Sustainability Potentials of Corporate Mobility as a Service Systems

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Abstract

Corporate Mobility as a Service (CMaaS) emerges as a promising approach to address the sustainability challenges associated with company-related mobility. Since corporate cars make up a significant share of the German vehicle fleet and contribute heavily to mobility-related damages, e.g., greenhouse gas (GHG) emissions, noise, air pollution, and congestion, current mobility practices in companies are often at odds with environmental and social sustainability goals. Despite increasing awareness of these issues, most companies still rely on exclusive, unimodal car fleets. CMaaS combines the benefits of exclusive mobility services, e.g., owned or leased cars, with public mobility services, e.g., bikesharing or taxis. While exclusive mobility services provide flexibility and reliability, public mobility services can help to cover the mobility demand during peak hours. Since CMaaS decreases the dependence on cars and provides low-emitting modes, e.g., electric cars, bikes, and scooters, it is expected to decrease the negative environmental and social impacts of corporate mobility.

Against this background, the aim of this dissertation is to contribute to the limited literature on CMaaS, provide decision support for integrating multiple mobility services with different technical characteristics and cost structures, and quantify the sustainability potentials of CMaaS. By creating general insights about the potentials of CMaaS to reduce the negative economic, environmental, and social impacts of corporate mobility, this research supports corporate mobility managers in deciding about the implementation of CMaaS in their companies, and political decision-makers in making better-informed decisions about our future mobility system. This cumulative dissertation contains three research papers, each conducting an assessment in one sustainability dimension.

The first research paper develops a tool that helps corporate mobility managers design their customized CMaaS system under a cost objective. It is the first strategic-tactical optimization model that identifies the optimal CMaaS design for a given mobility demand, while considering the relevant decisions for and restrictions of exclusive and public mobility services. Applying the model to a case study, the research paper assesses the cost implications of the determined CMaaS systems and deduces general insights for CMaaS.

The second research paper considers the fact that an increasing share of companies is obliged to decrease their GHG emissions. To quantify the GHG emissions of each regarded mobility service, a Life Cycle Assessment (LCA) is conducted that quantifies the life time CO_2 equivalents emitted per passenger kilometer. By transforming the decision-support tool into a bi-objective optimization model that minimizes corporate costs and GHG emissions, the trade-off between minimum economic and minimum environmental impacts is assessed.

The third research paper quantifies the social impacts of CMaaS, conducting a social cost assessment. Herein, the social burden of corporate mobility is evaluated by comparing the costs that are borne by the individual user (internal costs) with the costs that incur to society due to the mobility behavior of an individual (external costs). The underlying optimization model from the first research paper is adjusted to account for social costs, and new objective functions are implemented to minimize either the internal costs, the external costs, or the sum of both, which are the social costs.

To deduce general insights about CMaaS, the methodologies of all three research papers are applied to a comprehensive case study, which is based on trip data of 144 companies in Germany. By comparing the individual internal mobility costs, GHG emissions, and social costs of each company in a traditional setting with unimodal car fleets to an optimized CMaaS setting, the potentials of CMaaS to decrease the sustainability-related impacts of corporate mobility are quantified. Proposing the suitable methodology to analyze the potentials of CMaaS to reduce negative impacts in each dimension of sustainability and applying it to a common, comprehensive case study, this dissertation for the first time provides an integrated approach for the prospective design of CMaaS under economic, environmental, and social objectives, that also serves as decision support for corporate mobility managers.

Zusammenfassung

Corporate Mobility as a Service (CMaaS) stellt einen vielversprechenden Ansatz dar, um die Nachhaltigkeitsprobleme im Zusammenhang mit unternehmensbezogener Mobilität zu bewältigen. Da Firmenwagen einen erheblichen Anteil am Fahrzeugbestand in Deutschland ausmachen und stark zu mobilitätsbedingten Schäden wie Treibhausgasemissionen, Lärm, Luftverschmutzung und Staus beitragen, stehen aktuelle Mobilitätspraktiken in Unternehmen oft im Widerspruch zu ökologischen und sozialen Nachhaltigkeitszielen. Trotz eines zunehmenden Bewusstseins für diese Probleme setzen viele Unternehmen weiterhin auf exklusive, unimodale Fahrzeugflotten. CMaaS kombiniert die Vorteile exklusiver Mobilitätsdienste, z. B. firmeneigene oder Leasing-Fahrzeuge, mit öffentlichen Mobilitätsdiensten wie Bikesharing oder Taxis. Während exklusive Mobilitätsdienste Flexibilität und Verfügbarkeit sicherstellen, können öffentliche Mobilitätsdienste dazu beitragen, den Mobilitätsbedarf zu Spitzenzeiten zu decken. Da CMaaS die Abhängigkeit vom Auto verringert und emissionsarme Verkehrsmittel wie Elektrofahrzeuge, Fahrräder oder E-Scooter integriert, wird erwartet, dass es die negativen Umwelt- und Sozialwirkungen der Unternehmensmobilität reduziert.

Vor diesem Hintergrund verfolgt die Dissertation das Ziel, die bislang begrenzte wissenschaftliche Literatur zu CMaaS zu erweitern, Entscheidungshilfen zur Integration verschiedener Mobilitätsdienste mit unterschiedlichen technischen Anforderungen und Kostenstrukturen zu bieten und das Nachhaltigkeitspotenzial von CMaaS zu quantifizieren. Durch die Ableitung allgemeiner Erkenntnisse über das Potenzial von CMaaS, negative wirtschaftliche, ökologische und soziale Auswirkungen der Unternehmensmobilität zu reduzieren, unterstützt diese Forschung sowohl Verantwortliche für Unternehmensmobilität bei der Entscheidung über die Einführung von CMaaS als auch politische Entscheidungsträger bei der Gestaltung eines zukunftsfähigen Mobilitätssystems. Diese kumulative Dissertation enthält drei Forschungsarbeiten, die jeweils eine Dimension der Nachhaltigkeit untersuchen.

Die erste Studie entwickelt ein Instrument, das Verantwortliche für Unternehmensmobilität bei der kostenoptimierten Gestaltung eines maßgeschneiderten CMaaS-Systems unterstützt. Es handelt sich um das erste strategisch-taktische Optimierungsmodell, das auf Grundlage eines gegebenen Mobilitätsbedarfs das optimale CMaaS-Design ermittelt und dabei relevante Entscheidungen und Einschränkungen sowohl für exklusive als auch öffentliche Mobilitätsdienste berücksichtigt. Durch die Anwendung des Modells auf eine Fallstudie werden die Kostenimplikationen der ermittelten CMaaS-Systeme bewertet und allgemeine Erkenntnisse für CMaaS abgeleitet.

Die zweite Forschungsarbeit berücksichtigt die Tatsache, dass immer mehr Unternehmen gesetzlich verpflichtet sind, ihre Treibhausgasemissionen zu senken. Um die Treibhausgasemissionen der einzelnen Mobilitätsdienste zu quantifizieren, wird eine Lebenszyklusanalyse (LCA) durchgeführt, die die über die Lebensdauer emittierten CO_2-Äquivalente pro Personenkilometer quantifiziert. Das Entscheidungsmodell wird zu einem bi-objektiven Optimierungsansatz erweitert, der gleichzeitig Unternehmenskosten und Emissionen minimiert, um Zielkonflikte zwischen wirtschaftlicher und ökologischer Nachhaltigkeit sichtbar zu machen.

In der dritten Forschungsarbeit werden die sozialen Auswirkungen von CMaaS durch eine Bewertung der sozialen Kosten untersucht. Dabei wird die gesellschaftliche Belastung durch Unternehmensmobilität ermittelt, indem die individuellen (internen) Kosten mit den Kosten verglichen werden, die der Gesellschaft durch das Mobilitätsverhalten eines Einzelnen entstehen (externe Kosten). Das zugrundeliegende Optimierungsmodell aus der ersten Forschungsarbeit wird hierfür angepasst und es werden neue Zielfunktionen implementiert, die entweder die internen, die externen oder die Summe aus beiden, d. h. die sozialen Kosten, minimieren.

Um verallgemeinerbare Erkenntnisse über CMaaS abzuleiten, werden die Methoden der drei Forschungsarbeiten auf eine umfassende Fallstudie angewendet, die auf den Fahrprofilen von 144 deutschen Unternehmen basiert. Durch den Vergleich der individuellen Mobilitätskosten, Treibhausgasemissionen und sozialen Kosten eines traditionellen, unimodalen Mobilitätssystems mit einem optimierten CMaaS-System werden die Nachhaltigkeitspotenziale von CMaaS quantifiziert. Mit dem Vorschlag einer geeigneten Methodik zur Analyse der Potenziale von CMaaS zur Verringerung negativer Auswirkungen in jeder Nachhaltigkeitsdimension und deren Anwendung auf eine gemeinsame, umfassende Fallstudie bietet diese Dissertation erstmals einen integrierten Ansatz für die prospektive Gestaltung von CMaaS unter Berücksichtigung ökonomischer, ökologischer und sozialer Ziele, der auch als Entscheidungshilfe für Verantwortliche für Unternehmensmobilität dient.

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Preface

Chapter 1

Introduction

1.1 Background

Corporate mobility is responsible for a great share of mobility-induced damages, which include air pollution, the emission of greenhouse gases (GHGs), and noise, among many others (cf. European Environment Agency 2025). 44% of the European passenger car fleet are company cars (cf. Dataforce 2020) and more than every second new car in Germany is registered by companies (cf. KBA 2024). Companies often rely solely on cars to meet their mobility demand, providing unimodal car fleets to their employees, thereby causing negative impacts in all three dimensions of sustainability (cf. Graus and Worrell 2008). Environmental impacts of car-based mobility are widely discussed, since cars emit 43% of the entire mobility-induced GHG emissions in the European Union (cf. European Parliament 2024). Additionally, the congestion, noise, and air pollution caused by car traffic triggers environmental and health damages on a local level, which severely impede the well-being of the population. Likewise, social impacts of car-based mobility are manifold. For instance, a recent study suggests that one in 34 deaths is caused by cars and that the harm is distributed unevenly in the population, further disadvantaging already marginalized groups (cf. Miner et al. 2024). Other studies show that car usage is often not even economically beneficial, with users underestimating the costs of owning a car and other mobility options being less expensive (cf. Gössling et al. 2022). Against the background of these impacts of car-centric mobility and its particular dominance in corporate mobility, a sustainable transformation of the corporate mobility system is long overdue.

A paradigm change in the mobility sector was initiated by the dissemination of digital technologies, especially on mobile devices. Mobile internet connections, online payment options, and location determination via GPS enable a shift away from car-centricism to a needs-oriented mobility system. This paradigm change can be seen in the fast emergence of new mobility services, like shared e-scooters which emerged in Germany in 2019 and are now present in all medium-sized or large cities (cf. König et al. 2022). Their convenience is based on spontaneous booking and payment, flexible pick-up and return, as well as keyless access via smartphone.

However, traditional mobility service providers, like taxi or public transport companies, equally introduce mobile apps to allow for spontaneous booking and online payment. Accordingly, most users have a broad variety of mobility apps on their smartphones, one for each mobility service they use.

Mobility as a Service (MaaS) aims to integrate all these publicly available mobility services into one platform, providing centralized planning, booking, and payment (cf. Jittrapirom et al. 2017, Hietanen 2014). By making all mobility services available via a single registration, entry barriers are reduced and even trips with various different mobility services, e.g., by public transport and shared car, can be planned conveniently. The goal of many MaaS systems is to decrease car-dependence and enable users to make better-informed decisions about their mobility behavior. The positive impacts MaaS can have are widely recognized, e.g., by the European Union, which names MaaS as one key element for the creation of a sustainable mobility system (cf. European Commission 2021), and by the German government, which financially supports projects that develop MaaS systems (cf. BMDV 2024).

Likewise, Corporate Mobility as a Service (CMaaS) is a promising concept to support the corporate mobility transition. CMaaS refers to a MaaS system controlled by a company, that provides access to various mobility services with which company members can meet their company-related mobility demand (cf. Hesselgren et al. 2020). Within a CMaaS system, various exclusive mobility services can be provided, i.e., vehicles that are exclusively available to members of the company, like cars, bikes, or scooters that are owned or leased. CMaaS further provides access to public mobility services, which are available to the general public, like shared vehicles and taxis. By integrating exclusive and public mobility services, advantages of both can be utilized by the company. Exclusive mobility services are dedicated to the company and thereby provide flexibility and reliability. Public mobility services incur considerably lower or no fixed costs so that their usage can be scaled according to the fluctuating mobility needs, e.g., shared cars can be used for situations with high corporate mobility demand, avoiding the necessity to maintain additional exclusive vehicles that are only needed during these peak times.

When implementing CMaaS, corporate mobility managers need to make specific decisions regarding exclusive and public mobility services. First, for exclusive mobility services, managers must decide on the exact number and types of vehicles that should be provided by the company. Since exclusive vehicles are long-term investments, this is a strategic decision. Second, for each public mobility service, managers must choose one price tariff offered by the service provider. Herein, managers can usually choose between a basic tariff, with cost elements that are based on usage, e.g., distance-, time-, or trip-related costs, and an active tariff with a fixed membership fee and lower usage-dependent cost elements than in the basic tariff. Since the price tariff selection is typically bound to a minimum contract period, e.g., one month or one year, and cannot be modified at any time, this decision is a tactical decision. The profitability of these decisions depends on the company-specific mobility demand, e.g., the mileages of the trips made as well as the number of total and simultaneous trips. Therefore, the CMaaS configuration must be well aligned with the mobility demand to allow for an optimal outcome, e.g., minimum internal costs, which are the costs that arise to the company from its mobility behavior, and/or minimum environmental and social impacts.

In light of emerging regulatory and organizational priorities, CMaaS offers several opportunities for companies to comply with these new standards. A key driver is the increasing need for companies to report and decrease their Scope 3 emissions, which include GHG emissions from business-related mobility (cf. European Union 2022). These emissions represent a significant portion of the total Scope 3 emissions, e.g., up to 79% in knowledge-intensive organizations (cf. El Geneidy et al. 2021). Importantly, mobility-related emissions are among the most accessible levers for corporate intervention regarding Scope 3 emission reduction, making them a growing focal point in sustainability strategies (cf. Müller 2024). CMaaS can support these efforts by enabling a modal shift away from car use toward micromobility options, i.e., bikes and scooters, leading to reductions in GHG emissions. Beyond environmental benefits, implementations of CMaaS have demonstrated positive impacts on employee satisfaction, highlighting its potential to contribute to workplace well-being (cf. Hesselgren et al. 2020). Moreover, CMaaS can remove access barriers to sustainable mobility services by automatically registering employees for shared mobility, thereby promoting spillover effects into private mobility behavior and extending the system's influence beyond the organization.

However, the implementation of CMaaS systems faces several challenges. One core issue lies in the inherent complexity of CMaaS, which makes it difficult to fully capture and quantify its potential value (cf. Zhao et al. 2020). On the other hand, existing company car schemes represent deeply entrenched employee benefits and incentives, and make it necessary to provide reliable, detailed evidence of advantages in order to overcome institutional resistance (cf. Graus and Worrell 2008). The need for insights into sustainability potentials of CMaaS is therefore high, and until now, no detailed studies or experiences exist. In particular, it remains uncertain, whether the integration of new mobility services ensures reductions in the overall vehicle fleet size or improvements in vehicle utilization. The environmental, economic, and social performance of individual mobility services varies significantly, e.g., battery electric vehicles (BEVs) are environmentally favorable under renewable electricity use, but entail high upfront costs and only become economically competitive with internal combustion engine vehicles (ICEVs) after a certain mileage. Moreover, the inclusion of services such as taxis may even diminish sustainability outcomes due to their relatively high carbon footprint (cf. de Bortoli 2021).

By decreasing the car dependence and diversifying the available mobility services of corporate mobility, CMaaS is a promising concept that could enable a sustainable transformation of corporate mobility. However, the lack of research on CMaaS impedes its implementation. Without further insights into the potentials of CMaaS as well as decision support for the optimal design of customized CMaaS systems, organizations may find it difficult to justify CMaaS adoption internally, and policy-makers may lack the necessary basis to support it through subsidies or regulatory incentives.

1.2 Aim and Structure

Against this background, the main aim of this dissertation is to provide decision-support to companies for the design of their customized CMaaS system and create new insights about the potentials of CMaaS to reduce the negative impacts of corporate mobility. Herein, several research questions (RQs) need to be addressed. First, it must be considered that CMaaS is not a predefined system with a fixed configuration, but its design must cater to the mobility needs of the respective company. The first research question therefore aims at developing a tool that allows corporate mobility managers to determine the optimal CMaaS configurations for their individual company.

RQ1: How can a customized CMaaS system be designed that caters to the individual needs of the company?

By answering Research Question 1, each company can determine its optimal CMaaS design. Accordingly, the sustainability impacts of these diverse CMaaS systems will differ as much as the mobility demands of the companies differ. In order to assess the overall sustainability potentials of CMaaS, an approach is needed that enables the assessment of each individually determined CMaaS system. The second research question is therefore formulated as follows.

RQ2: How can the sustainability potentials of CMaaS be analyzed?

After developing a suitable model to analyze the sustainability potentials of CMaaS, detailed insights into the potentials to decrease negative impacts in each sustainability dimension must be generated. Due to the wide range of possible sustainability aspects, selected key elements are analyzed as representatives of each sustainability dimension. Economic viability, measured as the internal costs of CMaaS in comparison to unimodal car fleets, is a basic requirement for CMaaS, since it will otherwise not be implemented by companies. Within the environmental dimension, the most present topic in the corporate context and beyond is climate change, i.e., GHG emissions. Finally, social impacts of mobility can be quantified as social costs, which reflect the costs that arise to the traveling person as well as to society because of unwanted side effects, e.g., accidents and noise pollution. Research Questions 3a to 3c are formulated accordingly.

RQ3a: Are CMaaS systems economically viable for companies?

RQ3b: Can companies reduce their GHG emissions by implementing a CMaaS system?

RQ3c: What social costs arise to which extent from CMaaS systems?

Answering these three research questions individually gives an idea of the potentials in each sustainability dimension. CMaaS systems might be able to reduce internal costs and GHG emissions, but it remains unclear whether CMaaS can have positive impacts in the three dimensions simultaneously, or whether trade-offs between the dimensions are too pronounced to facilitate such improvements. The final research question therefore addresses the need to derive insights about the overarching sustainability potentials of CMaaS.

RQ4: What overarching sustainability potential can be identified for CMaaS?

To answer Research Questions 1-4, an optimization model needs to be developed that determines the optimal CMaaS designs for companies, reflecting the complex characteristics and interdependencies of exclusive and public mobility services. It should further facilitate the evaluation of sustainability potentials of the determined CMaaS designs by considering internal costs, GHG emissions, and social costs within the objective functions. To analyze the trade-offs between individual objectives, the model must also be able to solve for multiple objectives. Further, the model must be generic and applicable to a high number of companies, while also catering to the individual mobility demands and circumstances of the companies. The model should be validated by applying it to a comprehensive case study with high-quality input data and conducting in-depth scenario analyses. Finally, suitable methods must be identified and adjusted to quantify the internal costs, GHG emissions, and social costs that incur from the use of the regarded mobility services within CMaaS.

Figure 1-1 presents an overview of the two parts included in this dissertation, as well as an integration of the presented research questions into the structure of the dissertation. The Preface gives a general overview of the aim, methodology, and findings of the research. Herein, Chapter 2 presents the current research on CMaaS and previous studies in the context of the research questions. Chapter 3 introduces methods that can be used to determine customized CMaaS designs and analyze sustainability potentials. The applied methodologies as well as the key findings of the research papers are summarized in Chapter 4. Finally, the most important elements of the dissertation are summarized, highlighting the contribution of this dissertation, and elaborating on the practical implications, limitations, and future research in Chapter 5. The Cumulative Part of the Dissertation presents the three research papers in detail (Chapters 6-8).

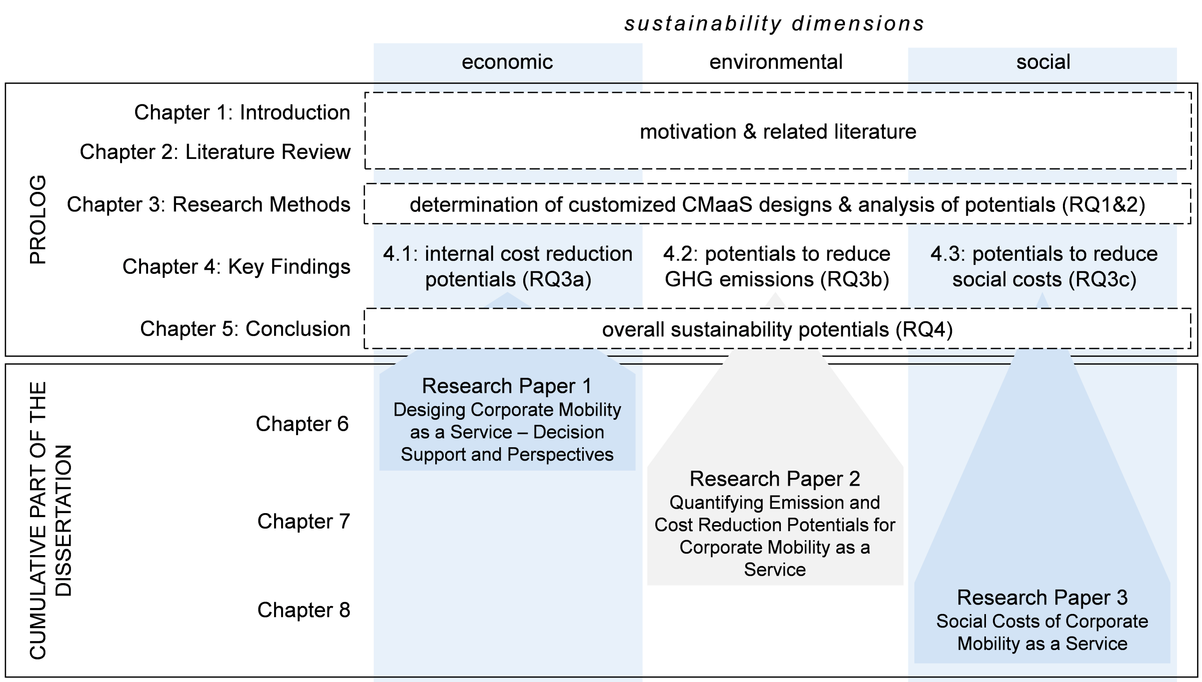

Figure 1-1: Classification of the research questions and papers according to their sustainability dimensions and structure of the dissertation.

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Chapter 2

Literature Review

Several prior studies address comparable research questions to this dissertation, providing solution approaches. The following review introduces the current state of the literature on CMaaS, as well as relevant methods for the presented research questions. First, this chapter gives an overview of CMaaS and related concepts (cf. Section 2.1). The subsequent section presents optimization models that design corporate or public mobility systems (cf. Section 2.2). Further, the state-of-the-art research methods for evaluating internal costs, life cycle GHG emissions, and social costs are presented (cf. Sections 2.3-2.5).

2.1 Introduction to Corporate Mobility as a Service and Related Concepts

MaaS is defined as a platform that integrates all available mobility services in a certain region, providing a single solution for planning, booking, and payment of trips (cf. Enoch and Potter 2023, Sochor et al. 2018, Jittrapirom et al. 2017, Giesecke et al. 2016, Kamargianni et al. 2016). Thus, MaaS systems ideally represent a one-stop interface that delivers a seamless travel experience for a wide range of mobility services (cf. Enoch and Potter 2023). Jittrapirom et al. (2017) further define tariff options, e.g., pay-as-you-go and mobility packages, the need for registration, and customization as core characteristics of MaaS. A wide range of research has emerged in the past ten years since the concept was first introduced by Hietanen (2014). One central field of research discusses how MaaS can be implemented successfully, and how the concept can be developed in the future. These articles put emphasis on the service ecosystem of MaaS (cf. Li et al. 2024, Schulz et al. 2024) and developments towards sustainable MaaS (cf. Enoch and Potter 2023, Hensher et al. 2021). Further studies analyze how MaaS can contribute to a sustainable mobility system, e.g., identifying a sustainable system design (cf. Musolino et al. 2024, Vitetta 2022) and providing simulation-based insights on welfare impacts (cf. Becker et al. 2020). An increasing number of empirical studies analyzes the willingness-to-adopt as well as the potential travel behavior when using MaaS to deduce sustainability-related insights (cf. Ali et al. 2025, Feneri et al. 2022, Lopez-Carreiro et al. 2021, Alyavina et al. 2020, Eckhardt et al. 2020, Jang et al. 2020, Lopez 2020).

As the corporate form of MaaS, CMaaS is a MaaS system that is controlled by a company and whose focus lies on transport within, to, and from a work site or campus (cf. Hesselgren et al. 2020). In contrast to MaaS, research on CMaaS is scarce and insights mainly come from two CMaaS trials that were accompanied by researchers. The main characteristics of the two trials are presented in Table 2-1. The first trial is a large-scale trial in Sweden, addressing 15,000 employees with the implemented CMaaS system and covering a broad range of mobility services. Interviews with the employees reveal high appreciation for the implemented CMaaS system, and that the inclusion of electric bikes evokes a change in travel behavior (cf. Hesselgren et al. 2020). Further, a system thinking approach identifies the key barriers of the trial and finds that the complexity of the system and difficulties in providing an accessible and flexible system limit the value creation (cf. Zhao et al. 2020). Likewise, Vaddadi et al. (2020) show that the shift from the private car to the CMaaS system is hindered by a lack of information. The second trial is based at the Technical University of Chemnitz with 2,500 employees. Günther et al. (2020) find that the introduction of this CMaaS system lead to a reduction of mobility costs by 23-25%. These first insights into the impacts of CMaaS suggest positive effects on the mobility of companies, once its inherent complexity is overcome.

