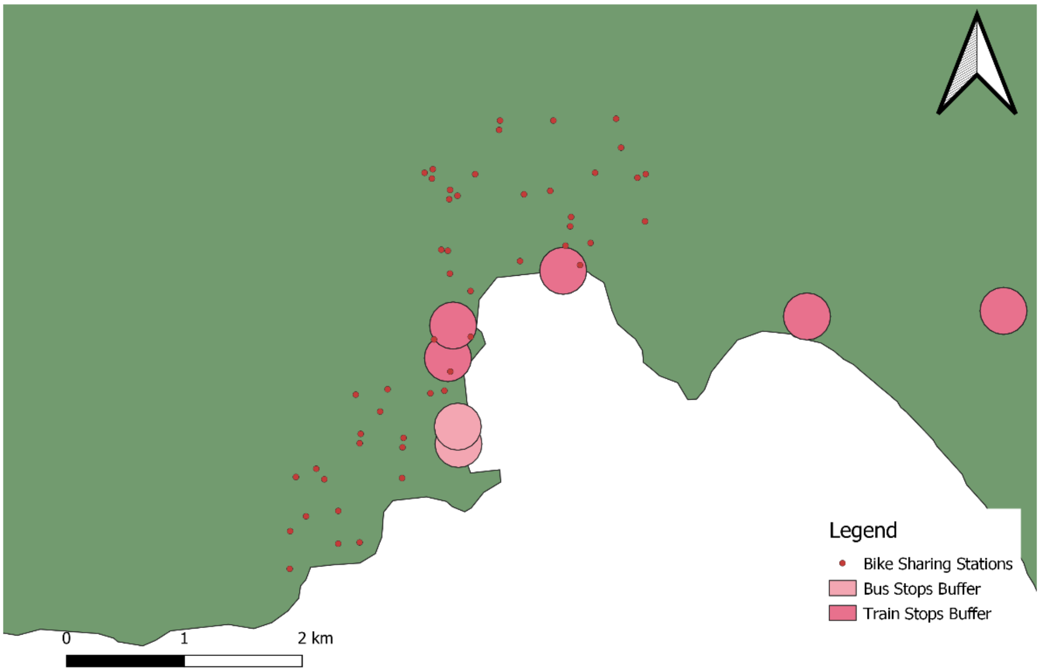

Figure 31. Station-based bikesharing services and PT Stations detail 2

Another result that the simulations bared were the use of mode as an access or egress mode from PT. Further, results show that both bikesharing and eScooter in Corsica are more likely to be used as egress modes from PT. Even if this pattern is not reported on any piece of literature available, the pattern can be correlated with the vehicle availability near the transit stations. According to Oeschger et al., the availability of vehicles near PT stations is the main driver for SMM-PT integration (2020). Furthermore, Oescheger et al. (2020) and Yang et al. (2019) establish that the integration of SMM-PT causes a high variation of the spatiotemporal supply. Thus, the redistribution algorithm must be improved to integrate the modes properly. In the case of the SMM framework and MATSim, there are no redistribution strategies for SMM.

As a consequence, the supply of SMM will be heavily skewed to the first destinations of the agents. Consequently, the vehicles may tend to be clustered near the PT stations after the agents' first trip of the day. Thus making it more plausible for agents to use the SMM modes as egress modes on their return home. Overall, the SMM framework fails to properly represent the usage patterns of SMM as a PT connector. In future developments, the creation of redistribution strategies must be added to the framework to reflect the integration of SMM-PT.

On the other hand, the mode share impact of SMM-PT also depicted the competence between SMM modes. In the study region, the implementation of bikesharing and eScooter simultaneously would hinder SMM-PT integration. In contrast, Reck et al.(2022) evaluated the competence of SMM services. Further, the author established that at small distances (less than 1 km), the probability of choosing was higher for free-floating eScooter than for station-based bikesharing services. Furthermore, the author also found that the probability of choosing any of the two modes would equal around the 1km trip. In the case of SMM-PT integration, on average, the trip length of an SMM mode trip ranges between 1400 and 1000 mts for bikesharing and 1500 to 900 mts for eScooter.Thus, the competition phenomenon in Corsica is well reflected in the SMM-framework.