Table 2-1
Key indicators of the two analyzed CMaaS trials.

trial	[1]	[2]
location	Stockholm, Sweden	Chemnitz, Germany
employees	15,000	2,500
company setup	70 buildings at dispersed locations	four locations within and outside the city
CMaaS system	taxi, shuttle bus, commuter bus, shared e-bikes	BEVs, e-bikes, public transport
interface	mobile app	web app

[1] Hesselgren et al. (2020), Vaddadi et al. (2020), Zhao et al. (2020);
[2] Günther et al. (2020)

Traditionally, companies meet their mobility demand by providing company cars to individual employees or a corporate car fleet that is shared internally by employees. Company cars are provided to employees with a high job level or the need to travel, as an incentive that is subsidized by the government in many European countries (cf. Graus and Worrell 2008). Additionally, free fuel cards are often provided to the employees with company cars (cf. Graus and Worrell 2008). Accordingly, studies find that company cars drive annual mileages that are considerably higher than those of average cars, and that the car usage is not only encouraged to the holder, but the holder's entire household (cf. Shiftan et al. 2012, Graus and Worrell 2008). Overall, company cars constitute an important part of the salary in many companies, but impair sustainable travel developments and corporate sustainability efforts. On the other hand, corporate car fleets are usually used by various company members, although the term is not closely defined and might include individually assigned company cars and shared vehicles, as well as passenger and goods vehicles, depending on the context. First studies analyze the adoption of innovations by corporate car fleets, mainly focusing on the integration of electric vehicles. These studies indicate that fleet managers often rely on cost estimates, experience, existing contracts and partnerships, and/or the public image of vehicles, when deciding on the fleet composition (cf. Di Foggia 2021, Mau and Woisetschläger 2018, Nehls 2015). Environmental or social impacts only play a minor role.

Besides CMaaS, further approaches exist that aim at a more sustainable mobility management, e.g., corporate carsharing, mobility budgets, and carbon travel budgets. Current research on corporate mobility mainly focuses on the reduction of the company's carbon footprint, while other sustainability aspects are rarely addressed (cf. Müller 2024, Gorges and Holz-Rau 2021). First works address the advantages of corporate carsharing (cf. Fleury et al. 2017, Boutueil 2016), but find that the complexity of their integration poses a barrier, because the adoption and profitability depends heavily on finding the right scale (cf. Boutueil 2016). To tackle these complexity issues, Frank and Walther (2023) provide an optimization model that facilitates the integration of public and corporate car fleets and find that the vehicle stock in cities as well as relocation efforts can be reduced. Empirical studies find that the easiness to use and the performance expectancy have high impacts for potential users to adopt corporate carsharing, while social influence and environmental friendliness only play a minor or indirect role (cf. Guzmics and Kutzner 2025, Fleury et al. 2017).

Mobility budgets are a solution to cover the employees' mobility demand without specifying or suggesting a specific mobility service to be used. Instead, the traveling employee manages a virtual budget and selects the most efficient combination of travel modes from various multimodal options (cf. Schlegel and Stopka 2022, Zijlstra and Vanoutrive 2018). The basic idea is comparable to CMaaS, i.e., having the choice between various mobility modes will lead to a substitution of trips by car with other modes. A further advantage for the company is that employees need to consider the costs of travel themselves and include them in their decision-making. However, in contrast to CMaaS, a mobility budget is often used for the commuting trips of employees, while business trips are still covered through other corporate budgets. Carbon travel budgets are comparable to mobility budgets and aim at reducing the number of business trips by putting a cap on the overall emissions from business travel (cf. Frers et al. 2022). A recent study shows that social comparisons and a climate-related moral appeal can cause a substitution of car use with micromobility modes, but not with public transport (cf. Gessner et al. 2024). Other measures to promote more sustainable mobility behavior in companies are financial incentives that compensate the disadvantage of using alternative modes of transportation, the provision of facilities, e.g., for e-bike charging, the diffusion of information, and parking management (cf. Van Malderen et al. 2012).

2.2 Strategic Planning of Corporate and Public Mobility Systems

Strategic models to design vehicle fleets include fleet size and composition models, which go back to Dantzig and Fulkerson (1954) and Gould (1969). Dantzig and Fulkerson (1954) propose a model to identify the minimum fleet size to deliver shipments. This model is extended by Gould (1969) who determines the optimal composition of owned and rented trucks of varying sizes and costs. Later models follow their approach and design unimodal, but heterogeneous fleets of freight transport, e.g., rail cars, trucks, or freight planes, while minimizing costs or maximizing profits. Relevant extensions are proposed by Papier and Thonemann (2008), who apply more realistic cost structures in their model, Nair and Acciaro (2018), who do not minimize overall costs but emission abatement costs, as well as Redmer (2015) and Żak et al. (2011) who adjust the objective function to account for maximum utilization. Extensive literature reviews on fleet size and composition models are provided by Baykasoğlu et al. (2019) and Hoff et al. (2010).

Within the literature on fleet design for passenger transportation, an important research area optimizes the design of shared fleets. Model requirements of shared fleets depend on the respective sharing system. Fleet sizing models differ in complexity for station-based roundtrip systems, where vehicles must be returned to the pick-up station (cf. Yoon and Cherry 2018), for station-based one-way systems, where vehicles can be returned to any station (cf. Ahani et al. 2023, Luo et al. 2020, Lemme et al. 2019, Maggioni et al. 2019, Hu and Liu 2016, Frade and Ribeiro 2015, George and Xia 2011), and for free-floating systems, where shared vehicles are provided via public parking spaces and can be returned flexibly within the service area (cf. Weikl and Bogenberger 2013). Aspects regarded in addition to the fleet size are for instance the available sharing station capacities (cf. Hu and Liu 2016), the fleet composition of heterogeneous BEVs (cf. Lemme et al. 2019, Yoon and Cherry 2018), the fleet composition for ridesharing fleets with heterogeneous ICEVs (cf. Wallar et al. 2019), as well as the station locations (cf. Frade and Ribeiro 2015), GHG emissions (cf. Luo et al. 2020), and the stochastic demand of bikesharing systems (cf. Maggioni et al. 2019).

While heterogeneous fleet size and composition models regard various types of the same mobility mode, multimodal fleet design identifies the fleet size and composition of various mobility modes, which typically differ substantially in their characteristics and the way they are used. So far, strategic fleet size and composition models for multimodal fleets do not exist, but first operational models have been introduced, which allow the derivation of strategic decisions. Enzi et al. (2017) propose an integrated optimization model that considers various mobility modes and services, e.g., bikesharing, carsharing, and public transport, including characteristics of BEVs, while minimizing costs and emissions. Enzi et al. (2021) maximize cost savings, while assigning trip requests to a car fleet, which is used for car- and ridesharing. In this model, multimodality is only applied to cover trips that cannot be covered by the car fleet. Finally, Knopp et al. (2021) propose a vehicle scheduling approach in multimodal fleets with a cost-minimizing objective. However, these models do not fulfill the requirements of CMaaS, since they do not regard the different price tariffs offered by public mobility service providers. Further, the models provide computational results, and are not applied to a real-world case.

In contrast to single-objective optimization models, multi-objective optimization models allow to optimize for two or more objective functions. Herein, not only the results of the individual objective functions can be compared, but also intermediary solutions are generated. Only few examples for multi-objective fleet size and composition models exist in the field of passenger transportation. Two studies regard heterogeneous carsharing, and minimize the operation and pollution costs (cf. Lemme et al. 2019), or maximize the benefits of the operator and the users (cf. Boyacı et al. 2015). Within passenger transportation, no multimodal multi-objective model includes life cycle emissions as a dimension, but in freight transport, Sen et al. (2019) minimize life cycle costs, life cycle emissions, and externality costs of air pollution for a fleet of heterogeneous trucks.

2.3 Internal Cost Assessments of Individual Passenger Mobility

Existing studies that quantify the internal costs of mobility mainly use a total cost of ownership (TCO) or a life cycle costing (LCC) approach (cf. Table 2-2). The two approaches have in common that they both evaluate costs over the entire life cycle, including, e.g., operation and disposal in addition to the initial purchase prices, and cover both direct and indirect costs. TCO and LCC are applied to compare alternatives not only based on upfront costs but on their overall economic efficiency. When applying a TCO assessment, the perspective of the buyer or the user is often taken and the regarded products are often consumer goods (cf. Gössling et al. 2022). For instance, various TCO assessments exist to evaluate the lifetime costs of cars, often to compare vehicles with different drive trains (cf. Figenbaum 2022, Parker et al. 2021), but further studies exist for mopeds (cf. Patil et al. 2022, Wortmann et al. 2021).

With LCC, more durable products are usually analyzed whose initial purchase price accounts for a small share of the entire life time costs, and the perspective of the owner or decision-maker is taken (cf. Hoogmartens et al. 2014). Often, the LCC is rather focused on systems and technologies with high investment costs and long runtimes, and is combined with an ecological evaluation (cf. Qiao et al. 2020). Few applications exist in the field of individual passenger mobility and mainly focus on the evaluation of BEVs in a specific regional context (cf. Khaled et al. 2024, Qiao et al. 2020). Other mobility-related applications of LCC are road pavement (cf. He et al. 2020, Yao et al. 2019), as well as freight vehicles and trains (cf. Correa et al. 2024, Zhou et al. 2017, Mitropoulos and Prevedouros 2015).

Table 2-2
Summary of the common methods to quantify internal costs.

example studies	method	internal costs	exclusive mobility	public mobility	flexible mobility behavior
Figenbaum (2022), Parker et al. (2021)	TCO	X	X	-	-
Khaled et al. (2024), Qiao et al. (2020)	LCC	X	X	-	-
Kunsmann and Letmathe (2025)	TCO/TCU	X	X	X	-

TCO and LCC are suitable methods to evaluate the internal costs of exclusive mobility services, but they are not applicable to public mobility services. Accordingly, these methods cannot be applied to CMaaS. One recent publication introduces the concept of total cost of usage (TCU) alongside TCO to compare exclusive and public mobility services (cf. Kunsmann and Letmathe 2025). Although this is an important step for the integrated assessment of exclusive and public vehicles, the TCU takes a static view with underlying assumptions on the lifetime mileage of a vehicle. In contrast, the analysis of CMaaS requires that costs are broken down to fixed and variable costs, so that the overall costs can be adapted to the mobility behavior of specific companies.

2.4 Life Cycle Assessments of Individual Passenger Mobility

The Life Cycle Assessment (LCA) is a standardized method to systematically evaluate the environmental impact of products, processes, or systems along their life cycles (cf. DIN EN ISO 14040:2021-02, DIN EN ISO 14044:2006-07). The selected functional unit of the LCA describes the function of the analyzed product, process, or system, to which the life cycle impacts are put into relation, and is relevant for comparisons between different studies. Common functional units for vehicle-related LCAs are one vehicle kilometer (vkm), i.e., one kilometer driven by a vehicle, and one passenger kilometer (pkm), i.e., one kilometer of transporting one person. Table 2-3 presents a selection of LCAs in the field of individual passenger transportation, describing the analyzed vehicles and the applied functional units. It shows that the most common functional unit among these studies is one passenger kilometer, which allows the consideration of varying transport capacities, e.g., when comparing cars and bikes. Two studies choose a temporal functional unit, analyzing the total life time impacts (cf. Kurkin et al. 2024) or three years of service (cf. Mao et al. 2021), while the remaining studies analyze environmental impacts per vehicle kilometer.

Based on the functional unit, a variety of environmental impacts can be analyzed within an LCA. Most of the studies presented in Table 2-3 analyze multiple environmental impacts. Herein, climate change is the only impact category that is analyzed in all studies, while other often regarded impact categories are resource depletion or resource scarcity, human toxicity, and acidification. However, some studies only analyze climate change (cf. Zhu and Lu 2023, Cheng et al. 2022, Wang and Sun 2022, D'Almeida et al. 2021, Schelte et al. 2021, Amatuni et al. 2020, de Bortoli and Christoforou 2020, Luo et al. 2020, Ding et al. 2019). The prevalence of LCAs comparing exclusive and shared vehicles shows that this method is well suited to analyze multimodal mobility systems with exclusive and public mobility services. Although some studies regard a wide range of mobility modes (cf. Felipe-Falgas et al. 2022, de Bortoli 2021, de Bortoli and Christoforou 2020), no single study regards all relevant mobility services for CMaaS with a common scope and assumptions.

2.5 Social Cost Assessments of Individual Passenger Mobility

The social cost assessment is an approach that aims at monetizing social costs, which consist of costs for the individual mobility user, i.e., internal costs, and costs that incur to society, i.e., external costs. External costs of mobility refer to the unintended and uncompensated consequences of individual mobility-related activities that affect society, but are not directly paid for by the entity causing them (cf. van Essen et al. 2019). Within the external cost assessment, these costs are quantified, typically following certain external cost dimensions. Table 2-4 highlights the most common dimensions, which are accidents, air pollution, climate change, congestion, and noise. Various other dimensions exist, but partly overlap with the five most common dimensions, e.g., well-to-tank emissions (W) usually include pollutants and GHG emissions that are included in the dimensions air pollution and climate change in other studies. Parking (P) is considered as an important dimension when comparing private cars with shared cars or smaller vehicles, like bikes or scooters. It includes the costs of providing parking spaces, e.g., maintenance, surveillance, and/or the land value of the occupied space, as well as incomes from parking tickets.

In the field of individual passenger mobility, only few social cost assessments exist. Instead, studies often focus on external costs exclusively. Examples for social cost assessments are the studies by Schröder and Kaspi (2024), Gössling et al. (2022), De Clerck et al. (2018), and Newbery and Strbac (2016), all of which regard cars exclusively. External cost assessments are conducted more often and studies analyzing multimodal mobility systems already exist. However, these approaches focus on public mobility systems rather than CMaaS and often regard only few mobility modes and services (cf. Maier et al. 2023, Pisoni et al. 2022, Matthey and Bünger 2020). Among the multimodal approaches, the study by Schröder et al. (2023) is particularly broad, analyzing exclusive and shared mobility services, while also including bikes, scooters, mopeds, and motorcycles. Findings identify walking, bikes, public transport, and moped sharing as the mobility services with the least external costs per kilometer. The results indicate that a shift of traveled mileage from cars to bikes, public transport, and/or mopeds decreases the external costs of mobility. No study so far analyzes both internal and external costs for a broad mobility system, but the previous studies show that social and external cost assessments are well suited to analyze systems with exclusive and public mobility services.

The current literature on CMaaS indicates that it can reduce the negative impacts of corporate mobility, but detailed research on sustainability potentials and models for decision support are lacking. Fleet size and composition models display the relevant basic characteristics to determine CMaaS designs, but no model exists that identifies the optimal configuration of multimodal mobility systems, while deciding for the number and types of exclusive vehicles and price tariffs for public mobility services. Sustainability assessments are often only conducted for either exclusive or public vehicles. No established method can be identified that quantifies the internal costs of exclusive and public mobility services, while allowing a flexible corporate mobility behavior. Multimodal mobility systems are analyzed in LCAs and external cost assessments, but no assessment covers all relevant mobility services for corporate mobility. Further, social cost assessments of multimodal mobility systems could not be identified. To answer the research questions presented in Chapter 1, the literature provides basics knowledge about CMaaS and the necessary methods. However, none of the research questions has been addressed in detail, and methods must be newly developed or adjusted significantly to fulfill the requirements of the dissertation.

Table 2-3
Comparison of selected LCAs in the field of individual passenger mobility.

study	specification	functional unit	exclusive mobility	public mobility
car				
Kurkin et al. (2024)	ICEV & BEV (E)	total	X	-
Petrauskienė et al. (2021), Puig-Samper Naranjo et al. (2021)	various drive trains	vkm	X	-
Bouter et al. (2020)	various drive trains	pkm	X	-
Ding et al. (2019)	ICEV & BEV (E+S)	vkm	X	X
moped				
Schelte et al. (2021)	electric (S)	pkm	-	X
bike				
Sun et al. (2023), Zhu and Lu (2023)	electric (S)	pkm	-	X
Cheng et al. (2022), Wang and Sun (2022), D'Almeida et al. (2021)	conventional (S)	pkm	-	X
Mao et al. (2021)	conventional (S)	3yrs service	-	X
Luo et al. (2020), Luo et al. (2019)	conventional (S)	vkm	-	X
Bonilla-Alicea et al. (2019)	conventional (E+S)	vkm	X	X
scooter				
Ishaq et al. (2022)	electric (E)	pkm	X	-
Moreau et al. (2020)	electric (S)	pkm	-	X
Severengiz et al. (2020), Hollingsworth et al. (2019)	electric (S)	pkm	-	X
system analysis				
Felipe-Falgas et al. (2022)	[a]	pkm	X	X
Huang et al. (2022)	ICEV, BEV, e-bike (E)	vkm	X	-
de Bortoli (2021)	[b]	pkm	-	X
Amatuni et al. (2020)	[c]	pkm	X	X
de Bortoli and Christoforou (2020)	[d]	pkm	X	X

(E) = exclusive, (S) = shared
[a]walking, conventional & electric bike (E+S), electric moped (E+S), electric scooter (E), motorbike (E), car (E), bus, train; [b]bike (S), electric scooter (S), electric moped (S); [c]car (E+S), bus, rail, bike (E); [d]bikes and motor scooters (E+S), car (E), taxi, ride-hailing, bus, streetcar, metro and mass rapid transit

Table 2-4
Comparison of selected social and external cost assessments in the field of individual passenger mobility.

		external cost dimensions					
study	analyzed service(s)	accidents	air pollution	climate change	congestion	noise	others
social cost assessments							
Schröder and Kaspi (2024)	BEV^{s}*	X	X	X	X	X	B,L
Gössling et al. (2022)	ICEV^{e}	X	X	X	X	X	B,L,P
De Clerck et al. (2018)	BEV^{e}, ICEV^{e}	X	X	X	X	X	-
Newbery and Strbac (2016)	BEV^{e}, ICEV^{e}	-	X	X	-	-	WP
external cost assessments							
Letmathe and Paegert (2024)	BEV^{es}**	X	X	X	X	X	W
Maier et al. (2023)	BEV^{e}, ICEV^{e}, e-bike^{e}, walking, PT	X	X	X	X	X	B,D,H,W
Schröder et al. (2023)	BEV^{es}, ICEV^{es}, bike^{e}, e-bike^{e}, e-scooter^{s}, moped^{es}, motorcycle^{e}, PT, walking	X	X	X	X	X	B,H,L,P
Pisoni et al. (2022)	ICEV^{e}, bike^{e}, motorcycle^{e}, PT, walking	X	X	X	X	X	D,W
Molloy et al. (2021)	ICEV^{e}	-	X	X	X	-	-
Baumgärtner and Letmathe (2020)	BEV^{e}, ICEV^{e}	-	X	X	-	X	-
Cui and Levinson (2020)	car(average)^{e}, motorcycle^{e}, truck	-	X	X	-	-	-
Matthey and Bünger (2020)	BEV^{e}, ICEV^{e}, moped^{e}, motorcycle^{e}, PT	-	X	X	-	-	L
Gössling et al. (2019)	ICEV^{e}, bike^{e}, walking	X	X	X	X	X	H,M,Q,S,W
van Essen et al. (2019)	ICEV^{e}, motorcycle^{e}, PT	X	X	X	X	X	D,W
Rizzi and De La Maza (2017)	ICEV^{e}, PT	X	X	X	X	X	R
Jochem et al. (2016)	BEV^{e}, ICEV^{e}	X	X	X	-	X	-

^{e}only exclusive, ^{s}only shared, ^{es}exclusive and shared, PT = public transport
B = barrier effects, D = habitat damage, H = health benefits, L = land use, M = traffic infrastructure maintenance, P = parking, Q = quality of life, R = road damage, S = perceived safety, W = well-to-tank emissions, WP = water pollution
*ridesharing, **human-driven vs. autonomous

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Chapter 3

Research Methods

To answer the research questions presented in Section 1.2, the following methods are applied. To design customized CMaaS systems and provide a method to analyze the potentials of CMaaS (RQ1&2), a strategic-tactical fleet size and composition model is developed (cf. Section 3.1). To analyze the potentials of CMaaS to reduce the impacts of corporate mobility in each dimension of sustainability (RQ3a-c), and thereby analyze the contribution of CMaaS to a more sustainable mobility system (RQ4), three sustainability assessments are applied, particularly an internal cost framework, an LCA, and a social cost assessment (cf. Section 3.2). In the following, the goal and approach of all applied methods are introduced.

3.1 Strategic-Tactical Optimization Model

To design CMaaS systems that are customized to the needs of individual companies, a strategic-tactical optimization model is developed that determines the optimal fleet size and composition of corporate fleets. Fleet size and composition models identify the most efficient configuration of a vehicle fleet to meet specific transportation needs (cf. Baykasoğlu et al. 2019, Hoff et al. 2010). The goal is to determine the optimal number, types, and usage of vehicles that minimize costs, emissions, or other relevant performance indicators while satisfying the mobility demand and operational constraints. These models enable organizations to manage complex mobility systems, e.g., CMaaS. Additionally, by identifying the optimal CMaaS configuration and thereby determining the best possible solution based on the defined constraints, the fleet size and composition model enables the analysis of the potentials of CMaaS to fulfill the given objectives.

In this context, fleet optimization involves strategic and tactical decision-making. Strategic decisions refer to long-term, structural choices, such as determining the fleet size and vehicle classes needed. These decisions are typically made infrequently and have lasting implications. Tactical decisions involve shorter-term aspects, e.g., the decision for one of the price tariffs offered by public mobility service providers. Such a decision cannot be changed anytime, but more frequently than strategic decisions. By considering these strategic and tactical aspects, the proposed optimization model supports the decision-making process of corporate mobility managers. At the same time, the optimization model constitutes a tool, with which multiple customized CMaaS systems incorporating different corporate settings, e.g., individual mobility demands, can be designed. When company-specific data of corporate mobility behavior is available for a significant number of companies, the tool can be applied to analyze the overall potentials of CMaaS by deriving general insights from the various individual system configurations.

Optimization models can optimize a single objective or balance several objectives. Single-objective models focus on optimizing one objective function, such as minimizing total costs or GHG emissions. In contrast, multi-objective optimization models consider two or more objectives simultaneously, often revealing trade-offs between the objectives. For instance, minimizing costs and minimizing GHG emissions may conflict, as the most environmentally friendly options are not always the cheapest. Various methods can be applied to solve a multi-objective optimization model (cf. Pinki et al. 2025). The augmented epsilon-constraint method (AUGMECON) addresses this by optimizing one primary objective while converting the remaining objectives into constraints bounded by varying threshold values (cf. Mavrotas 2009). By systematically adjusting these thresholds, the method identifies a set of optimal solutions that balance the different objectives.

Such a set of optimal solutions is typically visualized as a Pareto front, i.e., a curve or surface that depicts all Pareto-optimal solutions. A solution is Pareto-optimal, if no objective can be improved without worsening another (cf. Censor 1977). The Pareto front thus illustrates the trade-off space between objectives. By analyzing the shape and distribution of the Pareto front, decision-makers can evaluate how much they must sacrifice in one objective to gain improvements in another. For example, a steep section of the curve indicates that even small benefits in one objective, e.g., reducing GHG emissions, causes substantial drawbacks in another dimension, e.g., increasing costs, whereas flatter sections suggest more balanced trade-offs. The final choice among Pareto-optimal solutions depends on individual priorities.

3.2 Sustainability Assessments

The methods that are used for quantifying the potentials of CMaaS to contribute to a more sustainable mobility system are explained in the following. To explore whether CMaaS systems are economically viable for companies (RQ3a), an internal cost framework is developed (cf. Section 3.2.1). Potentials to reduce GHG emissions of corporate mobility (RQ3b) are measured via an LCA (cf. Section 3.2.2), and the social impacts (RQ3c) are quantified using a social cost assessment (cf. Section 3.2.3), as presented in Figure 3-1.

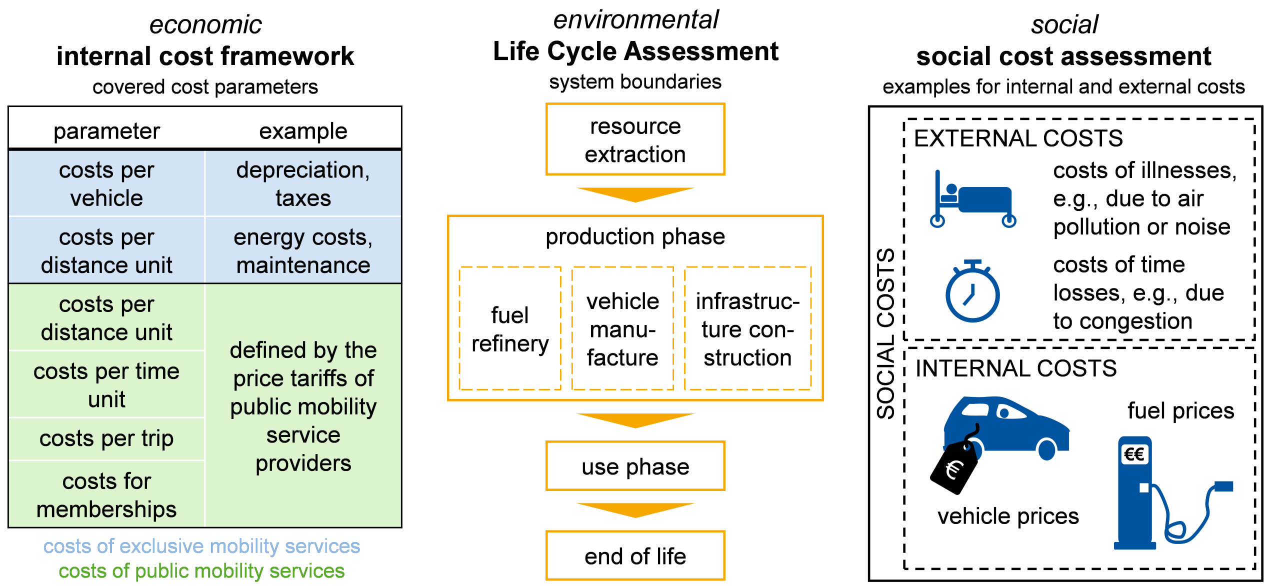

Figure 3-1: Overview of the sustainability assessments.

3.2.1 Internal Cost Framework

The economic viability of CMaaS can be evaluated based on an internal cost assessment. Within this dissertation, a framework is proposed that quantifies the internal costs of CMaaS. First, it accurately represents the cost structures of different mobility services, including exclusive and public mobility services, by distinguishing between fixed and variable cost elements. Second, fixed costs are calculated for representative periods, such as four weeks or one year, allowing flexibility in adapting the results to various company-specific planning horizons. This ensures that corporate mobility managers can project future costs based on their individual needs, including discounting methods and long-term planning. Third, all relevant costs are categorized into specific cost parameters.

The proposed internal cost framework consists of various cost parameters that differ for exclusive and public mobility services as presented in Figure 3-1. For exclusive mobility services, fixed costs incur per vehicle for each time period, regardless of usage, covering expenses such as depreciation and insurance. Additionally, variable costs arise per distance unit, including fuel or electricity consumption. In contrast, the costs of public mobility services are determined by the selected price tariffs. For instance, a basic price tariff typically does not include fixed costs, but variable fees are charged per trip, time unit and/or distance unit. With an active price tariff, these variable costs are usually lower than in the basic tariff, but an additional fixed membership fee is charged. The specific cost values for exclusive mobility services are influenced by factors such as vehicle prices, insurance rates, taxes, and energy costs, whereas public mobility service costs are set by the respective service providers. The overall internal costs of a company are quantified according to the usage structures of all used vehicles.

3.2.2 Life Cycle Assessment

Within the environmental sustainability dimension, the LCA is an established method to evaluate the GHG emissions of mobility. The goal of an LCA is to evaluate the environmental impacts associated with a product, service, or system throughout its entire life cycle. This includes all stages from raw material extraction, production, and use to end-of-life treatment such as disposal or recycling. The purpose is to identify the most significant environmental burdens, support decision-making, and improve sustainability by comparing alternatives or optimizing processes. An LCA is conducted within a structured framework that contains four phases, defined by international standards, i.e., DIN EN ISO 14040:2021-02 and DIN EN ISO 14044:2006-07, on which the following explanations are based.

The first phase contains the goal and scope definition. The goal refers to the intended application and the reasons to conduct the assessment. Within the scope, the analyzed product system, system boundaries, functional unit, as well as further assumptions, requirements and limitations are defined. The system boundaries define the stages within the life cycle that are covered by the LCA and should be as inclusive as possible. The functional unit is a clearly defined measure of the function that the analyzed product, service, or system provides. It serves as the basis for quantifying inputs and outputs, and allows for a consistent comparison between alternatives. Typical examples for functional units of LCAs in passenger mobility are listed in Section 2.4.

The inventory analysis involves the systematic collection and quantification of input and output data associated with the life cycle of the product system. This includes the material and energy flows entering and leaving the system boundaries across all life cycle stages. Inputs can include resources such as fossil fuels, water, and raw materials, while outputs consist of products, emissions to air, water, and soil, as well as waste. A consistent and transparent procedure of data collection is essential to ensure the reliability and reproducibility of the assessment.

Within the impact assessment, inventory data are translated into environmental impact categories to evaluate the potential consequences of the system's resource use and emissions. This step involves the classification, where inventory flows are assigned to relevant impact categories, e.g., climate change, eutrophication, or acidification, and the characterization, which applies scientifically derived factors to quantify the contribution of each flow to the respective impacts. For example, GHG emissions defined as outputs in the inventory analysis, e.g., CO_2, CH_4, and N_2O, are converted into CO_2-equivalents using the impact category climate change. Depending on the goal and scope of the study, the impact assessment may also include further elements, e.g., normalization, grouping, and weighting, which help contextualize the magnitude of impacts and support decision-making.

The interpretation phase of an LCA synthesizes the results of the inventory assessment and the impact assessment, aiming to derive meaningful conclusions that align with the goal and scope of the LCA. In this context, limitations should be explained, e.g., evaluating data quality and methodological choices, and conducting sensitivity, uncertainty, and completeness checks. This phase also facilitates the communication of results to stakeholders by deriving recommendations for decision-makers from the conclusions drawn.

To analyze the life time GHG emissions of CMaaS, the LCA approach in this dissertation takes a system perspective. Since the GHG emissions for various vehicles with differing characteristics need to be determined, the goal and scope definition is identical for all analyzed mobility services. Further, the system boundaries include processes that are often omitted in unimodal LCAs, as presented in Figure 3-1. For instance, the need for road and charging infrastructure differs for exclusive and shared mobility services, or for vehicles with different drive trains. Since the analyzed CMaaS system includes mobility services with varying transport capacities, e.g., bikes and cars, the functional unit is selected to be one passenger kilometer.

3.2.3 Social Cost Assessment

A method, which enables a broad coverage and quantification of the various social impacts of mobility, is the social cost assessment. It aims at comprehensively evaluating the total costs that a product, activity, or system imposes on society. These social costs consist of internal costs, which are borne directly by the users or providers of the system, e.g., fuel costs, maintenance costs, or parking fees, and external costs, which arise as indirect consequences of the system's operation and are not reflected in market prices (cf. Figure 3-1). The objective of a social cost assessment is to inform decision-makers about the full societal burden of a given activity, such as corporate mobility behavior, and to provide a foundation for designing effective policies that promote sustainable and economically efficient outcomes (cf. Santos et al. 2010). Internal costs can for instance be quantified by the internal cost framework presented in Section 3.2.1.

An external cost assessment typically takes a life cycle perspective and focuses on several key impact dimensions. The most commonly regarded external cost dimensions in the mobility-related assessments are accidents, air pollution, climate change, congestion, and noise (cf. Section 2.5), which are defined by van Essen et al. (2019). Accident costs are the material and immaterial costs that arise from accidents, e.g., vehicle damage and a reduced lifetime. Air pollution costs include the health and environmental damages from particulate matter, e.g., respiratory diseases and biodiversity loss. External costs of climate change incorporate the long-term effects of GHG emissions. Congestion costs refer to delays and productivity losses due to traffic, and noise costs to health damages and reduction of well-being due to traffic noise, e.g., heart diseases and annoyance. In general, only costs are regarded which are not covered by insurances, i.e., which are not internalized. To analyze CMaaS, these dimensions are all integrated into the assessment. Further, due to the intensifying discourse in cities about spatial justice (cf. Agora Verkehrswende 2022), the external cost assessment of CMaaS includes parking-related external costs, considering land value, operational expenses for parking spaces, as well as potential revenue from parking fees and special usage fees of shared vehicle parking, further developing previous approaches of Letmathe and Paegert (2024) and Schröder et al. (2023).

The quantification of these external costs generally follows a cost-factor approach, in which activity-specific emissions or effects, e.g., grams of CO_2 per kilometer or accident rates per vehicle kilometer, are multiplied by corresponding cost factors. These cost factors are typically standardized by governmental or academic institutions and reflect average damage estimates per unit of emission or activity, e.g., in Matthey and Bünger (2020) and van Essen et al. (2019). A methodological distinction is made between average and marginal external costs. Average external costs represent the total external costs divided by the total output or activity, e.g., the total external costs per vehicle kilometer traveled. This approach provides an overview of the overall burden of a system. In contrast, marginal external costs refer to the additional costs incurred by one more unit of activity, e.g., the cost of one additional kilometer driven. Marginal cost assessments are particularly important for policy design, as they indicate the societal impact of incremental changes in system usage and are commonly more relevant to design internalization policies than average costs (cf. van Essen et al. 2019). Therefore, marginal costs are applied in this dissertation to analyze the impacts of shifting from unimodal car fleets to CMaaS.

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Chapter 4

Key Findings

This chapter summarizes the approaches and main findings of the three research papers. All research papers analyze the potentials of CMaaS by juxtaposing the results of a sustainability-related assessment of CMaaS with the results for unimodal car fleets, applying an optimization model, which is adjusted to the requirements of each analysis. Each of the research papers conducts a comprehensive case study, which enables the deduction of general insights about CMaaS. Within the case study, a data base of 144 companies is analyzed, which provides detailed information about more than 46.000 trips conducted by corporate cars (cf. Fraunhofer 2021). The individual trip data of each company is regarded as the representative mobility demand, and forms the basis for determining the customized CMaaS designs. Further, the same mobility services are regarded in each research paper. Mobility services that are identified as relevant for corporate mobility are fossil-fueled cars (ICEV), electric cars (BEV), electric bikes, and electric scooters (cf. Table 4-1). All of these vehicles are available as owned, leased, and shared vehicles. Further, ICEVs can be used via a taxi service. Buses, trams, and other public transport is not available for all companies in the same quality, and comprehensive assumptions would be necessary to produce results. Therefore, public transport is not included to guarantee the quality of the results. When modeling CMaaS systems, they can be designed from all mobility services presented in Table 4-1, while unimodal car fleets can only consist of exclusive ICEVs and BEVs. Within the analyses, results are distinguished for companies from rural and urban regions (Research Papers I and II), or from cities, towns, and rural areas (Research Paper III). Basing each case study on the same data base facilitates comparisons across the three papers, although it should be noted that the required data are updated in each research paper, so that the data basis differs across the studies.

Table 4-1
Mobility services regarded to design customized CMaaS systems.

	exclusive mobility services		**public mobility services**	
	owned	leased	shared	taxi
car ICEV	X	X	X	X
car BEV	X	X	X	-
electric bike	X	X	X	-
electric scooter	X	X	X	-

Figure 4-1 presents the research design of the dissertation, depicting the aims and methods applied in each research paper. The first research paper develops a strategic-tactical optimization model for designing CMaaS and analyzes the economic viability for companies (cf. Section 4.1). The second research paper develops the optimization model into a multi-objective model and assesses the impacts on internal costs and GHG emissions (cf. Section 4.2). The third research paper analyzes the social costs of CMaaS, adjusting the optimization model accordingly (cf. Section 4.3).

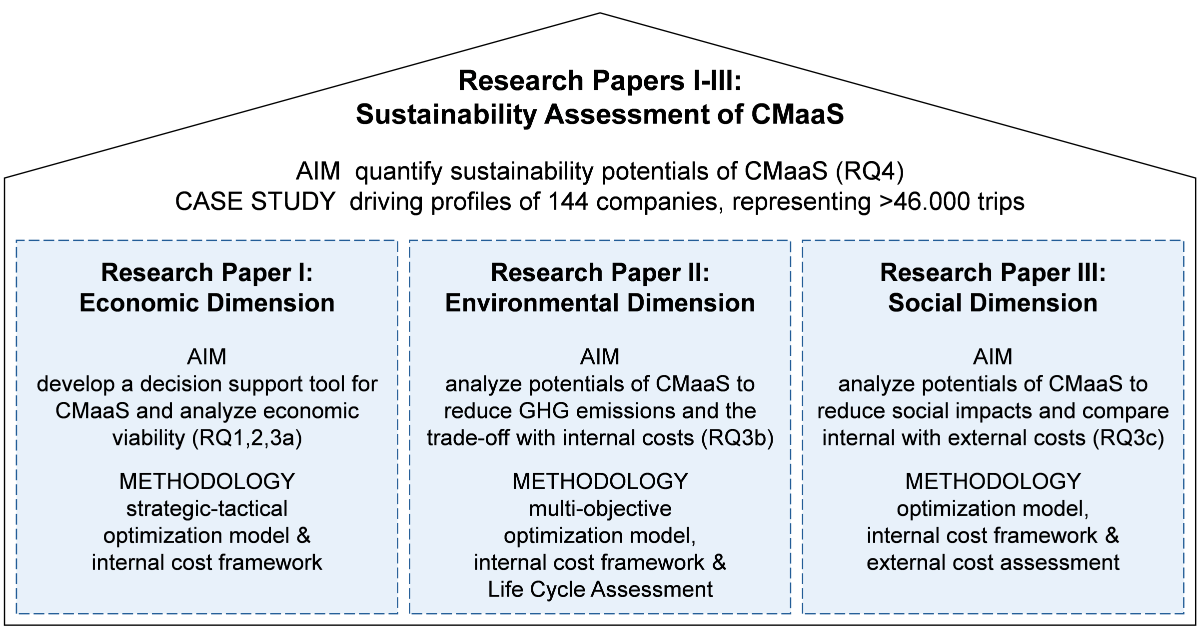

Figure 4-1: Approach of the dissertation, illustrating aims and methods of the three research papers.

4.1 Research Paper I

The first research paper develops a strategic-tactical optimization model, which provides decision support for corporate mobility managers by determining the cost-minimal CMaaS design for a given mobility demand. Strategically, the model determines the optimal fleet size and composition for company-exclusive mobility services, selecting the number and type of vehicles based on mobility mode (car, bike, scooter), drive train technology (ICEV, BEV, electric), type of provision (owned, leased, shared, taxi), and size (small, medium, large). Tactically, the model determines the cost-minimal price tariffs for public mobility services, balancing fixed membership costs with consumption-dependent pricing. The model guarantees that the given individual mobility demand of the company is met, allocating mobility services and vehicle classes to expected trips without performing detailed vehicle routing, instead ensuring that a sufficient number of appropriately equipped vehicles are available at all times. Further, to avoid an overestimation of the impacts of micromobility modes, e.g., bikes and scooters, the model considers the fact that not all employees might be willing to use these modes and includes a parameter that defines the maximum share of trips for which these modes are considered. Finally, technical restrictions of the vehicles, spatial restrictions at the company location for the exclusive fleet, vehicle availability of public mobility services, and transport capacity requirements are considered. To quantify the internal mobility costs, the cost framework presented in Section 3.2.1 is applied.

The main finding of the first research paper is that the implementation of CMaaS is profitable for each of the 144 analyzed companies, with cost savings ranging between 10% and 80% (25% on average). While fixed costs can be decreased substantially, anticipated variable costs increase slightly, since trips are shifted to public mobility services. Companies with few trips register the highest cost savings, since their vehicles usually have low utilization rates in unimodal car fleets. With CMaaS, utilization rates of exclusive vehicles increase by factor four.

Cost savings are achieved by a more versatile usage of mobility services. The majority of trips is still made by exclusive car, 18% of the trips are made by shared car, and 5% of the trips are made by exclusive and shared bike, respectively. Taxi and scooter trips play a subordinate role, although more than 40% of the companies use taxis at least once in the representative period of four weeks. Because of their low costs in comparison to cars, bikes have a considerable effect for reducing corporate mobility costs. At the same time, the open-mindedness of employees towards micromobility modes, like bikes and scooters, for business trips has a substantial impact. The assumptions for the willingness to consider micromobility for a certain trip and the maximum driving distance are based on prior studies and selected to be rather conservative. In a scenario analysis, the effects of less conservative values are analyzed, showing an especially strong impact of the willingness to use micromobility, and to a lesser extent also for the considered maximum driving distance. Cost decreases are almost 30% higher when employees consider micromobility for each trip.

Besides bikes, shared cars are used by most companies. The analysis shows that shared cars can be applied during peak hours, when exclusive vehicles are fully booked, or when the overall mobility demand is too low for exclusive cars to be more beneficial than shared cars. The study further shows that the currently limited availability of cars at carsharing stations results in a bottleneck. With more shared cars available, companies could further realize cost-saving potentials. The choice of price tariffs for shared vehicles depends on the mobility service and the driving behavior. Companies that use shared BEVs more than ICEVs are more likely to choose the active price tariff. For bike- and scootersharing, the active price tariff is rarely beneficial.

4.2 Research Paper II

In the second research paper, the optimization model developed in Research Paper I is further developed into a multi-objective model, minimizing GHG emissions in addition to internal mobility costs. The augmented epsilon-constraint method (AUGMECON) is applied as explained in Section 3.1, yielding insights about the trade-off between internal costs and GHG emissions of CMaaS and unimodal car fleets. Further, an LCA is conducted to quantify the GHG emissions for each mobility service per passenger kilometer. Within the system boundary of the LCA, all relevant life cycle stages are regarded: resource extraction, production, use, and end-of-life processes. Within the production phase, fuel refining, vehicle manufacturing, and infrastructure construction are covered. Unlike many prior LCAs, road space and charging infrastructure are also accounted for. This inclusion is particularly relevant for shared mobility services, as these typically require less parking space than exclusive vehicles, but dedicated sharing stations. The study quantifies GHG emissions in terms of CO_2 equivalents, applying the ReCiPe Midpoint (E) impact assessment method.

The findings suggests that CMaaS is more beneficial than unimodal car fleets, since all companies achieve internal cost and GHG emission reductions with CMaaS. However, the extent of the savings depends significantly on the companies' priorities. In the following, the results refer mainly to the two extreme points, i.e., cost-minimization as the primary objective and minimization of GHG emissions as the primary objective.

When comparing the cost minimum of CMaaS with the cost minimum of unimodal car fleets, all analyzed companies experience cost and GHG emission reductions, which on average amount to 43% and 2%, respectively. This result suggests that CMaaS can support economic and environmental goals, although cost savings do not necessarily lead to high GHG emission reductions. When prioritizing GHG emission minimization and juxtaposing CMaaS with unimodal car fleets, all companies successfully lower their GHG emissions by on average 8%, but cost reductions vary, increasing by 9% on average. Companies with fewer trips tend to see cost savings, while those with higher travel demand experience cost increases. Further analyses indicate that the total mileage in a company's driving profile is the primary factor influencing the extent of cost and GHG emission changes.

Achieving reductions in one dimension typically comes at the expense of the other dimension. The Pareto front of CMaaS shows that a 30% increase in costs from the cost-minimal point of the CMaaS system allows for a 46% reduction in GHG emissions. This relation is similar in the Pareto front of unimodal car fleets, but CMaaS consistently achieves lower absolute GHG emissions. If companies apply the cost minimum of unimodal car fleets to CMaaS, GHG emissions are less than half of those of unimodal car fleets. Thus, using CMaaS allows for GHG emission reductions of 50% while maintaining the costs of cost-minimal unimodal car fleets. Further reductions of GHG emissions are less pronounced and come at a considerable cost. The minimum GHG emissions achievable with CMaaS are 53% lower than in the cost-minimum of unimodal car fleets, while costs increase by 86%.

The research also identifies key mobility services that companies utilize to minimize costs or GHG emissions. When minimizing costs primarily, the services that are used by most companies are bikesharing and leased ICEVs. Shared cars are used for both, ICEVs and BEVs, and taxis are used by many companies, but only for few trips. In contrast, when minimizing GHG emissions primarily, nearly all companies use leased electric cars as well as owned bikes, and 83% use shared cars, mostly with BEVs. The greater variety of services in the cost-minimal point suggests that cost differences among mobility options are less pronounced than the differences in GHG emissions. However, a major limitation for the minimization of GHG emissions is the restricted availability of shared BEVs, which are fully booked in 41% of all time intervals. Accordingly, as companies shift from the cost-minimal point to the emission-minimal point, the number of trips with BEVs and owned bikes increases sharply, while the use of leased ICEVs, shared bikes, owned scooters, and taxis declines. Shared BEVs increasingly replace leased BEVs and shared ICEVs, and owned bikes consistently make a high share of trips.

In a scenario analysis, the study further analyzes the impacts of different policy strategies on the cost- and emission-saving potentials of CMaaS. Among the analyzed strategies, promoting the usage of micromobility modes like bikes and scooters is the most effective in further reducing the minimum emissions, achieving up to 23% lower emissions in the cost minimum and up to 45% lower costs in the emission minimum. Low-emission zones deliver the highest GHG emission reductions in the cost-minimal point, but cause a cost increase of 19%. In contrast, improving charging infrastructure reduces both costs and GHG emissions moderately without significant trade-offs. Expanding services with shared cars improves cost efficiency, reducing costs by up to 18% by increasing the availability of shared vehicles and the proportion of BEVs in shared cars. Overall, policies enhancing micromobility, charging infrastructure, and shared mobility services present the most balanced approach for reducing costs and GHG emissions, while low-emission zones, despite their high environmental benefits, impose financial burdens on companies.

4.3 Research Paper III

The third research paper analyzes the potential of CMaaS to reduce the social impacts of corporate mobility by adapting the optimization model to minimize external costs and social costs in addition to internal costs. The three objective functions are optimized independently of each other, so that a comparison between the three optima is possible. The internal costs are quantified according to the internal cost framework described in Section 3.2.1. To quantify the external costs of CMaaS, an external cost assessment for each regarded mobility service is conducted. The external costs are then aggregated in proportion to the kilometers driven with each mobility service to quantify the company-specific external costs of mobility. The assessment regards six external cost dimensions: accidents, air pollution, climate change, congestion, noise, and parking. The social costs of mobility amount to the sum of external and internal costs.

The external cost assessment of the individual mobility services reveals significant differences in both the magnitude and composition of external costs. Taxis incur the highest external costs at 24 cents per kilometer, primarily due to their contributions to climate change and congestion, while other car-based services range between 16 and 20 cents, with parking accounting for up to 31% of the total. Exclusive bikes have the lowest external costs at 6 cents per kilometer, whereas exclusive and shared scooters incur higher costs with about 14 cents per kilometer. With a share of 88-96%, accidents are the main driver of external costs of bikes and scooters. Notably, shared bikes and scooters have higher external costs than their exclusive equivalent due to emissions from vehicle relocation. Regionally, cities incur higher external costs than towns and rural areas for car-based services, especially due to increased parking-related impacts, while no regional differences are identified for bikes and scooters.

The optimization results show that implementing CMaaS can significantly reduce internal, external, and/or social costs, depending on the optimization objective, compared to unimodal car fleets. When companies minimize their internal costs, internal costs drop by 28% and external costs by 4%, primarily through reduced parking impacts due to a modal shift toward shared vehicles and micromobility. However, accident-related costs increase. Minimizing external costs leads to a 21% reduction in external costs, mainly in the dimensions parking, climate change, and air pollution, but internal costs more than double, resulting in an overall 18% reduction in social costs. When optimizing the social costs, external costs decrease similarly by 21%, with internal costs rising by 25%, yielding the highest social cost reduction of 20%. This scenario results in a dominant use of shared BEVs (82% of mileage), supplemented by bikes and a small share of other modes.

Across all scenarios, taxis and scooters play a negligible role, contributing less than 0.2% of total mileage or being entirely unused. When minimizing external costs, companies require a larger exclusive fleet dominated by BEVs and electric bikes. In contrast, minimizing internal and social costs allows for substantial reductions in the car fleet of 69% and 80%, respectively, when compared to unimodal car fleets. The overall fleet size reduction, i.e., including the number of exclusive bikes and scooters, amounts to 63% when minimizing internal costs and 46% when minimizing social costs. Shared cars remain a key mobility service across all objectives, consistently utilized via the active tariff, while shared bikes and scooters are primarily used when minimizing internal and social costs. Herein, they are typically used with the basic price tariff. When minimizing external costs, shared bikes and scooters are not used at all. Further, the analysis reveals that external costs per kilometer vary notably with the regional setting, with rural areas consistently showing 26–31% lower external costs than cities across all objectives. This difference arises from region-specific factors influencing certain external cost dimensions.

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Chapter 5

Conclusion

This dissertation develops a decision-support tool for corporate mobility managers that determines customized CMaaS systems and enables the evaluation of their potentials to contribute to a sustainable mobility system. Further, sustainability assessments are conducted to identify the relevant economic, environmental, and social parameters. Herein, an internal cost framework is developed to identify the mobility costs that arise to the company that implements CMaaS, an LCA is applied to quantify the GHG emissions from CMaaS, and a social cost assessment is conducted to describe the social costs that incur to society from the mobility behavior of the regarded company. The following sections evaluate the research presented in this dissertation. Section 5.1 discusses the methodological and contentwise contribution. Further, Section 5.2 summarizes the overall sustainability potential of CMaaS and highlights practical implications of the research for corporate mobility managers and political decision-makers. Finally, Section 5.3 reflects on the limitations of the dissertation and identifies knowledge gaps that should be addressed in future research.