Finally, the last results of the SMM-PT integration were the characterization of the access and egress trips. This characterization revealed that in the Corsica case, the average access egress distance for eScooter trips was 1160 mts; meanwhile, the average distance for bikesharing was 1160 mts. Although there is not much information on the characteristics of eScooter-PT trips, Fearnley et al.(2020) studied the usage pattern for eScooter access trips to PT in Oslo. Further, the author discovers that, on average, the access egress distance was 1000 mts. On the other hand, the characterization of bikesharing-PT trips has been much more studied. Most researchers seem to agree that the bikesharing-PT access/egress trips lie between 200-400 mts from the PT Station (Böcker et al., 2020; Ji et al., 2017; Yang et al., 2019). When comparing the literature values with the simulation scenarios and the reported values, it is clear that the free-floating eScooter integration with PT describes similar patterns to the literature.

Conversely, the region's station-based bikesharing access trips appear to be hugely overestimated. This is because the bikesharing station service and PT integration are heavily associated with parking stations. Further, the agents only can travel from the bikesharing station to other bikesharing stations, which means that the low density of stations in the Corsica region could lead to longer access/egress trips. Consequently, bike-sharing-PT integration simulation of bikesharing-PT integration is heavily influenced by station density and must be further explored in other scenarios.

After discussing the validity of the SMM results for multimodality, the conclusions can be mixed regarding the simulation of SMM-PT. The framework can simulate the effects of SMM-PT integration on the mode choice of PT accurately. Moreover, for the Corsica, the framework presents the eScooter services as a more effective PT connector to bikesharing due to the flexibility of the service. On the other hand, the SMM framework can simulate SMM competence at short distances. Additionally, the case scenario results reveal that the competition would harm PT-SMM integration due to the high competition between modes on short trips. Further, the SMM framework can simulate realistic access egress trips from PT using eScooter; for bikesharing trips, the simulation is heavily influenced by the impact of station density. Thus, the simulation of station-based bikesharing must be further investigated in different scenarios.

7. Conclusion

The thesis's main objective was to help advance the simulation of share micromobility modes. In that order of ideas, the literature review provided an overview of what SMM is and what influences the user behavior for SMM modes. Based on the latter, it was established that factors such as service supply, sociodemographic attributes, and economic factors, among others, were significant to the SMM user behavior (Elmashhara et al., 2022; Liao & Correia, 2020). Conversely, the literature review presented the available SMM simulation frameworks. Particularly, the Agent-Based models were popular in the SMM simulation.

From the ABM, MATSim was one of the most promising frameworks for simulating SMM modes in a multimodal environment (Tzouras et al., 2022). However, when the different instances of SMM simulation in MATSim were observed, it was determined that none of the contributions presented a comprehensive approach to the complex nature of SMM modes. Further, none of the more advanced SMM frameworks considered the explicit mode choice of the SMM users.

Based on the literature review, the research gap was identified as the lack of explicit modeling of user mode choice in SMM despite its documented importance in SMM adoption. Thus, the thesis assumed that the simulation of SMM modes would be enriched by incorporating discrete mode choice models. Consequently, the research question was whether the inclusion of the discrete mode choice model in MATSim would represent the different behaviors of SMM users and adoption. Further, the research question was evaluated by implementing different scenarios based on the price of service, vehicle/station density, and multimodality with PT.

In order to solve the research question, the methodological approach was the development of an integrated framework(SMM framework) based on MATSim that aggregated the supply side of SMM, the demand side, and the interaction with the multimodal environment. In order to incorporate the supply of SMM, the Sharing contrib by Balac and Hörl (2021) was implemented. Meanwhile, the demand side was represented by the Krauss et al. (2022) introduction using a custom implementation of the Discrete Mode Choice contrib by Hörl (2021). Finally, the multimodality relationships were represented by generating a custom mode that used SMM as access or egress from PT.

Several scenarios validating the framework's capacities were run in a 1% scaled Corsica MATSim scenario. In detail, two scenarios were established to evaluate the sensitivity to the user's mode choice. The first one referred to the sensitivity of user choice to price structures of the SMM modes. Meanwhile, the second evaluated the sensitivity of mode choice of the user as a function of the accessibility of the service. This relationship was modeled by alternating service scheme terms of station and vehicle density. Finally, the multimodality test would evaluate the effect of different service schemes on the SMM-Integration.