5.1 Contribution

This dissertation contributes to the literature with newly or further developed methods as well as new insights into the potentials of CMaaS. First, a fleet size and composition model is developed that determines the strategically optimal size and composition of a company's exclusive multimodal fleet, as well as the tactically optimal selection of price tariffs for public mobility services. It is the first tool to model both strategic and tactical CMaaS decisions while accounting for diverse structural factors such as spatio-temporal demand, costs, vehicle availability and restrictions, as well as micromobility acceptance. This model is proposed as a single- and bi-objective model, and serves as a decision-support tool for corporate mobility managers, that supports them in designing their customized CMaaS systems. Thereby, the proposed model facilitates a wide implementation and further analyses of CMaaS systems in the future. Second, a structured internal cost framework is developed, which considers the relevant requirements of CMaaS. It can be applied to other contexts, in which both exclusive and public mobility services are analyzed. Finally, a comprehensive framework to calculate external costs of parking is developed based on previous approaches, considering both exclusive and public mobility services. This approach is the first to take the land value, prices for parking tickets, as well as special usage fees for shared vehicle parking into account.

Contentwise, this dissertation contributes to the scarce literature about CMaaS. It presents the first comprehensive sustainability assessment and provides insights into the potentials of CMaaS to contribute to a more sustainable mobility system. Within the analyses, the properties of various different mobility services are considered, and results are differentiated for companies from different regional settings, describing how the design of CMaaS depends on the regional context. Taking a comprehensive data base of the corporate trips of 144 companies as a basis for the analysis, general results for CMaaS are provided that evaluate the potentials to reduce internal mobility costs, GHG emissions, and social costs. The presented insights help political decision-makers to make better-informed decisions about our future mobility system, and to decide whether to promote the wider implementation of CMaaS in companies.

5.2 Practical Implications

Implementing CMaaS shows notable sustainability benefits, including average reductions of 25% in internal costs, 53% in GHG emissions, and 20% in social costs when each respective indicator is minimized and compared with the cost-minimal setting of unimodal car fleets. Additional advantages of CMaaS include higher fleet utilization and smaller exclusive vehicle fleets. Bikes and shared cars, in particular, demonstrate consistent benefits across all sustainability dimensions and play crucial roles in optimized CMaaS systems, even under consideration of a limited willingness by employees to use bikes. Scenario analyses indicate that further sustainability gains can be realized by increasing the attractiveness of bike usage, increasing the number of available shared cars, as well as reducing the costs and improving the performance of BEV-related technologies. Nonetheless, even under varying optimization goals, a substantial share of trips still relies on exclusive cars. The share of trips made with exclusive cars ranges from 21% with minimized social costs to 73% with minimized internal costs. Herein, exclusive BEVs play a crucial role in CMaaS systems with minimum environmental and social impacts, while ICEVs are mostly used in the internal cost minimum.

From the presented results, the following recommendations can be derived for corporate and political decision-makers. Since consistent and substantial cost reduction potentials for companies could be identified and a decision-support tool to design customized CMaaS systems is provided, corporate mobility managers should consider to implement CMaaS by applying and adapting the developed optimization model to their individual requirements and evaluate the specific benefits for their company. Companies that have to report and decrease their Scope 3 emissions should further analyze their individual potentials to reduce GHG emissions. To maximize the internal cost and GHG emission reductions, mobility managers should provide the required infrastructure for bikes and shared cars, and ensure that booking, access, and usage is at least as convenient as for exclusive ICEVs. Finally, the willingness of the employees to use bikes has substantial influence on internal cost and GHG emission saving potentials. Therefore, corporate mobility managers should put a central focus on increasing this willingness.

From a political perspective, decision-makers should facilitate the adoption of CMaaS to achieve a reduction in environmental and social impacts, e.g., by removing regulatory barriers and promoting collaboration with public MaaS providers. However, facilitating the use of CMaaS alone does not necessarily capture all sustainability potentials of CMaaS, since internal cost-minimizing companies still conduct a high share of trips with exclusive ICEVs. Therefore, policymakers should reassess car-related policies, e.g., parking fees, and encourage the use of mobility modes with low emissions and social costs, e.g., bikes, shared cars, and BEVs. Effective measures highlighted in this research are an improvement of the road infrastructure for bikes, a denser network of carsharing stations improving the availability of shared cars, or low-emission zones that panel the use of ICEVs.

5.3 Limitations and Future Research

The presented research is subject to some limitations, which also highlight the potentials for future research. First, restrictions arise due to limited data availability. While internal cost data for exclusive and public mobility services are openly accessible online, LCAs and social cost assessments require differentiated and detailed information for a broad range of data points. For the conducted LCA and social cost assessment, not all required data are available and some assumptions are made to compensate for this lack of data. Further, since comparable assessments of multimodal mobility systems in the corporate context have rarely been conducted so far, results could not be verified comprehensively. However, the available studies indicate that the presented results are in line with prior findings.

Second, not all facets of the individual situation of companies could be covered in the presented analyses. The aim of the dissertation is to develop a generic and transferable method for the design of CMaaS and to analyze the potentials of CMaaS to reduce negative impacts of corporate mobility. Therefore, the model and assessments were implemented for a dataset with the mobility demand of 144 companies, and no verification or validation was done based on more detailed information of a single company or by performing an empirical analysis of CMaaS implementation in one specific context. The presented model determines the optimal system configurations of CMaaS, anticipating the mobility behavior based on a fixed value for micromobility acceptance. On the one hand, this value might differ across the analyzed companies, and on the other hand, the anticipated mobility behavior does not necessarily coincide with the real mobility behavior of the company members. Further, the specific spatial setting of the company influences the availability of mobility services. While it is assumed that all regarded mobility services are available to all analyzed companies, some mobility services might not be accessible in certain areas, e.g., shared scooters, or additional mobility services are available, e.g., public transport.

Therefore, instead of analyzing a broad range of anonymized companies, conducting a real-world CMaaS trial based on the developed optimization model could yield important insights about the real requirements and feasibility of CMaaS systems. Such a trial enables the consideration of the available mobility services, the employees' attitudes towards the usage of the different mobility services, and other structural factors that are specific to the individual case. Empirical research that accompanies the trial could provide information on the real reductions of sustainability impacts and juxtapose them to the potentials identified in this dissertation.

Future research could generate further knowledge about CMaaS by widening the scope of the analysis and including additional mobility concepts. First, it should be analyzed how commuting trips influence the potentials of CMaaS to improve sustainability potentials. Including not only business trips, but also trips from home to the work place in the analysis could highlight additional potentials to increase the efficiency of CMaaS systems. Since individually assigned company cars can often be used for private trips, it would be interesting to further analyze synergy effects with private mobility demand. If CMaaS systems include subscriptions to public mobility services, e.g., bikesharing, employees might also replace private car trips with public mobility services. Second, other mobility services should be included in future analyses. For instance, companies could own a fleet of internally shared vehicles, which are rented out to the public after office hours, thereby increasing the fleet's utilization rate and generating cash flows. Further, the inclusion of public transport would give insights into its role for decreasing sustainability measures within CMaaS systems. Therefore, additional data on the quality of public transport connections of the company locations could be surveyed and integrated into the proposed optimization model alongside the respective internal cost, GHG emission, and social cost data.

Part II

Cumulative Part of the Dissertation

Chapter 6

Designing Corporate Mobility as a Service - Decision Support and Perspectives

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Abstract

Corporate Mobility as a Service (CMaaS) integrates company-exclusive fleets and public mobility services, such as car sharing, bike sharing, or taxis, into one multimodal mobility system. As a result, companies may reduce their own vehicle fleet, their total mobility costs, as well as their emissions by shifting trips to alternative mobility modes. Against this background, we present a strategic-tactical decision support tool for corporate mobility managers to design a CMaaS system. We include strategic decisions on the fleet size and composition of company-exclusive fleets. The fleet composition addresses decisions on the inclusion of various mobility modes, e.g., cars and bikes, as well as on the choice of vehicle classes, e.g., regarding drive train technologies, and on how these vehicles are provided to the company, e.g., leased or owned vehicles. Further, we include tactical decisions on the choice of price tariffs offered by public mobility providers. Herein, our decision support tool accounts for structural requirements, such as the spatio-temporal corporate mobility demand, costs, upper bounds on the number of vehicles, technical vehicle restrictions, and the use of micromobility modes, like bikes and scooters. Finally, a comprehensive case study with ten mobility services and driving profiles of 144 companies enables us to draw general insights on the current and future potentials of CMaaS. Results promise average cost savings of 33 % and a shift of 21 % of trips to public mobility services.

6.1 Introduction

Striving for climate-friendly and sustainable mobility that is also cost-efficient, current mobility innovations are immensely changing our mobility behavior. We are observing a paradigm shift towards mobility that is less dependent on owning a car. Instead, app-based multimodal systems gain importance. Also referred to as Mobility as a Service (MaaS), these systems integrate public mobility services, like vehicle sharing, public transportation, and taxi services, into one platform (cf. Hietanen 2014, Jittrapirom et al. 2017). First pilots prove that MaaS can increase resource efficiency, improve accessibility, reduce costs, shift the demand away from the private car, and incentivize the use of low-emission mobility modes (cf. Sochor et al. 2018, Eckhardt et al. 2020).

However, not only private individuals, but also companies are rethinking their mobility behavior. In this regard, Corporate Mobility as a Service (CMaaS) conceptualizes multimodal mobility systems that offer a variety of mobility options to employees. In the past, many companies already changed their mobility management from classic company cars that are used only by one employee to corporate car fleets that are available to several or all employees. CMaaS is now even going further by complementing the so-far car-based fleets. Herein, CMaaS offers additional micromobility modes, such as bikes and scooters, and further aims to integrate public mobility services, like vehicle sharing or taxis. In contrast to the company-exclusive fleets that may only be booked by employees of the company, the public mobility services may also be booked by other users.

CMaaS provides potentials for companies, for public mobility providers, but also for the society as a whole. Companies may, for example, reduce their emissions by shifting trips to low-emission mobility modes, thereby meeting their environmental, economic, and public relation objectives. Further, while company-exclusive mobility services promise a high flexibility and reliability for employees, public mobility services incur considerably lower or no fixed costs for companies. In addition, the fleet size and idle times of company-exclusive vehicles can be reduced by shifting the corporate mobility demand partly to public mobility services, especially during corporate peak periods. Moreover, the providers of public mobility services can improve the efficiency of their fleet, as corporate mobility demand tends to be asynchronous with the existing private demand of these systems (cf. BMVI 2018, Giordano et al. 2021). Finally, the society benefits, as an increased use of shared and low-emission vehicles leads to a lower demand for parking spaces and reduced emissions.

Designing a CMaaS system is a complex planning task because of the wide range of options and the impact of the related strategic-tactical decisions taken by corporate mobility managers (cf. Jittrapirom et al. 2017). Strategic decisions have to be made on the size and the composition of the company-exclusive fleet, herein addressing decisions on the inclusion of various mobility modes, e.g., cars or bikes, on the available vehicle classes of these modes, e.g., regarding drive train technologies or vehicle sizes, and on how these vehicles are provided to the company, e.g., leased or owned vehicles. Tactical decisions have to be made on the choice of the price tariffs offered by public mobility services. Many providers of public mobility services offer basic tariffs, in which users pay higher consumption-dependent prices per distance covered, time used, and/or trip, while active tariffs charge reduced consumption-dependent prices, but a fixed monthly membership fee.

The strategic-tactical decisions depend on various structural requirements that corporate mobility managers must consider simultaneously in their decision-making. First, the temporal and spatial pattern of the company's mobility demand has a major impact on the decisions. Second, corporate mobility managers need to account for the technical restrictions of vehicles with regard to the capacity, speed, or driving range. Third, the availability of vehicles in public mobility services may be limited due to bookings by other users. Fourth, the acceptance of micromobility modes must be carefully considered by corporate mobility managers. For instance, employees might not consider to use bikes for a trip when it rains (cf. Zhu et al. 2020). Finally, corporate mobility managers are obliged to meet their economic targets and must therefore find the cost-minimizing CMaaS system that meets employee demand. To address the complexity of these interdependent decisions and requirements, corporate mobility managers require a quantitative decision support tool for designing a CMaaS system.

Prior research in this field underlines the complexity of CMaaS. First descriptive studies reveal that the synchronization of corporate requirements and the system capacity is explicitly challenging and that a lack of experience with CMaaS hinders the implementation (cf. Boutueil 2016, Hesselgren et al. 2020, Zhao et al. 2020). However, to the best of our knowledge, no prescriptive decision support tool exists that addresses all strategic-tactical decisions and structural requirements of CMaaS simultaneously. Existing optimization models on the fleet composition only consider unimodal fleets (cf. Gould 1969, Yoon and Cherry 2018, Lemme et al. 2019, Wallar et al. 2019) or disregard the acceptance of micromobility modes and do not present general insights (cf. Enzi et al. 2017, Enzi et al. 2021, Knopp et al. 2021). Although these works even include public services, they do not provide strategic-tactical decision support on which mobility services should be integrated at which price tariff.

We contribute to the literature both methodologically and contentwise. First, we provide a decision support tool that identifies a company's strategically optimal fleet size and composition of multimodal company-exclusive mobility services and the tactically optimal choice of price tariffs for public mobility services. The proposed decision support tool is the first to model strategic and tactical decisions of CMaaS, considering as many different structural requirements, i.e., spatio-temporal mobility demand, costs, technical vehicle restrictions, the availability of vehicles, and micromobility acceptance. Further, we apply the model in a comprehensive case study, demonstrating the decision support for companies and drawing general insights on the current and future potentials of CMaaS. We apply real-world driving profiles of 144 companies and include ten mobility services that offer cars, bikes, or scooters. Further, we analyze structural differences between rural and urban companies and highlight how CMaaS compositions vary in changing environments. The results thus offer companies not only a quantitative decision support tool for the design of a CMaaS system, but also an extensive evaluation on the different parameters influencing the (future) potential of the CMaaS design.

The remainder of this paper is structured as follows. In Chapter 6.2, we present a literature review on related research. In Chapter 6.3, we present our decision support tool based on model fundamentals and assumptions. In Chapter 6.4, we introduce our case study. In Chapter 6.5, we present and discuss the insights of our results. In Chapter 6.6, we summarize the findings and identify future research topics.

6.2 Literature Review

CMaaS is a new concept and therefore, comprehensive studies about its implementation are still rare. So far, research on CMaaS mainly consists of surveys about potentials and challenges of CMaaS as well as more general studies on MaaS in a public, not corporate, setting, which we present in Section 6.2.1. Further, in Section 6.2.2, we give an overview on related optimization models on unimodal and multimodal fleet design. Finally, in Section 6.2.3, we summarize these findings by identifying the research gaps.

6.2.1 Studies on the Potentials and Challenges of MaaS and CMaaS

CMaaS has been defined by Hesselgren et al. (2020) as a MaaS system that is controlled by a company and whose focus lies on transport within, to, and from a work site or campus. Such a multimodal corporate mobility solution must additionally fulfill the following criteria to count as a MaaS system: integration of several mobility modes, availability via a digital platform, provision of a "one-stop shop" for users, and required registration. Hesselgren et al. (2020) base these criteria on various definitions of MaaS in research (cf. Giesecke et al. 2016, Kamargianni et al. 2016, Jittrapirom et al. 2017, Matyas and Kamargianni 2017, Ho et al. 2018).

As public interest has grown in recent years, research on the adoption and environmental impacts of MaaS increased. Becker et al. (2020) conduct a joint simulation of various sharing services and find that an integrated transport system helps to increase system efficiency and reduce energy consumption substantially. First surveys in the context of MaaS find that the MaaS adoption can lead to a substitution of the private car and a more efficient use of resources (cf. Sochor et al. 2016, Brezovec and Hampl 2021). In their stated portfolio choice experiment on the MaaS design, Jang et al. (2020) support these results and conclude that MaaS contributes to improving sustainable transportation by shifting demand to more environmentally friendly mobility modes. However, Sarasini et al. (2017) analyze MaaS business models with regard to their potentials to generate sustainable value and point out that the positive impacts of MaaS cannot be guaranteed. They explain that MaaS can also support modal shifts from low-emission to high-emission modes, especially by moving the demand from public transport to on-demand services, and that the overall environmental effect of MaaS depends on the users' modal choice.

First CMaaS trials derive insights about the adoption patterns of employees as well as the challenges companies face during the implementation. Hesselgren et al. (2020) analyze the travel behavior in the context of a large-scale CMaaS system in Sweden and find that appreciation among employees is high, but that they rarely change their mobility patterns. The only significant change in mobility behavior was achieved by the inclusion of electric bikes. Zhao et al. (2020) identified key barriers of the CMaaS adoption during a large-scale CMaaS pilot, distinguishing barriers of the service design, the business model, travel attitudes and behaviors, and system impacts. Identified barriers include the complexity of CMaaS, which can severely limit value creation, and the difficulty to provide a flexible and accessible system. The latter challenge is in line with the findings of Vaddadi et al. (2020), which show that the lack of information on the system and its accessibility hindered the shift from the private car to CMaaS. Several trials reveal that one main obstacle of CMaaS is the synchronization of user requirements and system capacity (cf. Boutueil 2016, Hesselgren et al. 2020, Zhao et al. 2020).

6.2.2 Optimization Models on Unimodal and Multimodal Fleet Design

Related optimization models on unimodal fleet design aim to determine the fleet size and composition of corporate fleets. Many models that optimize the composition of corporate fleets go back to the work of Dantzig and Fulkerson (1954), who determine the minimum fleet size to carry out deliveries. Gould (1969) extends this model to identify the optimal composition of owned and rented trucks with different sizes and costs in freight transportation. Later, Papier and Thonemann (2008) included more realistic cost structures in their model and applied it to a large-scale case study on the optimization of a railcar fleet. Recently, fleet size and composition models increasingly consider the environmental impact of the fleet. Nair and Acciaro (2018) optimize the composition of a ship fleet with regard to the emission abatement costs of different fuels, while Sen et al. (2019) propose a multi-objective model to minimize costs and life cycle greenhouse gases (GHGs) as a solution for the transition to sustainable trucking, producing robust pareto-optimal solutions with a cutting-plane algorithm. Other related models yield the fleet size and composition with the maximum utilization (cf. Żak et al. 2011, Redmer 2015). Extensive literature reviews on fleet planning problems can be found in Hoff et al. (2010) and Baykasoğlu et al. (2019).

Public sharing services are an essential component of CMaaS, and extended models have been proposed to design shared fleets. Related models identify the cost-minimizing or profit-maximizing fleet size in unimodal car and bike sharing systems. Herein, models exist for station-based roundtrip systems, where vehicles must be returned to the pick-up station (cf. Yoon and Cherry 2018), for station-based one-way systems, where vehicles can be returned to any station (cf. George and Xia 2011, Frade and Ribeiro 2015, Hu and Liu 2016, Lemme et al. 2019, Maggioni et al. 2019, Luo et al. 2020), and for free-floating systems, where legal on-street parking is allowed (cf. Weikl and Bogenberger 2013). In addition to the fleet size, Hu and Liu (2016) determine the available station capacities applying extended mean value analysis algorithms. Yoon and Cherry (2018) and Lemme et al. (2019) incorporate the fleet composition with regard to characteristics of battery electric vehicles (BEVs). Herein, Yoon and Cherry (2018) base their strategic decisions on historic driving profiles to anticipate the future operation of the fleet. Wallar et al. (2019) model different types of internal combustion engine vehicles (ICEVs) to provide the optimally composed fleet for ride sharing, herein anticipating the fleet operations with historical taxi requests in Manhattan and Singapore, and propose a suitable solution algorithm. Recent models for public bike sharing systems determine the optimal fleet size, anticipate fleet operations based on the historical demand, and additionally account for the station locations (cf. Frade and Ribeiro 2015), GHGs (cf. Luo et al. 2020), or stochastic demand (cf. Maggioni et al. 2019).

In recent years, multimodality became a relevant factor in corporate fleet design, but respective models are still scarce. To the best of our knowledge, only three approaches exist that provide decision support on multimodal corporate fleets. These models focus on the operational vehicle scheduling, and also define the resulting fleet size. Enzi et al. (2017) propose an integrated optimization model that considers various mobility modes and services, like bike sharing, car sharing, and public transportation, while incorporating the characteristics of BEVs. The objective is to minimize costs and emissions while fulfilling the given demand of trips. In 2021, Enzi et al. (2021) introduce a model that maximizes savings while assigning trip requests to a fleet of cars, which can be used for both, car sharing and ride sharing. Multimodality is introduced to cover trips that cannot be covered by the car fleet. Knopp et al. (2021) design a cost-minimizing approach which schedules the vehicles of corporate multimodal fleets, considering a shared fleet of heterogeneous passenger vehicles as well as alternative mobility options like public transportation. All three models provide computational results, but are not applied to a real-world case.

6.2.3 Literature Gap

The studies in Section 6.2.1 reveal challenges when designing CMaaS systems, that are mainly connected to the complexity of CMaaS and the lack of experience with it. These findings suggest that a decision support tool that covers the entire structural complexity of the system would contribute to the success of a CMaaS implementation. However, the presented descriptive analyses on CMaaS give preliminary insights and are not able to provide decision support.

The models presented in Section 6.2.2 provide decision support for the design of corporate and shared fleets, but none of them fulfill all requirements for the implementation of CMaaS. For an overview of the models and their fulfilled requirements, compare Table 6-1. Most related strategic optimization models on fleet size and composition do not address multimodality and the inclusion of public mobility services into exclusive fleets. Only recently have multimodal models, i.e., Enzi et al. (2017), Enzi et al. (2021), and Knopp et al. (2021), provided decision support for CMaaS. These approaches provide solution methods for complex operational problems, but neglect essential requirements when aiming to provide strategic-tactical decision support for companies, e.g., the choice of different price tariffs of public mobility providers and the acceptance of micromobility modes. Additionally, these models were never tested with real-world data and do not yield general insights on CMaaS and its implementation.

With the decision support tool presented in this work, our approach addresses all decisions, structural requirements, and application conditions that we identified as relevant for corporate mobility managers aiming to design a CMaaS system. Herein, we extend the traditional fleet size and composition models to include requirements relevant for CMaaS, i.e., multimodality, public mobility services, price tariffs, vehicle availability, and micromobility acceptance. We formulate a straightforward optimization model to produce reliable insights regarding the potentials of

CMaaS, which does not require complex solving algorithms as some existing fleet size and composition models do (cf. Żak et al. 2011, Hu and Liu 2016, Sen et al. 2019, Wallar et al. 2019) and can therefore be easily applied by corporate mobility managers. By applying it to real-world data from a variety of companies and mobility services, and by analyzing the potentials of a multimodal system, we derive general managerial insights for future CMaaS implementations.

Table 6-1
Related literature and model requirements.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
strategic-tactical decisions														
company-exclusive services	✓	✓	✓	✓	✓	✓	-	✓	-	-	-	-	✓	✓
fleet size and composition	(✓)	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	(✓)	(✓)	(✓)	✓
multimodality	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓
public services	-	-	-	-	-	-	✓	-	✓	✓	✓	✓	✓	✓
price tariffs	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
structural requirements														
spatio-temporal demand	(✓)	(✓)	-	-	-	-	-	✓	-	✓	✓	✓	✓	✓
costs	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓	✓	✓
technical vehicle restrictions	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	-	-	✓	✓
availability of vehicles	-	-	-	-	-	-	✓	-	-	-	-	-	✓	✓
micromobility acceptance	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
application														
real-world data	✓	✓	✓	✓	-	✓	-	✓	✓	✓	✓	✓	-	✓
general insights	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓

(I) - (XIV) characterize modeling approaches as follows:
(I) Dantzig and Fulkerson 1954, (II) Gould 1969, Papier and Thonemann 2008, (III) Nair and Acciaro 2018, (IV) Sen et al. 2019, (V) Żak et al. 2011, (VI) Redmer 2015, (VII) George and Xia 2011, Hu and Liu 2016, (VIII) Yoon and Cherry 2018, (IX) Lemme et al. 2019, (X) Wallar et al. 2019, (XI) Frade and Ribeiro 2015, Luo et al. 2020, (XII) Maggioni et al. 2019, (XIII) Enzi et al. 2017, Enzi et al. 2021, Knopp et al. 2021, (XIV) this paper.

6.3 Mathematical Model

In the following, we introduce our mathematical model for designing a CMaaS system. In Section 6.3.1, we provide our problem setting including the system design and model assumptions. In Section 6.3.2, we present the formulation of the mathematical model.

6.3.1 Problem Setting and Assumptions

Our methodology provides a decision support tool for corporate mobility managers. The tool aims at determining the initial strategic-tactical decisions when designing a multimodal CMaaS system that offers flexible, cost-efficient, and low-emission mobility services to employees (Section 6.3.1.1). As these strategic-tactical decisions also depend on the operation of the system, we anticipate the operation in our approach (Section 6.3.1.2).

6.3.1.1 Strategic-Tactical Decisions

Corporate mobility managers face a variety of mobility options when designing a multimodal CMaaS system. To satisfy the mobility demand of their employees, they can provide company-exclusive mobility services, such as owned or leased car or bike fleets, that are only accessible by employees of the company. In addition, the employees can use public mobility services, such as car sharing, bike or scooter sharing, and taxis, which may also be booked by other users who are not employees of the company. Herein, each of these mobility services may comprise different vehicle classes including different mobility modes, drive train technologies, and vehicle sizes.