The different scenario results were used for the different evaluations. In the case of the cost scenario, it was concluded that the SMM framework could reproduce reasonable impacts on the impact of eScooter.However, the bikesharing scenario results did not comply with the reported patterns in literature due to the heavy influence of local conditions in the Corsica scenario. On the side of vehicle/station density, it can be established that the SMM framework can reflect the positive correlation between station density and mode choice. Meanwhile, the eScooter vehicle density differed from the positive correlation with mode choice. The analysis determined that the root of this variation could be linked to the input GBFS files in the test scenario. Finally, the multimodal scenarios demonstrated that the current state of the SMM framework has mixed results in simulating SMM-PT relationships. On one side, the SMM framework accurately depicted changes in mode choice. However, the multimodal trip patterns and characteristics were heavily skewed by the local conditions of the region and the lack of redistribution algorithms in the simulation.

In conclusion, the thesis successfully advanced the sharing micromobility simulation state-of-the-art by implementing discrete mode choice. However, the initial assumption was denied since implementing discrete mode choice models is not enough to represent their users' behaviors and mode adoption. Furthermore, the SMM framework was heavily influenced by local conditions in the Corsica test scenario and the lack of functionalities such as the redistribution of sharing modes. Additionally, the thesis opens new possible avenues for research, such as the integration of rebalancing algorithms and testing the framework in scenarios with different conditions than Corsica.

Appendix A

The following mod utilities were derived from the Krauss et al.(2022) mode

Bikesharing and bikes:

$$U_{BS} = \beta_{BS} + \beta time_{BS} * time_{BS} + \beta_{accessshared} * access_{BS} + \beta_{egressshared} * egress_{BS} + \beta_{parking} * parking_{BS} + \beta\_cost * cost_{BS}$$

Walking:

$$U_{WA} = \beta_{WA} + \beta time_{WA} * time_{WA}$$

PT:

$$U_{PT} = \beta_{PT} + \beta_{timePT} * time_{PT} + \beta accessshared * (access_{PT} + wait_{PT}) + \beta_{egress} * egress_{PT} + \beta_{cost} * cost_{PT} + \beta_{transfer} * transfer_{PT}$$

Car:

$$U_{CA} = \beta_{CA} + \varphi_{pool} * [\beta_{timeCA} * time_{CA} + \beta_{accessCA} * access_{CA} + \beta_{egress} * egress_{CA} + \beta_{parking} * parking_{CA} + \beta_{cost} * cost_{CA}]$$

$$\beta CA = \sigma CA$$

With personal utility β_{Mode}

$$\beta_{Mode} = \beta_{Mode_0} + \beta_{ageMode} * age + \beta_{carMode} * hhcar + \beta_{bikeMode} * hhbike + \beta_{ptpassMode} * ptpass$$

Finally, the following table describes the adopted cost structures for the DMC model.

Mode	***Cost per minute [Euro/min]***	***Cost per trip [Euro]***	***Unlocking cost [Euro]***	***Source***
Car	0.15	0	0	(Hörl & Balac, 2021)
PT	0	1.8	0	(Hörl & Balac, 2021)
BikeSharing	0.25	0	1	(Mona, 2015b)
eScooter	0.15	0	1	(Mona, 2015a)

References

1. Abduljabbar, R. L., Liyanage, S., & Dia, H. (2021). The role of micro-mobility in shaping sustainable cities: A systematic literature review. *Transportation Research Part D: Transport and Environment*, *92*, 102734. https://doi.org/10.1016/j.trd.2021.102734

2. Almannaa, M. H., Ashqar, H. I., Elhenawy, M., Masoud, M., Rakotonirainy, A., & Rakha, H. (2020). A Comparative Analysis of E-Scooter and E-Bike Usage Patterns: Findings from the City of Austin, TX. *ArXiv:2006.04033 [Cs]*. http://arxiv.org/abs/2006.04033

3. Arias-Molinares, D., Julio, R., García-Palomares, J. C., & Gutiérrez, J. (2021). Exploring micromobility services: Characteristics of station-based bike-sharing users and their relationship with dockless services. *Journal of Urban Mobility*, *1*, 100010. https://doi.org/10.1016/j.urbmob.2021.100010