Given this variety of options to choose from, corporate mobility managers need decision support regarding strategic and tactical challenges when designing a CMaaS system, as illustrated in Figure 6-1. For company-exclusive mobility services, we provide strategic decision support on the optimal fleet size and composition, i.e., how many vehicles of which mobility mode and which vehicle class the company requires. For public mobility services, we provide tactical decision support on the choice of the price tariffs, i.e., on the composition of fixed membership costs and consumption-dependent mobility costs.

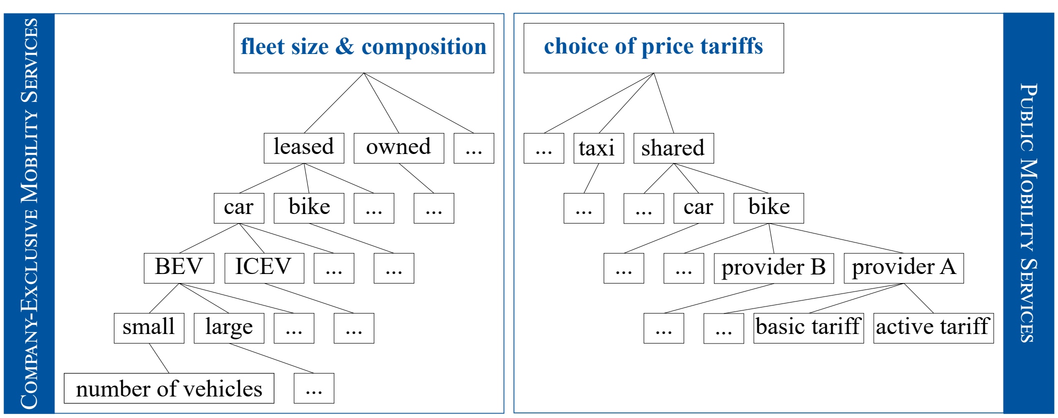

Figure 6-1: Illustration of the strategic-tactical decisions of designing a CMaaS system.

Corporate mobility managers are trying to design an efficient CMaaS system that fulfills the entire mobility demand at minimal costs. The strategic-tactical decisions on the design of the CMaaS system lead to fixed system costs for the company over the planning horizon. First, the fixed costs include the costs per vehicle incurred by maintaining company-exclusive fleets, e.g., continuous depreciation or leasing, as well as insurance, parking, maintenance, and taxes for the vehicles over the planning horizon. Second, for public mobility services, the fixed costs consist of membership costs that may vary between the different price tariffs.

The macroscopic strategic-tactical decisions and the resulting total costs depend on the microscopic operation of the CMaaS system. For example, the required fleet size depends on the maximum number of simultaneously needed company-exclusive vehicles. The choice of the price tariffs as optimal combination of membership and consumption-dependent costs offered by public mobility providers depends on the extent to which the public services are used. Therefore, it is necessary to anticipate the operation of the mobility system.

6.3.1.2 Anticipation of Operation

We anticipate the operation of the CMaaS system based on the microscopic spatio-temporal distribution of the mobility demand of the company. The mobility demand is based on historical data, i.e., information on past trips of employees accessible from GPS data of the existing vehicle fleet, from logbook data, or from business travel management data. To ensure the same mobility for employees as without the CMaaS system, we assume that the CMaaS system must meet the entire mobility demand in time and space. In our model, decision variables allocate mobility services and vehicle classes to these expected trips to anticipate the future operation of the CMaaS system. It should be noted that we do not perform an operational vehicle routing, i.e., allocating trips to specific vehicles. Instead, the strategic-tactical model ensures that enough vehicles with the required characteristics (e.g. range) are available at all times to cover operational mobility demand.

The allocation of the available mobility services and vehicle classes to trips may be restricted by the following constraints. First, we determine the feasibility of mobility services and vehicle classes for trips given technical restrictions, such as the driving ranges of BEVs, or physical restrictions, such as the maximum reasonable driving distance of bikes. Second, we regard for upper bounds on the number of vehicles. For example, the fleet size of company-exclusive mobility services may be restricted due to spatial restrictions at the company location. For public mobility services, the upper bound on the number of vehicles depends on the availability of vehicles, i.e., on the total vehicle capacity and on the temporal distribution of other users' bookings. Third, we account for the compliance with transport capacities, i.e., we regard that multiple vehicles may have to be booked depending on the number of employees attending the same appointment and the number of seats available in a vehicle.

In addition to these restrictions, we limit the availability of micromobility modes, such as bikes or scooters, in the mobility portfolio of a trip. Unlike the use of cars, the use of micromobility modes might be restrictred due to missing acceptance, limited comfort, or due to weather conditions. In order to derive reliable results and to avoid an overestimation of the use of micromobility modes, we specifically account for the probability that micromobility modes are considered for trips. To this end, we model two settings for each trip, i.e., one setting in which micromobility modes are considered in an employees's mobility portfolio for the trip, and one setting in which micromobility modes are ignored by the employee for this trip. For each trip, both settings are included in the decision making process with their respective occurrence probability and expected costs to determine the optimal design of the CMaaS system.

The optimal fleet size results from the maximum number of simultaneous trips with company-exclusive vehicles. To model the temporal occupation of vehicles, we divide the planning horizon into discrete periods. The temporal occupation for the same appointment varies depending on the used vehicle class. On the one hand, vehicles may have heterogeneous travel times. On the other hand, some mobility services only need to be booked during travel times, e.g., taxi, while others additionally need to be booked during the appointments, e.g., car sharing. Finally, BEVs are additionally occupied during charging times. We make the conservative assumption that BEVs are charged immediately after each trip.

The anticipated operation costs are considered in addition to the fixed system costs that are independent of the actual operation of the system (Section 6.3.1.1). The anticipated operation costs depend on the consumption of the respective services, i.e., the basic trip costs, the distance-related costs, and/or the time-related costs. For example, the total costs of a taxi trip usually consist of a basic fee as well as distance-related costs and include a profit margin for the provider, whereas a trip with a company-exclusive vehicle only incurs distance-related costs that cover the actual costs, e.g., loss in value and energy costs. We determine the consumption-dependent costs that would be incurred with the available mobility services and vehicle classes a priori for all trips.

6.3.2 Model Formulation

Our model notation is as follows: The studied time horizon is split into a set of discrete time periods $\mathcal{T}$. Let $\mathcal{S}$ be the set of all mobility services available to the company. Herein, set $\mathcal{S}^{\mathrm{E}} \subseteq \mathcal{S}$ denotes the subset of company-exclusive mobility services. For each mobility service s, set $\mathcal{V}_s$ defines all available vehicle classes and set $\mathcal{P}_s$ all available price tariffs. Set $\mathcal{W}$ denotes the set of micromobility settings, i.e., a setting in which employees consider using micromobility modes in their mobility portfolio and a setting in which they ignore them ($\mathcal{W} = \{\text{consMicro}, \text{ignMicro}\}$). Let I be the set of trips of employees of the company. Let $I^w_{svt} \subseteq I$ be the subset of trips for which a vehicle is occupied in period t if mobility service s with vehicle class v is used in micromobility setting w depending on the booked and charged time periods. Given micromobility setting w and maximum driving ranges, set $\mathcal{V}^w_{si}$ defines the mobility portfolio for trip i, i.e., the subset of feasible vehicle classes of mobility service s. Note that set $\mathcal{V}^{\text{ignMicro}}_{si}$ excludes micromobility modes for trip i due to the employee's decision to ignore these modes in the mobility portfolio even if mobility service s offers micromobility modes.

The decision variable x^{E}_{sv} determines the required fleet sizes for company-exclusive mobility services, i.e., the total number of required vehicles of class v within the fleet of mobility service s. Further, binary decision variable y_{sp} indicates for mobility service s if price tariff p is used. To determine both of these strategic-tactical decisions of companies, we also introduce auxiliary variables that capture the anticipated demand structure of the company and the uncertainty of the micromobility use. Auxiliary variable a^w_{svpi} is binary and indicates if mobility service s with vehicle class v and price tariff p is selected for trip i in micromobility setting w. Finally, auxiliary variable b^w_{svpt} determines the number of occupied vehicles of mobility service s in vehicle class v and price tariff p in period t in micromobility setting w. Table 6-2 gives an overview of the comprehensive model notation.

Our objective function (1) minimizes the expected corporate mobility costs over the planning horizon. First, we account for the total fixed system costs (2) over the planning horizon including the vehicle costs for fleets of company-exclusive mobility services (c^{veh}_{sv}) and the membership costs (c^{mem}_{sp}) for public mobility services. Second, we account for the anticipated operation costs for trips (3), i.e., the basic costs per trip (c^{trip}_{isvp}), the costs per distance covered (c^{dist}_{isvp}), and the costs per time period (c^{time}_{isvp}). Herein, we predict the expected costs given the probabilities of the micromobility settings.

$$\min \quad Z = C^{\text{system}} + C^{\text{operation}} \tag{1}$$

$$C^{\text{system}} = \sum_{s \in \mathcal{S}^{\text{E}}} \sum_{v \in \mathcal{V}_s} c^{\text{veh}}_{sv} x^{\text{E}}_{sv} + \sum_{s \in \mathcal{S} \setminus \mathcal{S}^{\text{E}}} \sum_{p \in \mathcal{P}_s} c^{\text{mem}}_{sp} y_{sp} \tag{2}$$

$$C^{\text{operation}} = \sum_{w \in \mathcal{W}} \sum_{s \in \mathcal{S}} \sum_{i \in I} \sum_{v \in \mathcal{V}^w_{si}} \sum_{p \in \mathcal{P}_s} (c^{\text{trip}}_{isvp} + c^{\text{dist}}_{isvp} + c^{\text{time}}_{isvp}) \gamma^w a^w_{svpi} \tag{3}$$

Constraints (4) - (13) of our IP hold as follows: Constraints (4) ensure that exactly one mobility

Table 6-2
Model notation.

Sets	
$\mathcal{T}$	set of time periods
$\mathcal{S}$	set of mobility services
$\mathcal{S}^{\mathrm{E}}$	set of company-exclusive mobility services
$\mathcal{V}_s$	set of vehicle classes of mobility service s
$\mathcal{P}_s$	set of price tariffs of mobility service s
$\mathcal{W}$	set of micromobility settings
I	set of trips
I^w_{svt}	set of trips that occupy a vehicle in period t if mobility service s with vehicle class v is used in micromobility setting w
$\mathcal{V}^w_{si}$	set of feasible vehicle classes of mobility service s for trip i in micromobility setting w
Parameters	
c^{veh}_{sv}	costs per vehicle of company-exclusive mobility service s in vehicle class v
c^{mem}_{sp}	total membership costs of public mobility service s in price tariff p
c^{trip}_{isvp}	basic trip costs of trip i with mobility service s in vehicle class v and price tariff p
c^{dist}_{isvp}	distance costs of trip i with mobility service s in vehicle class v and price tariff p
c^{time}_{isvp}	time costs of trip i with mobility service s in vehicle class v and price tariff p
N_{svt}	vehicle capacity of mobility service s in vehicle class v in period t
γ^w	probability of micromobility setting w
f_{svi}	number of required vehicles if mobility service s with vehicle class v is used for trip i
M	big M: large positive value
Decision variables	
x^{E}_{sv}	integer: fleet size of company-exclusive mobility service s in vehicle class v
y_{sp}	binary: 1 if price tariff p is selected for public mobility service s, 0 otherwise
a^w_{svpi}	binary: 1 if mobility service s with vehicle class v and price tariff p is selected for trip i in micromobility setting w, 0 otherwise
b^w_{svpt}	integer: number of occupied vehicles of mobility service s in vehicle class v and price tariff p in period t and micromobility setting w

service with one vehicle class and one price tariff is selected to perform trip i if micromobility setting w occurs. Constraints (5) determine the number of occupied vehicles of mobility service s in vehicle class v and price tariff p in period t if micromobility setting w occurs. Herein, the number of occupied vehicles in period t depends on the number of booked trips and their respective vehicle demand f_{svi}. For mobility services with BEVs, the number of occupied vehicles additionally depends on the number of vehicles that require recharging in the respective period. Constraints (6) determine the fleet size of company-exclusive mobility services as the maximum value of occupied vehicles over all periods and both micromobility settings. Thus, the fleet sizes are reliable with regard to the uncertainty of the micromobility use. Constraints (7) guarantee that in period t no more vehicles of class v of mobility service s are used than are actually available (N_{svt}). Constraints (8) indicate if the company uses mobility service s with price tariff p. Constraints (9) ensure that no more than one price tariff p is selected per mobility service s. More precisely, if the company does not use the mobility service, no price tariff is selected (= 0) and, vice versa, exactly one price tariff is selected (= 1) if the company uses the mobility service. Finally, Constraints (10) - (13) define integer and binary variables.

$$\sum_{s\in\mathcal{S}}\sum_{v\in\mathcal{V}_{si}^{w}}\sum_{p\in\mathcal{P}_s} a_{svpi}^{w} = 1 \qquad \forall w\in\mathcal{W}, i\in\mathcal{I} \quad (4)$$

$$\sum_{i\in\mathcal{I}_{svt}^{w}} f_{svi}a_{svpi}^{w} = b_{svpt}^{w} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, v\in\mathcal{V}_s, p\in\mathcal{P}_s, t\in\mathcal{T} \quad (5)$$

$$\sum_{p\in\mathcal{P}_s} b_{svpt}^{w} \leq x_{sv}^{\mathrm{E}} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}^{\mathrm{E}}, v\in\mathcal{V}_s, t\in\mathcal{T} \quad (6)$$

$$\sum_{p\in\mathcal{P}_s} b_{svpt}^{w} \leq N_{svt} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, v\in\mathcal{V}_s, t\in\mathcal{T} \quad (7)$$

$$\sum_{w\in\mathcal{W}}\sum_{i\in\mathcal{I}}\sum_{v\in\mathcal{V}_{si}^{w}} a_{svpi}^{w} \leq My_{sp} \qquad \forall s\in\mathcal{S}\setminus\mathcal{S}^{\mathrm{E}}, p\in\mathcal{P}_s \quad (8)$$

$$\sum_{p\in\mathcal{P}_s} y_{sp} \leq 1 \qquad \forall s\in\mathcal{S}\setminus\mathcal{S}^{\mathrm{E}} \quad (9)$$

$$x_{sv}^{\mathrm{E}} \in \mathbb{N} \qquad \forall s\in\mathcal{S}^{\mathrm{E}}, v\in\mathcal{V}_s \quad (10)$$

$$y_{sp} \in \{0;1\} \qquad \forall s\in\mathcal{S}\setminus\mathcal{S}^{\mathrm{E}}, p\in\mathcal{P}_s \quad (11)$$

$$a_{svpi}^{w} \in \{0;1\} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, i\in\mathcal{I}, v\in\mathcal{V}_{si}^{w}, p\in\mathcal{P}_s \quad (12)$$

$$b_{svpt}^{w} \in \mathbb{N} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, v\in\mathcal{V}_s, p\in\mathcal{P}_s, t\in\mathcal{T} \quad (13)$$

6.4 Case Study

In order to gain insights on CMaaS, we apply the decision support tool to a comprehensive case study in Germany in the following. Herein, we determine the optimal design of a CMaaS system for each company of a representative sample. First, in Section 6.4.1, we present the data on which we base our case study. Second, we describe the experimental design of our case study in Section 6.4.2.

6.4.1 Data Base

In our case study, we determine the optimal design of a CMaaS system for 144 companies with commercially licensed passenger cars based on the historic mobility demand from the REM 2030 driving profiles data base collected by the Fraunhofer Institute for Systems and Innovation Research (cf. Fraunhofer 2021). Table 6-3 shows an extract from the driving profile of a vehicle. For each trip, the data base provides the vehicle ID, time stamps of departure and arrival, as well as the distance. Commutes and trips with other vehicles than cars are not included. The respective companies are anonymized, but the data base gives further information, e.g., on the company size, the city size, and the economic sector, e.g., public administration, retail, insurance activities, or manufacturing. Since the driving profiles were collected over a period of four weeks, we consider a planning horizon of four weeks in our analysis with time intervals of 15 minutes. We neglect trips from the database below 500 m to account for potential recording errors. Further, we assume that each trip is made by one employee. Table 6-4 provides an overview on the key indicators of the driving profiles, separated for rural regions ($< 20,000$ inhabitants) and urban regions ($\geq 20,000$ inhabitants).

Table 6-3: Extract from the driving profiles.

	departure					arrival					
ID	year	month	day	hour	minute	year	month	day	hour	minute	distance
1106000341	2011	7	6	9	35	2011	7	6	11	46	26.19
1106000341	2011	7	6	13	36	2011	7	6	15	35	24.98
...	...	...	...	...	...	...	...	...	...	...	...

We base the mobility offer on the most common mobility services as listed in Table 6-5. We denote each mobility service by the mobility mode, i.e., car, bike, or (pedal-)scooter, and the type of provision. For company-exclusive mobility services, we consider ownership and leasing of vehicles. For public mobility services, we consider shared services, i.e., station-based car and bike sharing as well as free-floating scooter sharing, and taxis. With the exception of scooter

Table 6-4: Key indicators of the driving profiles.

	rural	urban	all companies
number of companies [-]	67	77	144
number of driving profiles [-]	197	231	428
∅ number of trips per company [-]	291	350	322
∅ trip distance per company [km]	11	14	13
∅ company mileage [km]	3,282	3,547	3,424
∅ trip duration per company [min]	17	21	19

sharing, we assume that all mobility services are available to all the considered companies and that stations of public mobility services are within a reasonable distance. Since scooter sharing is currently only available in cities in Germany (cf. Krauss and Scherf 2020), we neglect scooter sharing for companies in rural areas.

Table 6-5
Notation of mobility services.

		company-exclusive		**public**	
	provision	owned	leased	shared	taxi
mode	car	*CarOwned*	*CarLeased*	*CarShared*	*CarTaxi*
	bike	*BikeOwned*	*BikeLeased*	*BikeShared*	-
	scooter	*ScooterOwned*	*ScooterLeased*	*ScooterShared*	-

We consider several vehicle classes for cars defined by the drive train technology and by the size. The size of cars is relevant in terms of the battery characteristics of BEVs as well as the availability and costs of sharing offers. For bikes and scooters, we only consider BEVs. The technical details of each vehicle class are specified according to one real-world vehicle model, which fulfills the technical and informational requirements for our analysis. The required technical details include the access time, the speed in rural and urban regions, the maximum distance, and the consumption as well as the charging capacity in the case of BEVs as presented in Table 6-6. Note that not all vehicle classes are available for all mobility services. For a comprehensive overview of the available vehicle classes within a mobility service compare Appendix 6A-1.

The total duration during which a vehicle is occupied (I^w_{svt}) consists of the booking duration and, for BEVs, the charging duration. The booking duration of a vehicle includes the travel time, which we determine based on a fixed access time, the speed of the vehicle and the distance of the trip. The fixed access time represents the duration of accessing and exiting the mobility mode, e.g., for searching parking spaces and (un-)locking vehicles (cf. Umweltbundesamt 2014).

Table 6-6
Technical details of vehicle classes.

mode	vehicle class	access time [min]	speed rural—urban [km/h]	max. distance [km]	consumption per 100 km	charging capacity [kW]	reference
car	ICEV S	11	43.4—24.1	∞	4.1 l	-	[1],[2],[3]
	ICEV M			∞	5.2 l	-	[1],[2],[4]
	ICEV L			∞	5.7 l	-	[1],[2],[5]
	BEV S			321	14.0 kWh	11	[1],[2],[6]
	BEV M			359	15.6 kWh	11	[1],[2],[7]
	BEV L			394	16.6 kWh	11	[1],[2],[8]
bike	BEV	5	18.5	13	0.35 kWh	0.112	[1],[9],[10]
scooter	BEV	5	18.5	2	0.92 kWh	0.056	[1],[11],[12],[13]

[1] Umweltbundesamt 2014, [2] Cardelino 1998, [3] ADAC 2021g, [4] ADAC 2021h, [5] ADAC 2021d, [6] ADAC 2021c, [7] ADAC 2021f, [8] ADAC 2021e, [9] Shimano Inc. 2018, [10] Cairns et al. 2017, [11] Cao et al. 2021, [12] Grover 2021, [13] Zhu et al. 2020.

For station-based roundtrip sharing services which need to be returned at the pick-up station and for company-exclusive mobility services which need to be returned at the company location, we assume that the booking duration also includes the duration of the appointment. The charging duration of BEVs is based on the consumption (kWh) of the trip and the charging capacity (kW) of the vehicle (cf. ADAC 2021a). We assume that electric cars are charged at an AC charging station and disregard expensive fast charging stations. For simplicity, we also disregard charging losses and include an average plug-in time of 3 minutes.

We determine the feasibility of a vehicle class for a trip ($\mathcal{V}_{si}^{w}$) based on the distance of each trip and the maximum driving distance of the vehicle classes. We specify the maximum driving distance for electric cars as the battery range (cf. ADAC 2021a) and for bikes and scooters as the average driving distances per trip as surveyed in recent studies (cf. Cairns et al. 2017, Cao et al. 2021). In addition to driving distances, individual preferences and the weather condition also influence the use of micromobility modes (cf. Zhu et al. 2020). With regard to the probability to consider micromobility modes $\gamma^{\text{consMicro}}$, we therefore assume that 51 % of the employees would use micromobility modes on days without rainfall, which in Germany constitutes on average 50 % of the year (cf. DWD 2021).

The vehicle capacity N_{svt} of public sharing services depends on the maximum availability of vehicles accessible to the company and on the temporal distribution of other users' bookings. Table 6-7 presents an overview of the maximum availability of shared vehicles and of the fleet composition. Since there are notable regional differences in the availability of sharing services (cf. Boldrini et al. 2016), we distinguish between services in rural and urban areas. For station-based car and bike sharing, the maximum vehicle availability refers to the average fleet size at a station (cf. Boldrini et al. 2016, Luo et al. 2019, bcs 2021), whereas for free-floating scooter sharing, it refers to the average number of vehicles within walking distance (cf. Luo et al. 2019, KVB 2021, Stadt Köln 2021). For all sharing services, we assume the same temporal distribution of other users' bookings over the course of the day according to Boldrini et al. (2016). For other public mobility services as well as for company-exclusive mobility services, we do not limit the vehicle capacity N_{svt}.

Table 6-7
Characteristics of sharing systems.

		max. availability		**share of vehicle class [%]**		
mobility service	**system**	rural	urban	ICEV (S—M—L)	BEV	**reference**
CarShared	station-based	7	5	30—30—20	20	[1],[2]
BikeShared	station-based	12	10	0	100	[2],[3]
ScooterShared	free-floating	0	6	0	100	[3],[4],[5]

[1] Boldrini et al. 2016, [2] bcs 2021, [3] Luo et al. 2019, [4] KVB 2021, [5] Stadt Köln 2021.

Every combination of mobility service, vehicle class, and price tariff has a specific cost structure, which includes the fixed system costs, i.e., vehicle and/or membership costs, and the anticipated operation costs, i.e., basic trip, distance- and/or time-related costs. Appendix 6.A presents a full overview of the relevant cost factors. For company-exclusive mobility services, the costs per vehicle c_{sv}^{veh} include parking costs, taxes, insurance, and the installation costs for charging stations over the planning horizon of four weeks. For owned bikes and scooters, the costs per vehicle additionally consider the depreciation, maintenance costs, and the battery replacement for BEVs over a usage period of seven years (cf. BMF 2000). All fixed system costs refer to the regarded planning horizon of four weeks. Note that we include the loss in value for owned cars within the costs per km as specified by ADAC (2021a), considering a period of 5 years and an annual mileage of 20,000 km. To derive the leasing costs per car, we consider contract terms of 48 months and an annual mileage of 20,000 km (cf. Sixt Leasing 2021), while the leasing costs per bike and scooter are independent of contract terms and annual mileages (cf. Grover 2021, Swapfiets 2021). The costs per km c_{isvp}^{dist} of trips with company-exclusive mobility services consider the energy costs and, for cars, an average cost value for maintenance, and the loss in value as mentioned above. Herein, we apply the average energy prices of the year 2021, as presented in Table 6-8.

Table 6-8
Energy prices.

energy source	price	unit	reference
electricity	0.2138	€/kWh	[1]
gasoline	1.5795	€/l	[2]

[1] BDEW 2022, [2] en2x 2021.

The cost factors for the public mobility services are based on exemplary service providers with a high market share in Germany (cambio, nextbike and TIER). Please note that the cost factors of these providers are the same throughout Germany and that there are no differences between rural and urban areas. To determine the time-related costs c_{isvp}^{time} of each trip, we consider the specific invoice periods of car sharing (60 min), bike sharing (15 min), and scooter sharing (1 min). We regard a basic and an active price tariff as offered by the public sharing providers (cf. cambio 2020, nextbike 2021a, TIER 2021). Membership costs c_{sp}^{mem} incur per participating employee and usually become cheaper, the more employees participate. We assume that 20 % of the total number of employees participate. Note that we published our case study data on technical vehicle characteristics, sharing services, and costs in a GitHub repository (cf. Frank et al. 2022).

6.4.2 Experimental Design

First, we analyze the optimal CMaaS design for each of the considered companies in a base case derived from the specifications of the data presented in Section 6.4.1. Herein, we compare these base case results for a multimodal CMaaS system with the status quo, in which each company only uses the unimodal company-exclusive fleet, i.e., only leased or owned cars. Beyond this base case, we analyze how the CMaaS design and costs change (1) depending on the use of micromobility modes by the companies' employees, (2) in the context of technological developments of BEVs and their infrastructure, and (3) in the case of an increased availability of shared cars.