4. BACCI, M. (n.d.). *La marche à pied, le deuxième mode de déplacement en Corse*. Agence d'aménagement durable, d'urbanisme et d'énergie de la Corse. Retrieved 12 June 2022, from https://www.aue.corsica/La-marche-a-pied-le-deuxieme-mode-de-deplacement-en-Corse_a383.html

5. Balac, M., & Hörl, S. (2021). Simulation of intermodal shared mobility in the San Francisco Bay Area using MATSim. *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, 3278–3283. https://doi.org/10.1109/ITSC48978.2021.9564851

6. Becker, H., Balac, M., Ciari, F., & Axhausen, K. W. (2020). Assessing the welfare impacts of Shared Mobility and Mobility as a Service (MaaS). *Transportation Research Part A: Policy and Practice*, *131*, 228–243. https://doi.org/10.1016/j.tra.2019.09.027

7. Blazanin, G., Mondal, A., Asmussen, K. E., & Bhat, C. R. (2022). E-scooter sharing and bikesharing systems: An individual-level analysis of factors affecting first-use and use frequency. *Transportation Research Part C: Emerging Technologies*, *135*, 103515. https://doi.org/10.1016/j.trc.2021.103515

8. Böcker, L., Anderson, E., Priya Uteng, T., & Throndsen, T. (2020). Bike sharing use in conjunction to public transport: Exploring spatiotemporal, age and gender

dimensions in Oslo, Norway. *Transportation Research Part A: Policy and Practice*, *138*, 389–401. https://doi.org/10.1016/j.tra.2020.06.009

9. Campbell, A. A., Cherry, C. R., Ryerson, M. S., & Yang, X. (2016). Factors influencing the choice of shared bicycles and shared electric bikes in Beijing. *Transportation Research Part C: Emerging Technologies*, *67*, 399–414. https://doi.org/10.1016/j.trc.2016.03.004

10. Coretti Sanchez, N., Martinez, I., Alonso Pastor, L., & Larson, K. (2022). On the simulation of shared autonomous micro-mobility. *Communications in Transportation Research*, *2*, 100065. https://doi.org/10.1016/j.commtr.2022.100065

11. de Bortoli, A., & Christoforou, Z. (2020). Consequential LCA for territorial and multimodal transportation policies: Method and application to the free-floating e-scooter disruption in Paris. *Journal of Cleaner Production*, *273*, 122898. https://doi.org/10.1016/j.jclepro.2020.122898

12. Elmashhara, M. G., Silva, J., Sá, E., Carvalho, A., & Rezazadeh, A. (2022). Factors influencing user behaviour in micromobility sharing systems: A systematic literature review and research directions. *Travel Behaviour and Society*, *27*, 1–25. https://doi.org/10.1016/j.tbs.2021.10.001

13. Fearnley, N., Johnsson, E., & Berge, S. H. (2020). Patterns of e-scooter use in combination with public transport. *Transport Findings*. https://doi.org/10.32866/001c.13707

14. Fernández, A., Billhardt, H., Ossowski, S., & Sánchez, Ó. (2020). Bike3S: A tool for bike sharing systems simulation. *Journal of Simulation*, *14*(4), 278–294. https://doi.org/10.1080/17477778.2020.1718022

15. Grignard, A., Alonso, L., Taillandier, P., Gaudou, B., Nguyen-Huu, T., Gruel, W., & Larson, K. (2018). The Impact of New Mobility Modes on a City: A Generic Approach Using ABM: Proceedings of the Ninth International Conference on Complex Systems. In *Springer Proceedings in Complexity* (pp. 272–280). https://doi.org/10.1007/978-3-319-96661-8_29

16. Grosshuesch, K. (2020). Solving the First Mile/ Last Mile Problem: Electric Scooter and Dockless Bicycles are Positioned to Provide Relief to Commuters Struggling with a Daily Commute. *William & Mary Environmental Law and Policy Review*, *44*(3), 847.

17. Hebenstreit, C., & Fellendorf, M. (2018). A dynamic bike sharing module for agent-based transport simulation, within multimodal context. *Procedia Computer Science*, *130*, 65–72. https://doi.org/10.1016/j.procs.2018.04.013

18. Heineke, K., Kloss, B., & Scurtu, D. (2020). *The future of micromobility: Ridership and revenue after a crisis*. 6.

19. Heyns, W., & Van Jaarsveld, S. (2017). TRANSPORTATION MODELLING IN PRACTICE: CONNECTING BASIC THEORY TO PRACTICE. In I. M. Schoeman (Ed.), *WIT Transactions on State-of-the-art in Science and Engineering* (1st ed., Vol. 1, pp. 3–27). WIT Press. https://doi.org/10.2495/978-1-78466-233-2/001

20. Hollingsworth, J., Copeland, B., & Johnson, J. X. (2019). Are e-scooters polluters? The environmental impacts of shared dockless electric scooters. *Environmental Research Letters*, *14*(8), 084031. https://doi.org/10.1088/1748-9326/ab2da8

21. Hörl, S. (2021). Integrating discrete choice models with MATSim scoring. *9th International Workshop on Agent-Based Mobility, Traffic and Transportation Models,(ABMTRANS)*, *148*, 704–711. https://doi.org/10.1016/j.procs.2021.03.088

22. Hörl, S., & Balac, M. (2021). Introducing the eqasim pipeline: From raw data to agent-based transport simulation. *Procedia Computer Science*, *184*, 712–719. https://doi.org/10.1016/j.procs.2021.03.089

23. Horni, A., Nagel, K., & Axhausen, K. W. (2016). The Multi-Agent Transport Simulation MATSim. In *Ubiquity Press*. Ubiquity Press. https://doi.org/10.5334/baw

24. IEA ,. (2021). *Tracking Transport 2021*. https://www.iea.org/reports/tracking-transport-2021

25. Inseee. (2022). *Comparateur de territoire − Comparez les territoires de votre choix—Résultats pour les communes, départements, régions, intercommunalités.* https://www.insee.fr/fr/statistiques/1405599?geo=REG-94

26. Ji, Y., Fan, Y., Ermagun, A., Cao, X., Wang, W., & Das, K. (2017). Public bicycle as a feeder mode to rail transit in China: The role of gender, age, income, trip purpose, and bicycle theft experience. *International Journal of Sustainable*

Transportation, *11*(4), 308–317. https://doi.org/10.1080/15568318.2016.1253802

27. Jin, Y., Ruiz, C., & Liao, H. (2022). A simulation framework for optimizing bike rebalancing and maintenance in large-scale bike-sharing systems. *Simulation Modelling Practice and Theory*, *115*, 102422. https://doi.org/10.1016/j.simpat.2021.102422

28. Khalil, J., Yan, D., Guo, G., Sami, M. T., Roy, J. B., & Sisiopiku, V. P. (2021). Realistic Transport Simulation for Studying the Impacts of Shared Micromobility Services. *2021 IEEE International Conference on Big Data (Big Data)*, 5935–5937. https://doi.org/10.1109/BigData52589.2021.9671681

29. Krauss, K., Krail, M., & Axhausen, K. W. (2022). What drives the utility of shared transport services for urban travellers? A stated preference survey in German cities. *Travel Behaviour and Society*, *26*, 206–220. https://doi.org/10.1016/j.tbs.2021.09.010

30. Krümmel, K., Gernant, E., Stolt, R., Stolze, B., & Moschner, H. (2019). *Deconstructing the Micromobility Phenomenon* (p. 17). Porsche Consulting. https://www.porsche-consulting.com/fileadmin/docs/04_Medien/Publikationen/SRX03976_Deconstructing_the_Micromobility_Phenomenon/Deconstructing_the_Micromobility_Phenomenon_C_2019_Porsche_Consulting.pdf

31. Liao, F., & Correia, G. (2020). Electric carsharing and micromobility: A literature review on their usage pattern, demand, and potential impacts. *International Journal of Sustainable Transportation*, 1–30. https://doi.org/10.1080/15568318.2020.1861394

32. Liu, Y., Tang, Y., & Liu, Y. (2022). *All one needs to know about shared micromobility simulation: A complete survey* (arXiv:2203.03707). arXiv. http://arxiv.org/abs/2203.03707