The use of micromobility modes (1) is influenced by the probability of employees to consider bikes and scooters within their mobility portfolio for a trip (base case: 50 %) and the maximum driving distances of these modes (base case: 13 km and 2 km). However, these parameters can vary considerably between companies and are, for example, highly dependent on internal factors, such as the attitude and fitness of the workforce, as well as on external factors, such as weather or road conditions. Therefore, we analyze the effects of factors restricting the use of micromobility modes. Specifically, we vary the probability of employees to consider these modes between 0 % and 100 % and increase the maximum distances with bikes, scooters, and both between 0 and 100 % compared to the base case.

The profitability of BEVs (2), especially electric cars, in CMaaS systems is highly dependent on technological developments and climate regulations, e.g., CO_2 prices and subsidies of charging infrastructure. Therefore, in an additional case, we apply the expected BEV developments by 2030. Based on several studies on the future development of BEVs (cf. BMUB 2016, ICCT 2019, Fraunhofer 2020, BloombergNEF 2021), we adjust costs for 2030 as follows: The costs of purchasing a car decrease by 25 % for BEVs and increase by 1.1 % for ICEVs, the costs of charging infrastructure decrease by 46.3 %, electricity costs decrease to 0.117 € per kWh and gasoline costs increase to 1.87 € per litre. The driving ranges of electric cars double and we therefore assume that they can be charged overnight and no longer need intra-day charging.

As many studies suggest that policy makers will promote and facilitate car sharing, especially with electric cars (cf. BMUB 2016), we analyze a possible expansion of car sharing (3) in a final case. Herein, we analyze the impact of both, an increased availability of shared cars at a station by up to 100 % and different drive train compositions at a station, i.e., 50 % and 100 % BEV compared to 20 % BEV in the base case.

6.5 Results

In the following, we present our case study results. We solved the model to optimality on a 16-GB-RAM/intel-i7-4790 workstation using the Gurobi-8.1.0-MIP-solver with maximum solution times of less than 100 sec. Section 6.5.1 gives an overview of the base case results, providing the strategic-tactical decisions for an exemplary company and aggregating the results of all companies of the data base to derive general insights on the potentials of CMaaS. Further, in Sections 6.5.2 - 6.5.4, we analyze how the adoption of micromobility modes, future developments of BEVs, and the expansion of car sharing influence results. In Section 6.5.5, we summarize the insights on the potentials of CMaaS.

6.5.1 Base Case

First, we present the base case results for an exemplary company from the REM data base to illustrate the decisions that are supported by the proposed tool. From the REM data base, we select an average company in terms of total mileage (3,396 km) and number of trips (309) that operates in administrative and support service activities. For this company, we solve the model to optimality in 0.7 sec. The optimal CMaaS system in the base case enables the company to reduce the company-exclusive fleet from one electric car and three ICEVs to one ICEV (cf. Table 6-9). Thus, the average utilization of cars in the company-exclusive fleet increases from 4 % to 16 %. The cost-minimal solution additionally includes car and bike sharing services. Herein, it is optimal for the company to use the active price tariff for car sharing to profit from lower consumption-dependent costs and the basic price tariff for bike sharing to avoid fixed monthly membership costs. Taxis and scooters are not used. By introducing CMaaS, the analyzed company can decrease its total monthly mobility costs by 25 % compared to the status quo. The reduced number of company-exclusive vehicles contributes to a decrease of fixed system costs by 51 %, while the shift of 34 % of the trips to sharing services increases the anticipated operation costs by 27 %.

In the following, we aggregate the results of the optimal CMaaS design for the considered companies from the REM data base to derive general insights on the potentials of CMaaS. On average, the runtime of the model in the base case is 1.2 seconds per company. Figures 6-2 and 6-3 illustrate the changes in the cost structure in the base case compared to the status quo for each company. In addition, Table 6-10 compares key indicators in the status quo and the base case. Results show that the analyzed companies can save on average 33 % of their mobility costs and that a multimodal CMaaS system is profitable for all considered companies. Further, the potentials for cost-savings are on average higher for companies with a low number of trips and lower in urban (30 %) than in rural areas (3 %). The implementation of CMaaS also causes changes in the cost structure. The high overall potentials to save costs are associated with a strong decrease in fixed costs per km (-58 %), while the anticipated operation costs increase (+58 %). Thereby, the share of anticipated operation costs increases from 24 % to 56 %. The reduction in fixed system costs results from the average reduction of the company-exclusive car fleets by 67 %, mainly eliminating owned cars. At the same time, the companies increase the efficiency of their car fleets by almost four times. The share of trips and mileage traveled with

Table 6-9: Strategic-tactical decisions for the exemplary company.

	company-exclusive: number of vehicles			**public: price tariff**	
	owned	leased	$\sum$	basic	active
car	0	1	1	-	✓
bike	0	0	0	✓	-
scooter	0	0	0	-	-

Table 6-10: Key indicators of the corporate mobility systems in the status quo and the base case.

	status quo	base case
∅ company-exclusive fleet size of cars [-]	4.2	1.4
∅ company-exclusive fleet size of owned cars [-]	3.1	0.3
∅ company-exclusive fleet size of leased cars [-]	1.1	1.0
∅ utilization of the car fleet [%]	5	17
trips with BEVs [%]	50	36
trips with public mobility services [%]	-	21
trips with micromobility modes [%]	-	9
mileage with BEVs [%]	55	40
mileage with public mobility services [%]	-	12
mileage with micromobility modes [%]	-	3

BEVs decreases due to a higher share of trips with car sharing, in which ICEVs are cheaper than BEVs.

Figure 6-4 illustrates the share of companies that use a specific mode and Figure 6-5 the anticipated share of trips made with a specific mode, i.e., the modal split of trips, both classified for the type of provision. The figures show that ICEVs have the largest share of trips and are profitable via all available mobility services. Further, in contrast to the status quo, more

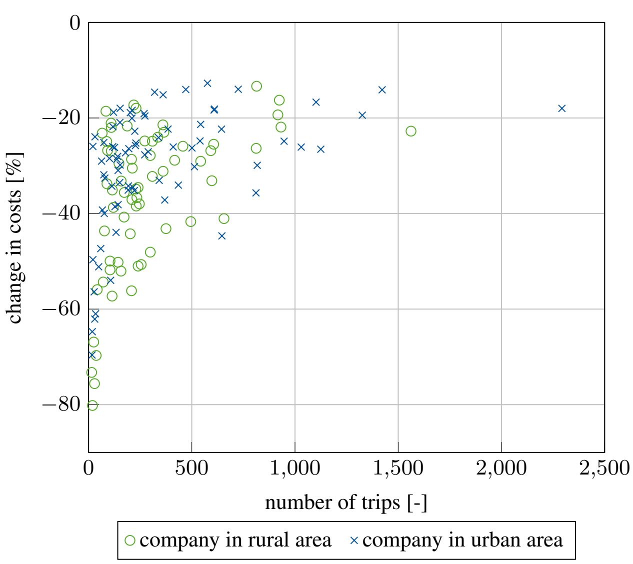

Figure 6-2: Change in total mobility costs depending on the number of trips of the company in the base case compared to the status quo.

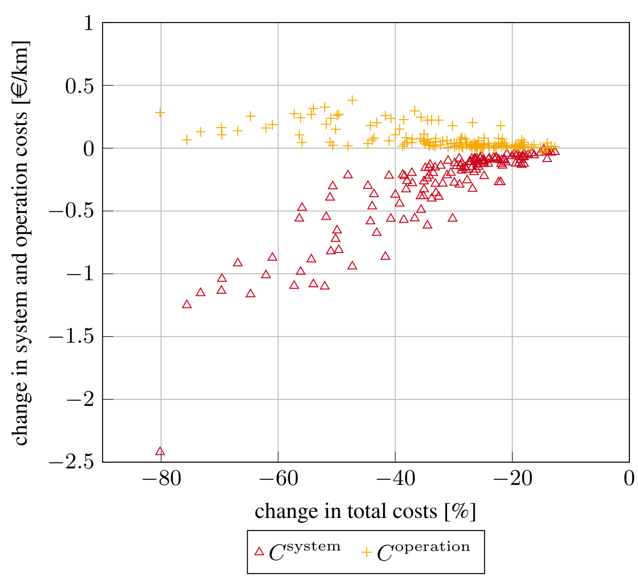

Figure 6-3: Change in fixed system (C^{system}) and anticipated operation ($C^{\text{operation}}$) costs per km depending on the change in total mobility costs in the base case compared to the status quo.

companies lease than own company-exclusive cars, while bikes and scooters are not leased at all. Companies that use shared electric cars more likely select the active price tariff because of the higher anticipated operation costs of electric cars. Note that further analyses show that it is advantageous for all companies to use car and bike sharing. Despite the comparatively high distance-related costs, almost half of the companies uses taxis, but only for a marginal share of trips. Although considerably more companies use the basic price tariff for shared bikes, half of the shared bike trips is conducted via the active price tariff. Trips with shared scooters can be neglected.

Figure 6-5 additionally shows the differences in the modal split of trips between companies in rural and urban areas. It can be seen that the modal split of trips is similar in both settings, but electric cars account for a higher share of trips in urban areas, replacing mostly trips with fossil-fueled cars. Further, due to the higher availability of shared cars at rural stations (see Section 6.4.1), car sharing is more advantageous for trips in rural areas. Further analyses yield that in urban areas, shared electric cars are already fully booked by other users 26 % of the time, so companies have a lower chance of using them.

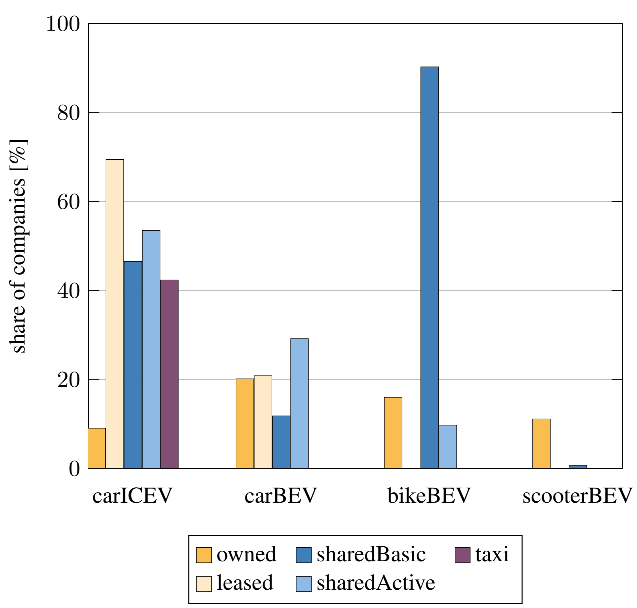

Figure 6-4: Share of companies using a mode classified for the type of provision and the selected price tariff in the base case.

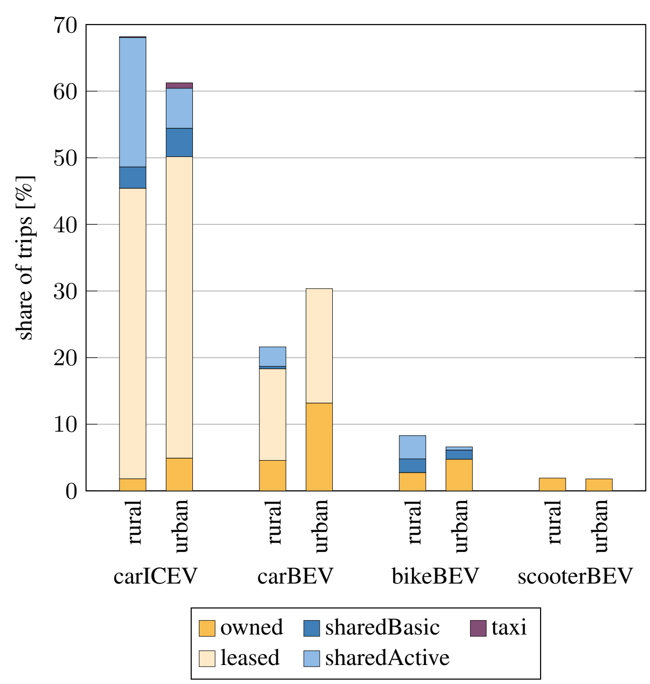

Figure 6-5: Share of trips per mode classified for the type of provision and the price tariff comparing companies in rural and urban areas in the base case.

6.5.2 Micromobility Use

Analyzing the factors that influence the use of micromobility modes, we first regard the effects of a variation in the probability of employees to consider micromobility modes for a trip, followed by the changes caused by an increased maximum driving distance of these modes. An increased probability of employees to consider micromobility modes, e.g., due to a higher tolerance to the weather conditions or due to nudges or incentives of the company, enables companies to further reduce their mobility costs (see Figure 6-6). If the employees always consider these modes in their mobility portfolio ($\gamma^{\text{consMicro}} = 100\,\%$, $\gamma^{\text{ignMicro}} = 0\,\%$), the costs are reduced by more than 30 % compared to the base case and by 50 % compared to the status quo. Instead, if micromobility modes are never considered ($\gamma^{\text{consMicro}} = 0\,\%$, $\gamma^{\text{ignMicro}} = 100\,\%$), the costs increase by 2 % compared to the base case, but are still by 32 % lower than in the status quo.

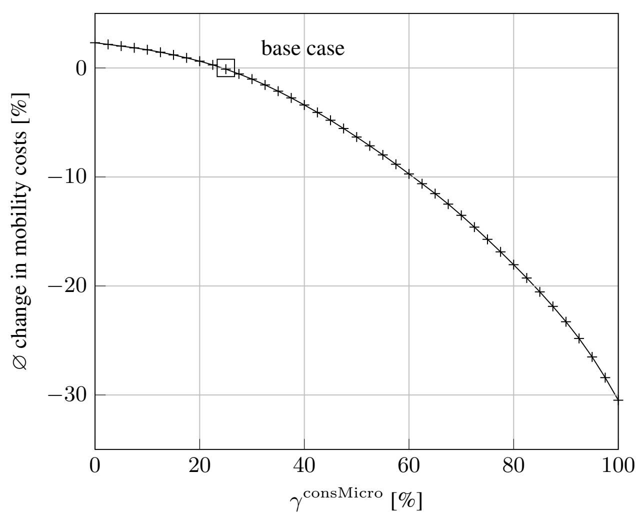

Figure 6-6: Average change in mobility costs compared to the base case for a variation in the probability $\gamma^{\text{consMicro}}$ of considering micromobility modes.

Figures 6-7 and 6-8 illustrate the change in the average fleet sizes and in the modal split of trips for a variation of the probability to consider micromobility modes for a trip. On average, the fleets consist of nearly six times as many bikes and three times as many scooters as in the base case, while the number of company-exclusive cars is cut in half. This trend is also reflected in the share of trips made by bike and car. For scooters, the increase in the fleet size results in only a slight increase in the share of trips. The fact that the total share of trips by car decreases to only 23 % indicates that at least 77 % of the trips are shorter than the maximum driving distance by bike of 13 km. Also, while company-exclusive cars become considerably less attractive for companies, the share of trips with shared cars decreases only slightly.

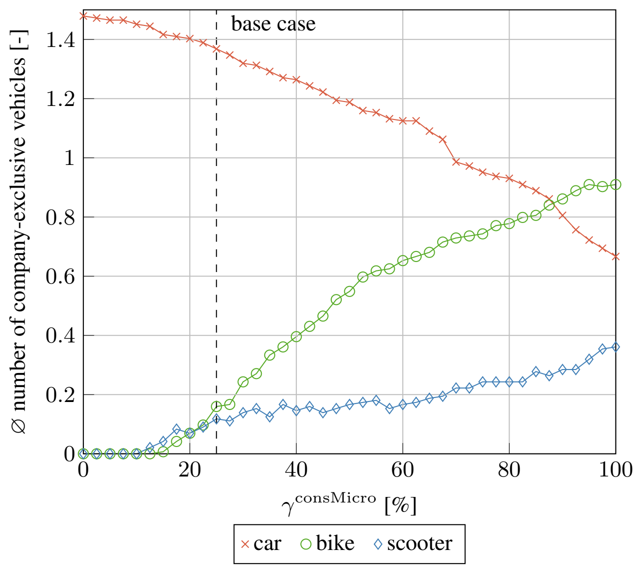

Figure 6-7: Average fleet size of company-exclusive car, bike, or scooter fleets for a variation in the probability $\gamma^{\text{consMicro}}$ of considering micromobility modes.

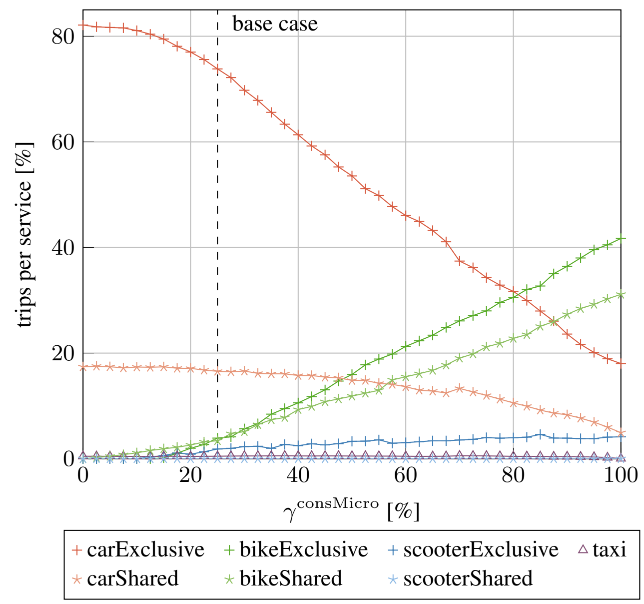

Figure 6-8: Share of trips per service for a variation in the probability $\gamma^{\text{consMicro}}$ of considering micromobility modes.

Figure 6-9 illustrates the change of average mobility costs compared to the base case for an increase of the maximum driving distances of bikes, scooters, and both modes. Results show that higher driving distances allow for additional cost-savings of up to 1.5 %, mainly due to the increased bike distance. Increasing the maximum driving distance of scooters has comparatively low potentials to save costs, because scooters do not replace costly company-exclusive cars, but bikes.

To analyze the interdependencies between car, bike, and scooter in more detail, Figure 6-10 displays that doubling the driving distances of bikes and scooters leads to an increase of trips with shared bikes and company-exclusive scooters, and a strong decrease of trips with company-exclusive cars. Despite higher driving distances of bikes, the share of trips with company-exclusive bikes falls below the share in the base case. Accordingly, further analyses show that the optimal company-exclusive fleet size of bikes decreases compared to the base case. At the same time, the average number of company-exclusive scooters increases constantly up to 153 % compared to the base case.

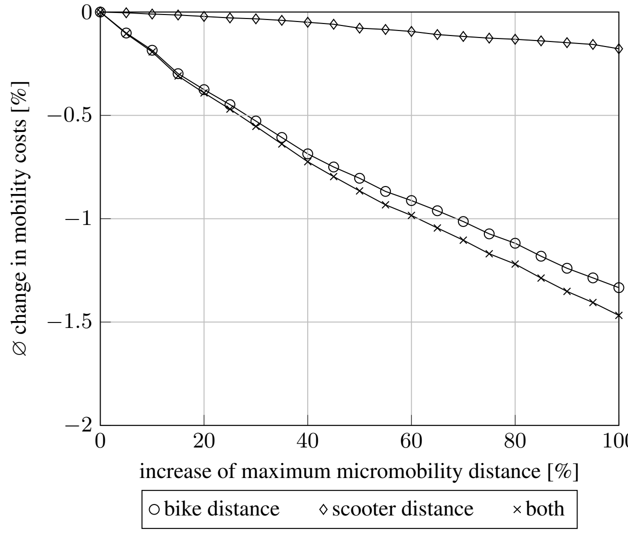

Figure 6-9: Average change in mobility costs compared to the base case for an increase of the maximum micromobility distance.

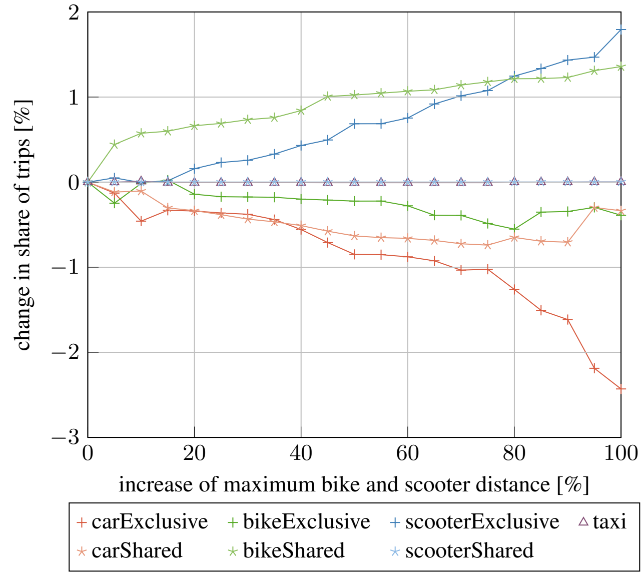

Figure 6-10: Change in the share of trips compared to the base case for an increase of the maximum bike and scooter distance.

6.5.3 BEV Developments by 2030

The future technology developments of BEVs as well as the subsequent overall price reductions allow the analyzed companies to reduce their mobility costs by 8 % compared to the base case (see Table 6-11). These potentials for relative cost-savings are slightly higher in urban than in rural areas, which is also reflected in the higher share of trips and mileage with BEVs in urban areas. The average mileage with BEVs increases from 40 % in the base case to 92 %, while the mileage with public mobility services decreases from 12 % in the base case to 9 %.

Table 6-11: Change in key indicators regarding BEV developments by 2030.

	rural	urban	all
∅ change of costs compared to status quo [%]	42	37	40
∅ change of costs compared to base case [%]	7	10	8
trips with BEVs [%]	83	91	87
trips with public mobility services [%]	23	11	16
trips with micromobility modes [%]	9	9	9
mileage with BEVs [%]	89	94	92
mileage with public mobility services [%]	12	7	9
mileage with micromobility modes [%]	3	3	3

Figure 6-11 presents the company-exclusive car fleet composition when considering future

BEV developments compared to the base case. It shows that BEVs will be the dominating cars in company-exclusive fleets in the future. While many companies use company-exclusive fossil-fueled cars in the base case, the advantages of ICEVs, i.e., lower fixed costs and higher driving ranges, vanish when BEVs improve. BEVs with higher driving ranges (M, L) are rarely implemented in company-exclusive fleets indicating that the driving range of the predominating small BEVs is sufficient for most of the analyzed trips.

Figure 6-12 compares the modal split of trips when considering BEV developments by 2030 with the base case. Due to the cost reductions, it is now most profitable to conduct trips with electric cars. The results show that the BEV developments lead to a slight substitution of trips with shared vehicles by trips with company-exclusive vehicles. The impact of the expected decrease of the electricity price on the share of trips by bike and scooter is small. The fact that electric cars rarely replace trips with bikes and scooters shows that the cost optimal solution is still multimodal, i.e., that a multimodal CMaaS system remains profitable.

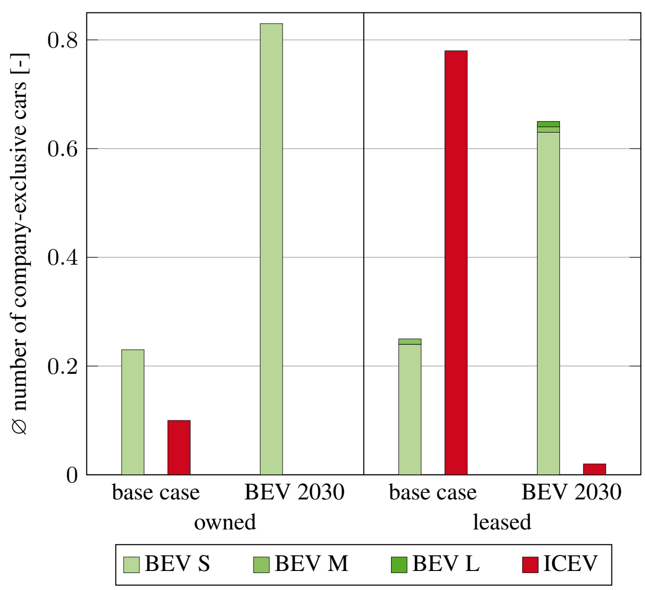

Figure 6-11: Average fleet size of company-exclusive car fleets regarding BEV developments by 2030.

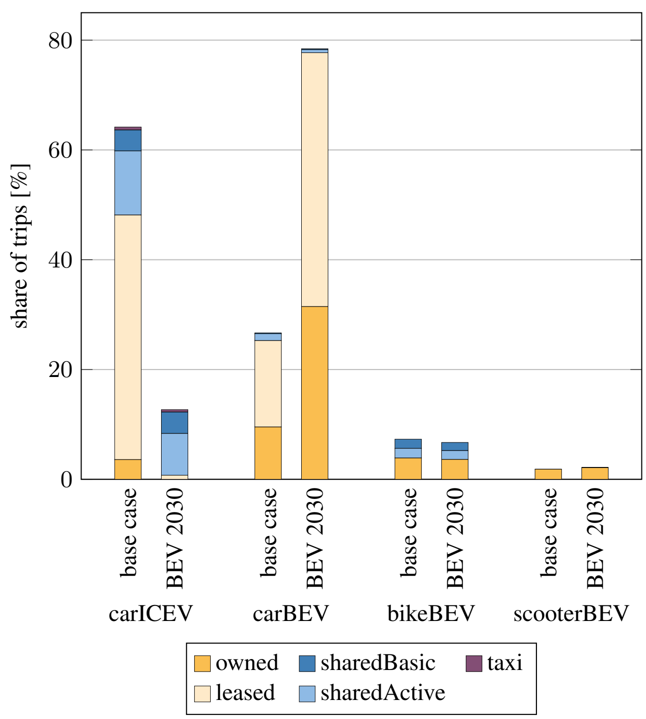

Figure 6-12: Share of trips per mode classified for the type of provision and the price tariff comparing the BEV developments by 2030 with the base case.