33. Ma, X., Zhang, S., Jin, Y., Zhu, M., & Yuan, Y. (2022). Identification of Metro-Bikeshare Transfer Trip Chains by Matching Docked Bikeshare and Metro Smartcards. *Energies*, *15*(1), 203. https://doi.org/10.3390/en15010203

34. Marques, D. L., & Coelho, M. C. (2022). A Literature Review of Emerging Research Needs for Micromobility—Integration through a Life Cycle Thinking Ap-

proach. *Future Transportation*, *2*(1), 135–164. https://doi.org/10.3390/futuretransp2010008

35. Mason, J., Fulton, L., & McDonald, Z. (2015). *A Global High Shift Cycling Scenario: The Potential for Dramatically Increasing Bicycle and E-bike Use in Cities around the World, with Estimated Energy, CO2, and Cost Impacts*. https://trid.trb.org/view/1375683

36. *MATSim-Extensions by SBB*. (2022). Swiss Federal Railways (SBB). https://github.com/SchweizerischeBundesbahnen/matsim-sbb-extensions (Original work published 2018)

37. Mclean, R. (2021). *Simulation Modeling of Calgary's E-Scooter System*. https://doi.org/10.11575/PRISM/39235

38. Milakis, D., Gedhardt, L., Ehebrecht, D., & Lenz, B. (2020). Is micro-mobility sustainable? An overview of implications for accessibility, air pollution, safety, physical activity and subjective wellbeing. *Handbook of Sustainable Transport*, 180–189.

39. Mona. (2015a, May 27). Comparison of Rental Electric Scooter Services in Paris. *France Hotel Guide's Blog*. https://www.france-hotel-guide.com/en/blog/electric-scooters-paris/

40. Mona. (2015b, September 2). Bicycle Sharing Systems in Paris: The 4 Companies Compared. *France Hotel Guide's Blog*. https://www.france-hotel-guide.com/en/blog/shared-bicycle-paris/

41. Moreau, H., de Jamblinne de Meux, L., Zeller, V., D'Ans, P., Ruwet, C., & Achten, W. M. J. (2020). Dockless E-Scooter: A Green Solution for Mobility? Comparative Case Study between Dockless E-Scooters, Displaced Transport, and Personal E-Scooters. *Sustainability*, *12*(5), 1803. https://doi.org/10.3390/su12051803

42. NABSA. (2022a). *General Bikeshare Feed Specification*. North American Bike Share Association. https://github.com/NABSA/gbfs (Original work published 2015)

43. NABSA. (2022b). *General Bikeshare Feed Specification(GBFS) V.2.3*. North American Bike Share Association.

https://github.com/NABSA/gbfs/blob/4f0cc7024ff5ba71d3c3e861c3ff23a281ef71f8/gbfs.md (Original work published 2015)

44. NACTO. (2019). *Guidelines for Regulating Shared Micromobility* (No. 2; p. 56). NACTO. https://nacto.org/sharedmicromobilityguidelines/

45. Nagel, K., & Axhausen, K. W. (2016). *Some History of MATSim*. https://doi.org/10.14279/depositonce-7761

46. Oeschger, G., Carroll, P., & Caulfield, B. (2020). Micromobility and public transport integration: The current state of knowledge. *Transportation Research Part D: Transport and Environment*, *89*, 102628. https://doi.org/10.1016/j.trd.2020.102628

47. Peng, H., Nishiyama, Y., & Sezaki, K. (2021). Estimation of Greenhouse Gas Emission Reduction from Shared Micromobility System. *2021 IEEE Green Energy and Smart Systems Conference (IGESSC)*, 1–6. https://doi.org/10.1109/IGESSC53124.2021.9618701

48. Reck, D. J., & Axhausen, K. W. (2021). Who uses shared micro-mobility services? Empirical evidence from Zurich, Switzerland. *Transportation Research Part D: Transport and Environment*, *94*, 102803. https://doi.org/10.1016/j.trd.2021.102803

49. Reck, D. J., Martin, H., & Axhausen, K. W. (2022). Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility. *Transportation Research Part D: Transport and Environment*, *102*, 103134. https://doi.org/10.1016/j.trd.2021.103134

50. Rodriguez, H. B., Jenelius, E., Lansner, E., & Montero, M. (2021). *Modelling of Micromobility (M3) Prestudy on Knowledge Needs and Usage Patterns*. 68.

51. Rose, J., Schellong, D., Schatezberger, C., & Hill, J. (2020). *How E-Scooters Can Win a Place in Urban Transport*. https://www.bcg.com/publications/2020/e-scooters-can-win-place-in-urban-transport

52. Severengiz, S., Finke, S., Schelte, N., & Wendt, N. (2020). Life Cycle Assessment on the Mobility Service E-Scooter Sharing. *2020 IEEE European Technology and Engineering Management Summit (E-TEMS)*, 1–6. https://doi.org/10.1109/E-TEMS46250.2020.9111817

53. Shaheen, S. (2019). *Micromobility Policy Toolkit: Docked and Dockless Bike and Scooter Sharing*. https://doi.org/10.7922/G2TH8JW7

54. Shaheen, S., & Chan, N. (2016). Mobility and the Sharing Economy: Potential to Facilitate the First- and Last-Mile Public Transit Connections. *Built Environment*, *42*(4), 573–588. https://doi.org/10.2148/benv.42.4.573

55. Shaheen, S., & Cohen, A. (2019). *Shared Micromoblity Policy Toolkit: Docked and Dockless Bike and Scooter Sharing*. https://doi.org/10.7922/G2TH8JW7

56. Shaheen, S., Cohen, A., & Broader, J. (2021). What's the 'Big' Deal with Shared Micromobility? Evolution, Curb Policy, and Potential Developments in North America. *Built Environment*, *47*(4), 499–514. https://doi.org/10.2148/benv.47.4.499

57. Shaheen, S., Martin, E., & Cohen, A. (2013). Public Bikesharing and Modal Shift Behavior: A Comparative Study of Early Bikesharing Systems in North America. *International Journal of Transportation*, *1*, 35–54. https://doi.org/10.14257/ijt.2013.1.1.03

58. Soriguera, F., Casado, V., & Jiménez, E. (2018). A simulation model for public bike-sharing systems. *Transportation Research Procedia*, *33*, 139–146. https://doi.org/10.1016/j.trpro.2018.10.086

59. Tavassoli, K., & Tamannaei, M. (2020). Hub network design for integrated Bike-and-Ride services: A competitive approach to reducing automobile dependence. *Journal of Cleaner Production*, *248*, 119247. https://doi.org/10.1016/j.jclepro.2019.119247

60. Twisse, F. (2020). *The Rise of Micromobility*. https://www.eltis.org/resources/case-studies/rise-micromobility

61. Tzouras, P. G., Mitropoulos, L., Stavropoulou, E., Antoniou, E., Koliou, K., Karolemeas, C., Karaloulis, A., Mitropoulos, K., Tarousi, M., Vlahogianni, E. I., & Kepaptsoglou, K. (2022). Agent-based models for simulating e-scooter sharing services: A review and a qualitative assessment. *International Journal of Transportation Science and Technology*, S2046043022000016. https://doi.org/10.1016/j.ijtst.2022.02.001

62. Wang, Y., Wang, Y., Wu, X., & Li, J. (2020). Exploring the Risk Factors of Infrastructure PPP Projects for Sustainable Delivery: A Social Network Perspective. *Sustainability*, *12*(10), 4152. https://doi.org/10.3390/su12104152

63. Yang, Y., Heppenstall, A., Turner, A., & Comber, A. (2019). A spatiotemporal and graph-based analysis of dockless bike sharing patterns to understand urban flows over the last mile. *Computers, Environment and Urban Systems*, *77*, 101361. https://doi.org/10.1016/j.compenvurbsys.2019.101361

64. Yanocha, D., Mason, J., Patlán, M., Benicchio, T., Alfred, I., & Laksmana, U. (2018). *The Bikeshare Planning Guide*. https://trid.trb.org/view/1586864

65. Ziemke, D., Knapen, L., & Nagel, K. (2021). Expanding the analysis scope of a MATSim transport simulation by integrating the FEATHERS activity-based demand model. *Procedia Computer Science*, *184*, 753–760. https://doi.org/10.1016/j.procs.2021.04.022

Declaration

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

12.06.2022 , Munich Juan P Rendón A

Place, Date, Signature