6.5.4 Expansion of Car Sharing Services

First, we regard an expansion of car sharing services by only increasing the number of available vehicles at a sharing station compared to the base case. Herein, Figure 6-13 illustrates average cost changes and Figure 6-14 changes of the average company-exclusive car fleet size. Results show that increasing the number of available cars at a station without changing the composition (20 % BEVs) decreases average costs by up to 4 % and the average number of company-exclusive cars by up to 18 % compared to the base case. Improvements are higher in urban areas, while minimal mobility costs and fleet sizes are achieved in rural areas when four cars are added to the stations. The results confirm that the demand of companies for shared cars is not met in the modeled base case.

Additionally, we regard how changes in the fleet composition at car sharing stations influence average cost-savings and the company-exclusive car fleet sizes in Figures 6-13 and 6-14. Results show that the improvements strongly depend on the composition of the drive trains. If we only increase the share of BEVs at a station (50 % BEVs, 100 % BEVs) without changing the total number of available cars, average costs increase compared to the base case. With a combined increase of the car availability and the BEV share, these additional costs and also the car fleet sizes decrease. The increasing costs are mainly caused by the higher costs for shared electric than for shared fossil-fueled cars. Due to the low average distances of trips, the limited driving range of electric cars has rather low impacts.

6.5.5 Insights on the Potentials of CMaaS

Analyzing the above results, several managerial insights on the potentials of CMaaS can be drawn. Those insights can be summed up in five key findings:

The implementation of CMaaS is profitable for companies, especially for those with few trips. With the implementation of CMaaS, all analyzed companies reduce their total mobility costs, but potentials for relative cost-savings increase with a decreasing number of trips. Herein, the fixed system costs of the companies are significantly reduced. In contrast, anticipated operation costs increase slightly due to a shift of trips to public mobility services, especially to car and bike sharing. The reduction in company-exclusive cars, especially owned cars, nearly quadruples the utilization of the company-exclusive car fleets compared to the status quo. As a result, the total potentials for cost-savings are higher for companies with few trips as their fleets were less utilized in the status quo.

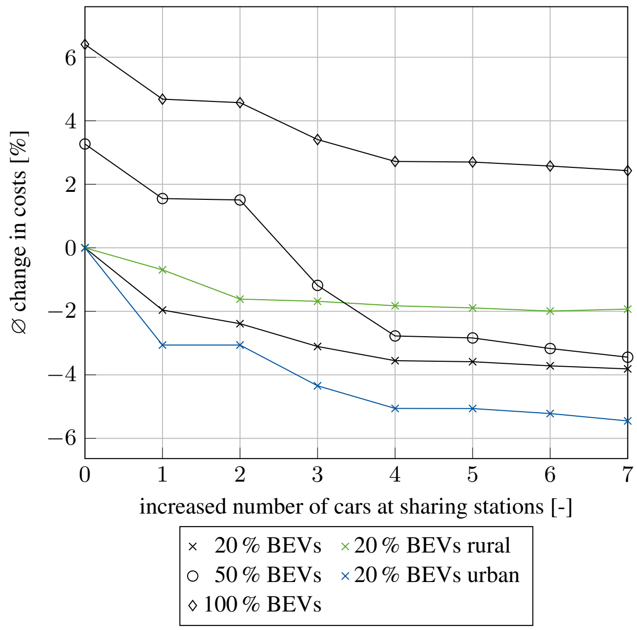

Figure 6-13: Average change in mobility costs compared to the base case for an increase in the availability of cars as well as for a variation in the composition of the drive trains at sharing stations.

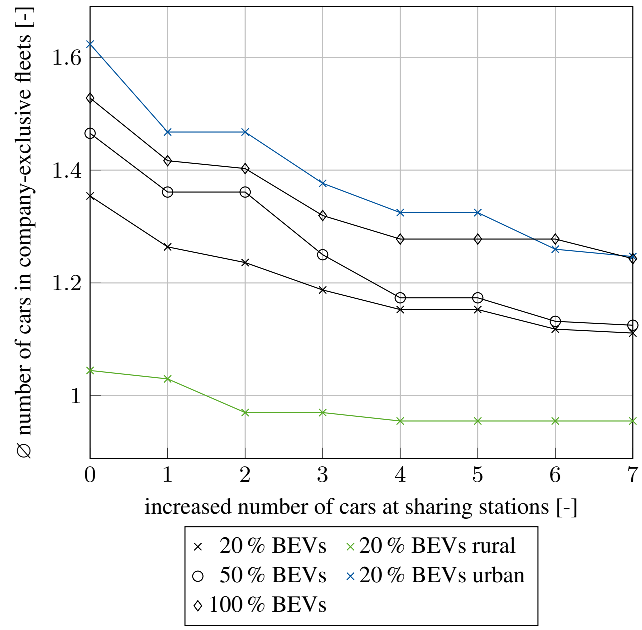

Figure 6-14: Average company-exclusive car fleet size for an increase in the availability of cars as well as for a variation in the composition of the drive trains at sharing stations.

The use of micromobility modes should be promoted in a company. Especially bikes were found to have a considerable impact on the mobility costs of companies and are favorable for most of the considered companies. In this context, the employees' general acceptance of micromobility modes, i.e., the probability to consider bikes or scooters for a trip, has a strong impact on the potentials for cost-savings and the related reduction in company-exclusive car fleets. If employees always consider to use bikes and scooters for trips below certain trip distances, costs can on average be cut in half. With an increase in the maximum driving distances per trip, bikes and scooters can replace more and more car trips and thereby save costs and emissions. Our analyses show that most trips are relatively short, so there is a high potential to use cheap and low-emission micromobility modes instead of cars, as long as no other circumstances, such as the transport of material, prevent its use.

Electric cars will outperform fossil-fueled cars in multimodal corporate fleets in the future. Given the current cost structure, it is still profitable for companies to own more fossil-fueled than electric cars in a CMaaS system. However, the expected future developments of BEVs offer high potentials for reducing costs and emissions. BEVs are expected to replace fossil-fueled cars almost completely in company-exclusive fleets by 2030. However, the developments of BEVs only eliminate fossil-fueled cars in company-exclusive fleets and rarely affect the use of bikes, scooters, and shared cars, indicating that a multimodal system continues to be beneficial.

Bike and car sharing are a good complement to company-exclusive fleets, but the corporate demand for car sharing would currently exceed the supply. Bike and car sharing is used by nearly all companies, while the basic tariff is more profitable for bike sharing and the active tariff for car sharing. Scooter sharing, on the other hand, is rarely profitable for companies. The analyses also reveal that the demand for shared cars can not be met with the current availability of cars at sharing stations. This bottleneck would be exacerbated by the simultaneous decisions of many companies based on this model. Increasing the amount of cars at a sharing station reduces the company-exclusive car fleet and thus the mobility costs. However, increasing the share of electric cars at sharing stations, increases costs. As long as shared BEVs are more expensive than shared ICEVs, an increased electrification rate of shared cars increases the profitability of company-exclusive cars.

Results for rural and urban companies vary, mainly due to the different regional conditions of car sharing. In general, companies in rural areas have higher potentials for cost-savings. Herein, car sharing as well as company-exclusive ICEVs and bikes are more profitable for rural companies. In contrast, electric cars are more profitable in urban areas. As sharing stations in rural areas provide on average more cars, rural companies can meet most of their sharing demand. Accordingly, urban companies profit more from a car sharing expansion and BEV developments.

6.6 Conclusion

In this paper, we presented a strategic-tactical decision support tool for corporate mobility managers to design the cost-minimal CMaaS system for their company. Our model includes strategic decisions on the fleet size and composition of company-exclusive fleets, as well as tactical decisions on the choice of price tariffs offered in public mobility services. By providing decision support for the implementation of a multimodal mobility system in companies, we contribute to a new research stream on the optimization of CMaaS.

In a comprehensive case study with ten mobility services and driving profiles of 144 companies, we drew general insights on the current and future potentials of CMaaS. We demonstrated how the model determines the cost-minimal CMaaS design for a single company and analyzed the aggregated results of all companies. Our results show a high potential to reduce corporate mobility costs by shifting trips to public services and to micromobility modes, especially for companies with few trips and companies in rural areas. Reducing the company-exclusive car fleet has a considerable impact on decreasing the companies' fixed system costs and increasing the fleet utilization. Further, bike and car sharing are both a good complement to company-exclusive fleets, but the corporate demand would currently exceed the supply of cars within car sharing systems, especially in urban areas. The enormous potential identified for the use of micromobility modes instead of cars should encourage companies to promote modes such as bike and scooter. Considering expected future BEV developments, electric cars are expected to replace fossil-fueled cars almost completely in company-exclusive fleets by 2030. Although the optimal strategic-tactical decisions depend on various factors, CMaaS can consistently improve the corporate mobility system.

Our model can be extended in future research. On the one hand, an integration of the mobility demand of commuters offers even higher potential to improve the efficiency of the entire mobility system. On the other hand, in a multi-criteria approach, the objective could be extended by an environmental dimension to analyze the correlation of costs and ecological impacts of mobility services in detail. With regard to BEV developments, future research could further address the transformation process to indicate the optimal strategy for replacing fossil-fueled by electric cars over the course of time. Regarding the application of the model, a specific use case that considers additional aspects, e.g., by including non-driving travel in the mobility demand or incorporating company-specific cost structures, could provide further insights into the quality of our model.

Acknowledgment

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6.A Appendix

Table 6A-1
Cost factors of all considered mobility services and vehicle classes.

service	vehicle class	price tariff	costs in € per vehicle	membership	distance in km	invoice period	trip	references
CarOwned	ICEV M	-	152.42	-	0.32	-	-	[1],[2],[3],[4]
CarOwned	BEV S	-	160.17	-	0.23	-	-	[1],[2],[3],[4]
CarOwned	BEV M	-	161.33	-	0.27	-	-	[1],[2],[3],[4]
CarOwned	BEV L	-	188.42	-	0.34	-	-	[1],[2],[3],[4]
CarLeased	ICEV M	-	291.45	-	0.08	-	-	[1],[4],[5]
CarLeased	BEV S	-	390.21	-	0.02	-	-	[1],[4],[5]
CarLeased	BEV M	-	411.88	-	0.02	-	-	[1],[4],[5]
CarLeased	BEV L	-	490.62	-	0.02	-	-	[1],[4],[5]
CarShared	ICEV S	basic	-	-	0.25	2.00 **	-	[6]
CarShared	ICEV S	active	-	22/+2*	0.23	1.00 **	-	[6]
CarShared	ICEV M	basic	-	-	0.25	3.00 **	-	[6]
CarShared	ICEV M	active	-	22/+2*	0.24	1.40 **	-	[6]
CarShared	ICEV L	basic	-	-	0.25	4.00 **	-	[6]
CarShared	ICEV L	active	-	22/+2*	0.26	1.90 **	-	[6]
CarShared	BEV M	basic	-	22/+2*	0.25	3.00 **	-	[6]
CarShared	BEV M	active	-	22/+2*	0.24	1.40 **	-	[6]
BikeOwned	BEV	-	42.00	-	0.0005	-	-	[7],[8],[9],[10]
BikeLeased	BEV	-	75.00	-	0.0005	-	-	[11]
BikeShared	BEV	basic	-	-	-	2.00 ***	-	[12],[13]
BikeShared	BEV	active	-	15/4/3/2*	-	-	-	[12],[13]
ScooterOwned	BEV	-	17.01	-	0.001	-	-	[8],[9],[14]
ScooterLeased	BEV	-	39.90	-	0.001	-	-	[15]
ScooterShared	BEV	basic	-	-	-	0.22 ****	1.00	[16]
ScooterShared	BEV	active	-	4.99	-	0.22 ****	-	[16]
CarTaxi	ICEV M	-	-	-	2.00	-	3.90	[17]

* For car sharing, the first employee costs 22 € and every further employee 2 €. Costs for public bike sharing refer to companies with <50/50-100/101-500/>500 participating employees, respectively. ** per 60 minutes, *** per 30 minutes, **** per 1 minute [1] ADAC 2021a, [2] Generalzolldirektion 2021, [3] De Clerck et al. 2018, [4] ADAC 2021b, [5] Sixt Leasing 2021, [6] cambio 2020, [7] Dimpker 2019, [8] CHECK24 2021, [9] BMF 2000, [10] Shimano Inc. 2018, [11] Swapfiets 2021, [12] nextbike 2021a, [13] nextbike 2021b, [14] Segway 2021, [15] Grover 2021, [16] TIER 2021, [17] Rat der Stadt Köln 2021

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Chapter 7

Quantifying Emission and Cost Reduction Potentials of Corporate Mobility as a Service

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Abstract

Corporate Mobility as a Service (CMaaS) combines the advantages of company-exclusive and public mobility services, like carsharing, bikesharing, or taxis. Although prior research indicates that CMaaS has positive impacts on the GHG emissions and costs of corporate mobility, detailed analyses are still lacking. Against this background, we propose a methodology to quantify the potentials of CMaaS to reduce the GHG emissions and costs of corporate mobility. We apply a cost estimation, a Life Cycle Assessment, and a multi-objective optimization model to determine the pareto-optimal CMaaS designs for companies aiming to minimize GHG emissions and costs. Within the CMaaS design, we determine the fleet size and composition of company-exclusive, and the choice of price tariffs for public mobility services. By applying our methodology to a comprehensive case study that covers 428 driving profiles of 144 different companies, we deduce general insights on the potentials of CMaaS.

7.1 Introduction

Corporate mobility managers are increasingly confronted with the environmental consequences of corporate mobility behavior. On the one hand, car traffic accounts for 60% of all transport emissions in the EU (excluding international aviation) (cf. EEA 2021). Since companies have a significant impact on transport-induced emissions, e.g., by registering more than half of the new cars in the EU, governmental decision-makers increasingly address them with defossilization policies (cf. Lopez 2020). For instance, the Corporate Sustainability Reporting Directive from 2023 addresses approximately 50,000 companies in the EU and stipulates the publication of corporate emission reduction plans (cf. EC 2023, European Union 2022). Further, first EU countries tax corporate vehicles according to their level of greenhouse gas (GHG) emissions (cf. ACEA 2022). On the other hand, companies face the pressure of society to reduce their environmental footprints, and the demand by their employees for sustainable and innovative mobility solutions. Corporate mobility managers are therefore forced to decrease emissions from corporate fleets, and provide their employees with environmentally friendly and flexible mobility solutions.

Corporate Mobility as a Service (CMaaS) is one concept that might solve the challenges of car-based company fleets, which are associated with high GHG emissions and idle times (cf. Frank et al. 2024). CMaaS describes a multimodal mobility system that can be deployed in companies to meet the corporate mobility demand (cf. Hesselgren et al. 2020). In contrast to traditional fleet management, where owned or leased cars are the only available mobility options, CMaaS provides further alternatives to carry out a corporate trip. First, a CMaaS system can comprise all kinds of mobility modes, e.g., allowing for trips with micromobility modes like bikes and scooters in addition to car trips. Second, CMaaS combines the advantages of company-exclusive and public mobility services. Herein, company-exclusive mobility services are exclusively available to company members, e.g., vehicles that are owned or leased by the company, while public mobility services are available to all members of society, e.g., carsharing or taxi services. By shifting trips from cars to low-emission modes and public mobility services, companies can reduce corporate mobility costs, and simultaneously decrease the environmental impact of their mobility, which benefits society as a whole.

However, to consider CMaaS as a realistic alternative to conventional unimodal fleets, corporate mobility managers need detailed information on its potentials to reduce emissions and costs, which is emphasized by first research on CMaaS. These studies, which accompany real-world trials, yield empirical evidence about the barriers of CMaaS, and show that a lack of experience hinders implementation (cf. Hesselgren et al. 2020, Zhao et al. 2020, Boutueil 2016).

Specifically, the scale of savings due to CMaaS is hard to convey to the management, and the complexity of the multimodal system limits value creation (cf. Hesselgren et al. 2020, Zhao et al. 2020, Boutueil 2016). Accordingly, corporate mobility managers are confronted with considerable challenges when aiming to implement CMaaS. Few works address these challenges so far. Frank et al. (2024) propose a decision support tool that predicts the cost-minimal CMaaS configuration and find that corporate mobility costs can be decreased by 37% on average. Günther et al. (2020) compare the introduction of CMaaS with conventional business travel accounting, and again identify a considerable potential to reduce costs. While these studies analyze the economic potentials of CMaaS, no previous work quantifies its potentials to reduce the GHG emissions of corporate fleets, simultaneously to analyzing the respective costs that would arise for the company.

We contribute to the literature on CMaaS by quantifying its potentials to reduce emissions from corporate mobility, and evaluate the effects of emission reductions on corporate mobility costs. We create general insights on the potential environmental and economic impacts of CMaaS, and identify the optimal system configurations for various companies. Thereby, our work addresses corporate as well as political decision-makers. First, we enable corporate mobility managers to decide on whether and how to implement a CMaaS system in their company. Second, the direct juxtaposition of emissions and costs yields important insights about the impacts of CMaaS systems on the environment, enabling political decision-makers to make better-informed decisions on the design of future mobility systems.

To this end, we apply a mixed-integer multi-objective optimization model, which identifies the optimal configuration of a CMaaS system, minimizing GHG emissions and corporate mobility costs. The model considers the strategic decision of deciding on the fleet size and composition of company-exclusive mobility services, and the tactical decision of choosing price tariffs for public mobility services. We further conduct a cost estimation and a Life Cycle Assessment (LCA) to quantify the costs and GHG emissions for each regarded mobility service. In a comprehensive case study, we apply our methodology to a data base of 144 companies in Germany, considering ten different mobility services. The optimization model generates pareto-optimal solution frontiers, which allow us to evaluate the trade-off between GHG emissions and costs, as well as the overall reduction potentials for companies.

The following work is structured as follows. In Section 7.2, we present a detailed review of previous environmental and cost analyses in the context of CMaaS, as well as of optimization models on the strategic fleet design of public mobility services. Section 7.3 gives an overview of the methodological approach, and in Section 7.4, we present the setting of our case study and the analyzed scenarios. Finally, we present our results in Section 7.5 and draw a conclusion on the insights of our research in Section 7.6.

7.2 Literature Review

CMaaS is defined by Hesselgren et al. (2020) as the corporate specification of Mobility as a Service (MaaS), which is a central platform that meets the mobility demand of customers by integrating the available mobility services (cf. Hietanen 2014). MaaS is characterized by offering a seamless and customized transport service, which integrates all mobility services of a certain region into one digital platform, via which users can plan, book, and pay their trips (cf. Enoch and Potter 2023, Ho et al. 2018, Jittrapirom et al. 2017). Accordingly, CMaaS refers to such a system which is controlled by a company and satisfies the mobility demand of company members within, to, and from the company site by making use of the various mobility services available (cf. Hesselgren et al. 2020). In the following, we first give an overview of existing approaches to assess the environmental impacts and cost advantages of public and corporate MaaS systems (cf. Section 7.2.1). Although the approach presented in this paper has not been performed on MaaS before, related approaches exist, which include single- and multi-objective optimization models on the strategic fleet design of public mobility services and are presented in Section 7.2.2.

7.2.1 Environmental and Cost Assessments of Mobility as a Service

First studies assess environmental impacts of public MaaS systems. Becker et al. (2020) conduct an agent-based simulation of Zurich, finding that a less biased mode choice through the usage of MaaS would lead to both, reduced energy consumption and increased energy efficiency. Eckhardt et al. (2020) monitor various rural MaaS pilots in Finland with workshops and surveys, identifying improved resource efficiency by higher occupancy rates and reduced emissions due to fewer kilometers driven. Further studies deduce insights about the environmental impact of MaaS from the stated or observed mode choice. Herein, most studies suggest a reduction of transport emissions under MaaS and improved sustainability of the transport system (cf. Labee et al. 2022, Jang et al. 2020, Strömberg et al. 2018). However, some studies are ambiguous regarding the environmental impact of MaaS as they find an increase in both, the use of public transportation and the use of carsharing (cf. Sochor et al. 2016, "Implementing Mobility as a Service: Challenges in Integrating User, Commercial, and Societal Perspective" n.d.). Alyavina et al. (2020) point out that the desired behavior changes are hardly achieved without additional incentives. Further literature analyses exist on risks and opportunities of MaaS (cf. Lindkvist and Melander 2022, Wittstock and Teuteberg 2019) and of new mobility services in general (cf. Storme et al. 2021). Only Chi and Mazzer (2022) analyze the economic impacts of MaaS, quantifying the economic benefits of different options. They find that promoting public and active travel creates the largest economic benefits of MaaS.

Only few studies focus on the evaluation of CMaaS and to the best of our knowledge, no environmental assessments exist for CMaaS systems. Hesselgren et al. (2020) conduct interviews in the context of a CMaaS pilot, evaluating how CMaaS can be implemented sustainably, and find that changes in the mobility patterns of employees are achieved by the inclusion of electric bikes. Vaddadi et al. (2020) develop and test an evaluation framework, in which they deduce and quantify KPIs for CMaaS systems and include GHG emissions as one relevant dimension. Zhao et al. (2020) take a system thinking approach to evaluate the barriers to CMaaS implementation, and find that cost advantages could not be fully captured due to the complexity of CMaaS and lacking integration with different departments. All three works analyze a large-scale CMaaS trial in Sweden. Further, Amaral et al. (2020) describe the implementation of CMaaS in a Portuguese trial, identifying an improvement in the company's environmental KPIs. Günther et al. (2020) evaluate the potentials for cost reductions and the user attitudes during a CMaaS trial in Germany, and find that costs can be saved by implementing the analyzed CMaaS system. All works primarily regard the perspective of the implementing company, and rarely put emphasis on the concrete environmental and cost impacts of the system.

7.2.2 Strategic Fleet Design of Public Mobility Services

Optimization models on strategic fleet design, which are related to the approach of this work, determine the optimal fleet size and composition, typically by minimizing mobility costs (cf. Gould 1969, Dantzig and Fulkerson 1954). Within this field, one publication considers a multimodal mobility system and identifies the cost-minimal configuration of various mobility services (cf. Frank et al. 2024). Further research focuses mainly on the optimal size and composition of shared unimodal vehicle fleets. Herein, models exist for station-based roundtrip systems where vehicles must be returned to the pick-up station (cf. Yoon and Cherry 2018), for station-based one-way systems where vehicles can be returned to any station (cf. Ahani et al. 2023, Luo et al. 2020, Maggioni et al. 2019, Hu and Liu 2016, Frade and Ribeiro 2015, George and Xia 2011), and for free-floating systems where legal on-street parking is allowed (cf. Weikl and Bogenberger 2013). In addition to the fleet size, Hu and Liu (2016) determine the available carsharing station capacities. Yoon and Cherry (2018) incorporate the fleet composition with regard to characteristics of battery electric vehicles (BEVs) and base their strategic decisions on historic driving profiles to anticipate the future operation of the fleet. Wallar et al. (2019) model different types of internal combustion engine vehicles (ICEVs) to provide the optimally composed car fleet for ridesharing, anticipating the fleet operations with historical taxi requests in Manhattan and Singapore. Recent models for public bikesharing systems determine the optimal fleet size, anticipate fleet operations based on the historical demand, and additionally account for the station locations (cf. Frade and Ribeiro 2015), GHG emissions (cf. Luo et al. 2020), or the stochastic demand (cf. Maggioni et al. 2019).

Only few works apply multi-objective optimization in the field of strategic fleet design of public mobility services. Lemme et al. (2019) regard a heterogeneous carsharing fleet in Fortaleza, Brazil, and minimize operation as well as pollution costs to identify the optimal fleet composition of BEVs and ICEVs. Boyacı et al. (2015) maximize the benefits of both, the operator and the users of a carsharing system in Nice, France, to identify the optimal fleet size. While no multi-objective optimization model includes life cycle emissions as a dimension for public mobility services, related models can be found in sustainable trucking. Sen et al. (2019) maximize the transport capacity of trucks and further minimize life cycle costs, life cycle emissions, and externality costs of air pollution regarding various types of trucks. Herein, they integrate national economic input-output tables into traditional process-based LCA to better account for the requirements of complex supply chains. Sawik et al. (2017) identify the truck fleet composition with the maximum transport capacity while minimizing operational GHG emissions, fuel consumption, and noise emissions, applying data from the literature.

The literature on CMaaS does not only lack a thorough analysis about its potentials to reduce emissions (cf. Section 7.2.1), but also a suitable methodology. To the best of our knowledge, no existing work optimizes the fleet size and composition of a multimodal mobility system, while considering its emissions. Existing models are mainly single-objective and focus on cost minimization or regard cost equivalents instead of the immediate emissions. A comparable approach exists in sustainable trucking, although it does not consider multimodality. Therefore, we develop a methodological approach, in which we first quantify the GHG emissions and costs of mobility services, and then integrate these results into a multi-objective optimization model, which optimizes the CMaaS design for companies.

7.3 Methodological Approach

CMaaS has the potential to provide companies with a cost-efficient mobility system which has a minimum impact on the environment. So far, there is no information about the scope of possible emission reductions by CMaaS as well as the interrelation of costs and GHG emissions, which impedes a wide implementation in companies. To generate insights on the environmental potentials of CMaaS, we propose a model that identifies the optimal CMaaS design with respect to costs and emissions. Herein, our methodology consists of four parts. First, we present the problem setting and define the relevant decisions (cf. Section 7.3.1). Subsequently, we conduct a structured cost estimation and an LCA to quantify consistent costs and life cycle emissions for all regarded mobility services (cf. Sections 7.3.2 and 7.3.3). Finally, we present our multi-objective optimization model, which identifies the pareto-optimal CMaaS designs (cf. Section 7.3.4).

7.3.1 Problem Setting

When designing a CMaaS system, corporate mobility managers need to consider the various mobility options available to meet their mobility demand. Each mobility option is specified by a combination of mobility service and vehicle class. We define a mobility service as the type of provision via which a vehicle is made accessible to the company, e.g., being owned, leased, or shared. Herein, we differentiate between those mobility services, which are exclusively available to members of the company (company-exclusive mobility services) and those, which are available to the general public (public mobility services). The vehicle class is defined as the combination of the mobility mode, e.g., car or bike, and the technical specifications of the vehicle, e.g., regarding the drive train technology and the size or passenger capacity. Some types of provision, e.g., shared services, require a special service infrastructure.

Specifying the optimal CMaaS design among the variety of mobility options requires two decisions. First, the fleet size and composition of the company-exclusive fleet must be defined. Specifically, it must be determined how many vehicles from a specific vehicle class are provided to the company via which mobility service. Second, the price tariffs for public mobility services must be chosen, because they may differ in terms of the amount of the costs and the types of fees included. One common example is the distinction between a basic and an active price tariff. When using a basic price tariff, users pay certain fees per trip, per time unit, and/or per distance unit. These fees are lower in the active price tariff, but an additional membership fee is charged. The decisions made regarding the company-exclusive fleet size and composition and the price tariffs of public mobility services directly influence the costs and GHG emissions of the company's CMaaS system.

7.3.2 Cost Estimation Framework

We analyze the costs of the regarded mobility services by identifying and quantifying the relevant costs and summarizing them under a framework of cost parameters. The framework considers the following requirements. First, the cost structures of the different mobility services must be reflected, e.g., the differentiation of fixed and variable costs. Second, the fixed costs should refer to a representative period, e.g., four weeks, so that the results of our analyses can be flexibly adapted to the time scope of the company-specific input data (cf. Section 7.3.4), enabling corporate mobility managers to project these costs into the future, according to their individual requirements, e.g., planning horizon and discounting methods. Third, all relevant costs are assigned to one of the cost parameters.

The relevant cost parameters of the CMaaS system depend on whether company-exclusive mobility services, public mobility services, or both are used. For company-exclusive vehicles, companies must cover fixed costs per vehicle, which occur for each considered time period and independently of the vehicle's usage, e.g., depreciation or insurance. Additionally, distance-related costs, e.g., for fuel or electricity, occur in consequence of the driven number of kilometers with a specific vehicle. When using public mobility services, the costs depend on the chosen price tariff and can include fixed costs for memberships, and variable costs per trip, per time unit and/or per distance unit. The specific amounts of costs for company-exclusive mobility services are predetermined by the prices of vehicles and insurances, by the amount of taxes, and by average energy prices, while the costs of public mobility services are determined by the service providers. All cost parameters and the considered costs are presented in Table 7-1. A detailed view of the used data and respective data sources is provided in the appendix.

Table 7-1
Cost parameters.

	cost parameter	**considered costs**
company-exclusive mobility services	costs per vehicle	- purchase prices, charging infrastructure, depreciation, taxes, parking spaces, leasing rates, insurances
	costs per distance-unit	- energy costs, maintenance
public mobility services	costs per distance-unit costs per trip costs per time-unit costs for memberships	- defined by the price tariffs of mobility service providers

7.3.3 Life Cycle Assessment

LCAs are generally applied to calculate the environmental impacts of a product, service, or system during its life cycle related to a functional unit (cf. ISO 2006). Analogously, we apply an LCA to assess the environmental impacts of the considered mobility services over their lifetime. We quantify the life cycle emissions for each combination of mobility service and vehicle class for a functional unit of one passenger kilometer (pkm), following the approach of current LCAs on passenger transportation (cf. Ishaq et al. 2022, de Bortoli 2021). We use the ecoinvent database v3.71 in openLCA 1.10.3. The full inventory, including underlying data and the respective data sources, is provided in the appendix. We focus our analysis on CO_2 equivalents as measured by the category "Global Warming Potential" of the impact assessment method ReCiPe Midpoint (E), considering the fact that most companies base their sustainability reporting on CO_2 emissions.

A uniform setting with consistent definitions and assumptions underlies our LCA, which allows us to directly compare the environmental impacts of the different mobility options. Figure 7-1 shows the system boundary of the LCA. Resource extraction, the production phase, the use phase, and end-of-life processes for all mobility options are regarded. The production phase includes fuel refinery, vehicle manufacture, as well as the construction of road and service infrastructure. While required road space and charging infrastructure is often omitted in LCAs on conventional transportation modes, its consideration becomes relevant for new sharing mobility services as shared vehicles require considerably less parking space than individual or company-exclusive cars (cf. bcs 2019), and shared micromobility modes often require a sharing station, e.g., with docks and charging options (cf. Luo et al. 2019). Most data could be retrieved directly from scientific and official publications, however, some values are approximated according to the following specifications. First, to quantify the demand for road and parking space of the mobility options, we follow the procedure of Spielmann et al. (2007), using updated data for Germany. Second, electricity is assumed to be provided as the national grid mix in the phases resource extraction, the production phase, and the end-of-life phase, while we assume that the companies utilize renewable energy in the use phase to reach their climate targets (cf. ALDI 2022, BMW 2023).

7.3.4 Multi-Objective Optimization Model

We identify the CMaaS designs with minimal costs and GHG emissions for each company by applying a strategic-tactical optimization model, for which we build on the single-objective

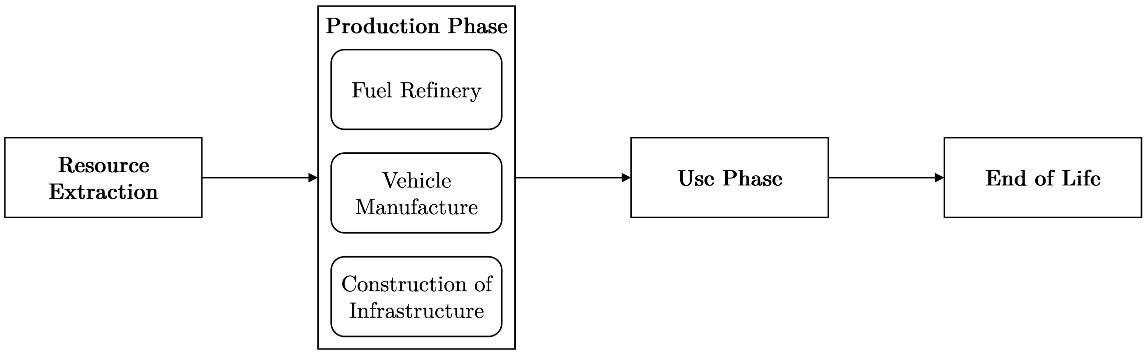

Figure 7-1: Scope of the LCA.

optimization model previously developed by Frank et al. (2024). The model determines the optimal fleet size and composition of company-exclusive mobility services (strategic decision) and the optimal price tariffs of public mobility services (tactical decision). To solve the model for two objectives simultaneously, we apply the augmented ε-constraint method (AUGMECON) as proposed by Mavrotas (2009). The model generates a set of pareto-optimal solutions regarding costs and GHG emissions, i.e., the company's pareto-front. Solutions are pareto-optimal when one objective cannot be improved without impairing another objective (cf. Censor 1977). In each pareto-optimal setting, the fleet size and composition is determined by the maximum number of simultaneously required company-exclusive vehicles, while price tariffs are determined by the usage patterns of public mobility services.

The pareto-optimal CMaaS designs must meet the entire mobility demand of the regarded company. Therefore, the decision support tool requires a representative set of trips with explicit information on start and end times, as well as distances traveled, as data input, e.g., from logbooks of existing vehicles or from records of the travel management department. The model allocates these trips to available mobility services, identifying the optimal combination of mobility services, vehicle classes, and price tariffs. We restrict the range of feasible mobility services and vehicle classes as follows. First, the technical characteristics of the used vehicle class must comply with the needs of the regarded trip, e.g., regarding driving range or passenger capacity. Second, the number of available vehicles might be limited, e.g., due to space restrictions at the company site or due to reservations of public mobility services by company-external users. Finally, we account for the fact that not every employee is willing to use micromobility modes, e.g., due to personal preference, limited comfort, or the weather condition. Thus, we include a factor in our model, which indicates to what extent employees consider micromobility modes.

We notate the two regarded objectives as follows. The first objective function minimizes the total costs of the CMaaS system over the planning horizon, differentiating between fixed system costs (C^{system}) and anticipated costs of operation ($C^{\text{operation}}$), which represent the variable costs (cf. Equation 1). Fixed system costs, which occur independently of the undertaken trips, consist of the costs per vehicle (c_{sv}^{veh}) within the company-exclusive fleet (x_{sv}^{E}) as well as the costs of memberships (c_{sp}^{mem}) for the selected price tariffs of public mobility services (y_{sp}) (cf. Equation 2). Anticipated costs of operation occur in dependence of the mobility behavior and include costs per distance unit (c_{isvp}^{dist}), as well as costs per time unit (c_{isvp}^{time}) and per trip (c_{isvp}^{trip}) as claimed by public mobility service providers (cf. Equation 3). Herein, we account for the limited willingness to consider micromobility modes by modeling two micromobility settings (w) for each trip, i.e., a setting in which micromobility modes are considered in the mobility portfolio of the employees and a setting in which they are ignored ($w = consMicro, ignMicro$). To this end, we define factor γ^w that represents the occurrence of micromobility setting w. We further consider the different trip characteristics, which influence the allocation of mobility service and vehicle class (a_{svpi}^w). The second objective function minimizes the anticipated GHG emissions per passenger kilometer (e_{isv}^{dist}) for each company (cf. Equation 4). Like the anticipated costs of operation, the anticipated GHG emissions depend on the employees' willingness to consider micromobility modes and the trip characteristics. Table 7-2 gives an overview of the model notation of the objective functions. For the comprehensive model notation, compare the appendix.

$$\min \quad Z_1 = C^{\text{system}} + C^{\text{operation}} \tag{1}$$

$$C^{\text{system}} = \sum_{s \in \mathcal{S}^{\text{E}}} \sum_{v \in \mathcal{V}_s} c_{sv}^{\text{veh}} x_{sv}^{\text{E}} + \sum_{s \in \mathcal{S} \setminus \mathcal{S}^{\text{E}}} \sum_{p \in \mathcal{P}_s} c_{sp}^{\text{mem}} y_{sp} \tag{2}$$

$$C^{\text{operation}} = \sum_{w \in \mathcal{W}} \sum_{s \in \mathcal{S}} \sum_{i \in I} \sum_{v \in \mathcal{V}_{si}^w} \sum_{p \in \mathcal{P}_s} (c_{isvp}^{\text{dist}} + c_{isvp}^{\text{time}} + c_{isvp}^{\text{trip}}) \gamma^w a_{svpi}^w \tag{3}$$

$$\min \quad Z_2 = \sum_{w \in \mathcal{W}} \sum_{s \in \mathcal{S}} \sum_{i \in I} \sum_{v \in \mathcal{V}_{si}^w} \sum_{p \in \mathcal{P}_s} e_{isv}^{\text{dist}} \gamma^w a_{svpi}^w \tag{4}$$

Table 7-2
Model notation.

Sets	
$\mathcal{S}$	set of mobility services
$\mathcal{S}^{\mathrm{E}}$	set of company-exclusive mobility services
$\mathcal{V}_s$	set of vehicle classes of mobility service s
$\mathcal{P}_s$	set of price tariffs of mobility service s
$\mathcal{W}$	set of micromobility settings
I	set of trips
I^w_{svt}	set of trips that occupy a vehicle in period t if mobility service s with vehicle class v is used in micromobility setting w
$\mathcal{V}^w_{si}$	set of feasible vehicle classes of mobility service s for trip i in micromobility setting w
Parameters	
c^{veh}_{sv}	costs per vehicle of company-exclusive mobility service s in vehicle class v
c^{mem}_{sp}	total membership costs of public mobility service s in price tariff p
c^{trip}_{isvp}	basic trip costs of trip i with mobility service s in vehicle class v and price tariff p
c^{dist}_{isvp}	distance costs of trip i with mobility service s in vehicle class v and price tariff p
c^{time}_{isvp}	time costs of trip i with mobility service s in vehicle class v and price tariff p
e^{dist}_{isv}	GHG emissions of trip i with mobility service s in vehicle class v
γ^w	factor determining the occurrence of micromobility setting w ($\sum_{w\in\mathcal{W}}\gamma^w = 1$)
Decision variables	
x^{E}_{sv}	integer: fleet size of company-exclusive mobility service s in vehicle class v
y_{sp}	binary: 1 if price tariff p is selected for public mobility service s, 0 otherwise
a^w_{svpi}	binary: 1 if mobility service s with vehicle class v and price tariff p is selected for trip i in micromobility setting w, 0 otherwise

7.4 Case Study

We create insights on the potentials of CMaaS by applying our methodology to a comprehensive data base of companies in Germany. In our case study, we compare the results of a CMaaS system with traditional fleet management. We additionally apply a scenario analysis to analyze how companies can be encouraged to choose the CMaaS design with lower environmental impacts. In the following, we will first present the data on which we base our case study (cf. Section 7.4.1) and then describe our experimental design (cf. Section 7.4.2).

7.4.1 Setting

In our case study, we determine the optimal design of a CMaaS system for 144 companies with commercially licensed passenger cars based on the historic mobility demand from the REM 2030 driving profiles data base collected by the Fraunhofer Institute for System and Innovation

Research (cf. Fraunhofer 2021). The driving profiles were collected from existing corporate vehicle fleets over a course of four weeks, providing information on each trip made with a company car, i.e., type and size of the vehicle, time stamps of departure and arrival, as well as distance, and on the company, i.e., company size, economic sector, and city size. The following trips are neglected in our analysis: trips below 500m, trips with transporters and special vehicles, as well as trips by taxi companies. We regard time intervals of 15 minutes in our analysis. An extract of the driving profiles is presented in Table 7-3 and the key indicators of the analyzed companies are presented in Table 7-4.

Table 7-3: Exemplary trip as listed in the driving profiles.

	departure					arrival					
vehicle ID	year	month	day	hour	minute	year	month	day	hour	minute	distance
1106000341	2011	7	6	9	35	2011	7	6	11	46	26.19

Table 7-4: Key indicators of the analyzed driving profiles and an exemplary company.

	data base
number of companies [-]	144
number of driving profiles [-]	428
∅ number of trips per company [-]	322
∅ trip distance per company [km]	13
∅ company mileage [km]	3,424
∅ trip duration per company [min]	19

We regard the mobility services listed in Table 7-5 and denote them by the mobility mode, i.e., car, bike, or scooter, and/or the type of provision, i.e., owned, leased, shared, or taxi. We assume that all regarded mobility services are available to all considered companies and that shared vehicles are accessible within a reasonable distance from the company location. For each mobility service, we consider the vehicle classes as defined in Table 7-6. The vehicle class is defined by the drive train technology and by the size. For cars, we consider ICEVs and BEVs in two different sizes, while bikes and scooters are unanimously BEVs in a single size. The different sizes of the considered cars impact the battery characteristics of BEVs as well as the availability and costs of shared mobility services. The technical details of each vehicle class are specified according to one real-world vehicle model, which fulfills the technical and informational requirements for our analysis, a.o., access time, speed, maximum driving distance, and consumption as well as charging capacity in the case of BEVs. Note that not all vehicle classes are available for all mobility services. For a comprehensive overview of the considered vehicle classes and further assumptions, compare the appendix.

Table 7-5
Notation of mobility services.

		company-exclusive		**public**	
	provision	owned	leased	shared	taxi
mode	car	*carOwned*	*carLeased*	*carShared*	*taxi*
	bike	*bikeOwned*	*bikeLeased*	*bikeShared*	-
	scooter	*scooterOwned*	*scooterLeased*	*scooterShared*	-

Table 7-6
Technical details of vehicle classes.

mode	**vehicle class**	**access time [min]**	**speed [km/h]**	**max. distance [km]**	**consumption per 100 km**	**charging capacity [kW]**	**reference**
car	ICEV S	11	24.1	∞	4.1 l	-	[1],[2],[3]
	ICEV M			∞	5.5 l	-	[1],[2],[4]
	BEV S			190	13.0 kWh	11	[1],[2],[5]
	BEV M			353	15.8 kWh	11	[1],[2],[6]
bike	BEV	5	18.5	13	0.35 kWh	0.112	[1],[7],[8]
scooter	BEV	5	18.5	2	0.92 kWh	0.056	[1],[9],[10],[11]

[1] Umweltbundesamt 2014, [2] Cardelino 1998, [3] ADAC 2023d, [4] ADAC 2023e, [5] ADAC 2023b, [6] ADAC 2023c, [7] Shimano Inc. 2018, [8] Cairns et al. 2017, [9] Cao et al. 2021, [10] Grover 2021, [11] Zhu et al. 2020.

The vehicles that serve a trip are occupied for a fixed access time, the travel time, and the charging duration of BEVs. The access time represents the duration of accessing and exiting the mobility mode, e.g., for searching parking spaces and (un-)locking vehicles. The travel time is determined with respect to the vehicle speed as well as the trip distance, and includes the duration of the appointment for most mobility services. Taxis are an exception, being available at all times and locations, so that they are only booked during the drive to and from the appointment. The charging duration of BEVs depends on the vehicle's consumption (kWh) and charging capacity (kW) under the condition that they are charged at conventional AC charging stations. For simplicity, we disregard charging losses and assume an average plug-in time of three minutes.

The willingness of employees to use micromobility modes depends on external and internal determinants, like the weather and personal preference (cf. Zhu et al. 2020). We follow the literature and assume that 51% of the employees are willing to use micromobility modes on days without rainfall, which in Germany constitute on average 50% of the year (cf. DWD 2023). While the feasibility of electric cars for a trip is limited by their battery range, we specify the maximum driving distance of bikes and scooters as the average driving distances per trip as surveyed in recent studies (cf. Cao et al. 2021, Cairns et al. 2017).

The availability of shared vehicles is determined by data from the literature. We assume that a maximum amount of seven shared cars is available at a sharing station, of which small BEVs and medium-sized ICEVs each constitute 30%, and small ICEVs 40% of the available vehicles. Medium-sized BEVs are disregarded here, since shared electric cars are rarer and have a lower variety of vehicle classes in shared fleets than ICEVs (cf. bcs 2023, cambio 2020). The maximum number of available shared bikes and scooters are twelve and six, respectively (cf. KVB 2021, Stadt Köln 2021, Luo et al. 2019). The availability of shared vehicles is further restricted by bookings from users outside the company as surveyed by Boldrini et al. (2016).

The cost estimation framework and the LCA presented in Sections 7.3.2 and 7.3.3 determine the costs and GHG emissions of each combination of mobility service, vehicle class, and price tariff. In the cost estimation, we apply average fuel and electricity prices of 2022 for all mobility services (cf. BDEW 2023, en2x 2023). A sensitivity analysis, which examines the dimension of fuel and electricity price impacts, can be found in the appendix. We further regard a basic and an active price tariff as offered by many sharing service providers (cf. nextbike 2021, TIER 2021, cambio 2020). Since membership costs incur per participating employee and usually become cheaper with increasing participation, we assume that 20% of the employees per company are included. Owned and leased vehicles do not differ with regard to their GHG emissions, but the following assumptions are made for shared vehicles in the LCA. First, we assume that shared cars require 87.5% less parking space per pkm than company-exclusive cars as studies show that one shared car fulfills the mobility demand of eight company-exclusive cars (cf. bcs 2019). Second, we model fixed docking stations for shared bikes (cf. Luo et al. 2019). Third, shared scooters require on average 1.5 batteries during their lifetimes and they are heavier than company-exclusive scooters to be more robust (cf. ADAC 2020, Severengiz et al. 2020). Fourth, shared bikes and scooters have a reduced expected lifetime compared to company-exclusive vehicles due to vandalism, and they require relocation efforts to guarantee a uniform distribution over the serviced area (cf. de Bortoli 2021).

7.4.2 Experimental Design

We analyze the optimal CMaaS design for each of the considered companies in a base case (BC), applying the specifications as presented in Section 7.4.1. Herein, we compare the base case results with the status quo (SQ), where fleets are exclusively composed of owned and leased cars (BEVs and ICEVs), as in traditional fleet management. Beyond this main analysis, we analyze how political measures can support companies in designing their CMaaS system more environmentally friendly in a scenario analysis. First, we regard the impact of an increased willingness to use micromobility modes, which can be achieved by improving the transport infrastructure for micromobility (cf. Kraus and Koch 2021). To model this change, we increase the occurrence factor for the setting in which micromobility is considered ($\gamma^{consMicro}$) to up to 1 (SC1). Second, we consider the fact that policy-makers globally implement sustainable mobility policies for passenger car usage within municipalities. First, we model a penalization of ICEVs by regarding the introduction of low-emission zones to reduce the negative impacts of fossil-fueled cars on the city (SC2a). Specifically, we analyze how a fee of 5€ per trip with ICEVs changes the optimal CMaaS designs of companies, following the example of the city of London (cf. TfL 2023). Second, we analyze how a dense network of high-quality charging stations for electric cars impacts the results, following the examples of Amsterdam, Netherlands, and Auckland, New Zealand (SC2b) (cf. IEA 2021). Herein, we assume that fast charging stations are universally accessible, so that charging times become negligible. Third, we investigate how the optimal CMaaS designs of companies are impacted by the availability of sharing services, which can be increased by a more intense collaboration between city officials and carsharing operators (cf. Tuominen et al. 2019). Herein, we analyze the impact of doubling the maximum available number of shared vehicles, while keeping the share of BEVs and the number of bookings by the general public constant (SC3a), and additionally increasing the share of BEVs to 60% of the vehicles, i.e., 30% small and medium-sized BEVs, as well as 20% small and medium-sized ICEVs (SC3b).

7.5 Results

We present our case study results in the following chapter. Section 7.5.1 gives an overview of the base case results compared to the results of the status quo. Herein, we first present the pareto fronts and the strategic-tactical decisions for one exemplary company. We further present the aggregated results for all analyzed companies to derive general insights on the potentials of CMaaS. Since companies are often forced to minimize costs and forfeit the further potentials of CMaaS to reduce GHG emissions, we analyze in Section 7.5.2 how different political measures could encourage companies to implement a more sustainable CMaaS design.

7.5.1 Base Case

We first conduct a basic analysis for an exemplary company, which is representative regarding the number of performed trips, to illustrate the results of our model. The exemplary company performs 375 trips with a total mileage of 1460.6 km and an average trip distance of 3.9 km/trip (min: 0.5 km/trip, max: 29.8 km/trip). Figure 7-2 juxtaposes the pareto fronts of the company in the status quo and in the base case. Each point on the pareto front is a combination of the cost objective value (in Euros) and the emission objective value (in kg CO_2 equivalents), calculated as the sum of costs and GHG emissions of this company over the time horizon of four weeks. We denote the extreme points highlighted in the figure as pareto optimum $minC$, where costs are minimized primarily, and pareto optimum $minE$, where GHG emissions are minimized primarily. In these points, the other objective is minimized under the condition that the primary objective takes its minimal value. Each other point on the pareto front corresponds to a pareto-optimal combination of the two objective values. For the exemplary company, the curve progressions in Figure 7-2 show that overall improvements of costs and GHG emissions can be achieved in the base case. However, the mobility costs in $minE$ increase by 159€ to reduce the GHG emissions by further 14 kg CO_2 equivalents compared to the status quo. Table 7-7 presents the determined fleet size and composition of the company-exclusive mobility services, as well as the price tariffs for public mobility services in $minC$ and $minE$. In the status quo, the company can only choose from owned and leased cars with different drive trains to minimize costs or GHG emissions. Herein, the results show that more BEVs than ICEVs are needed due to recharging after the trips. In the base case, the CMaaS system with the minimal costs and GHG emissions consists of various company-exclusive as well as public mobility services.

In the following, we analyze the results over all regarded companies. Figure 7-3 presents the average pareto front for each scenario and Table 7-8 gives further details on objective values, fleet sizes, and trip shares. Both pareto fronts have a strictly convex shape, illustrating that costs and GHG emissions can be reduced at the expense of the other dimension. The slope of the two pareto fronts is similar, with cost increases of 30% from $minC$ enabling GHG emission reductions of approx. 46%. However, we find that the pareto front of the base case allows for lower overall GHG emissions, reducing the maximum GHG emissions in $minC$ by 2% and the

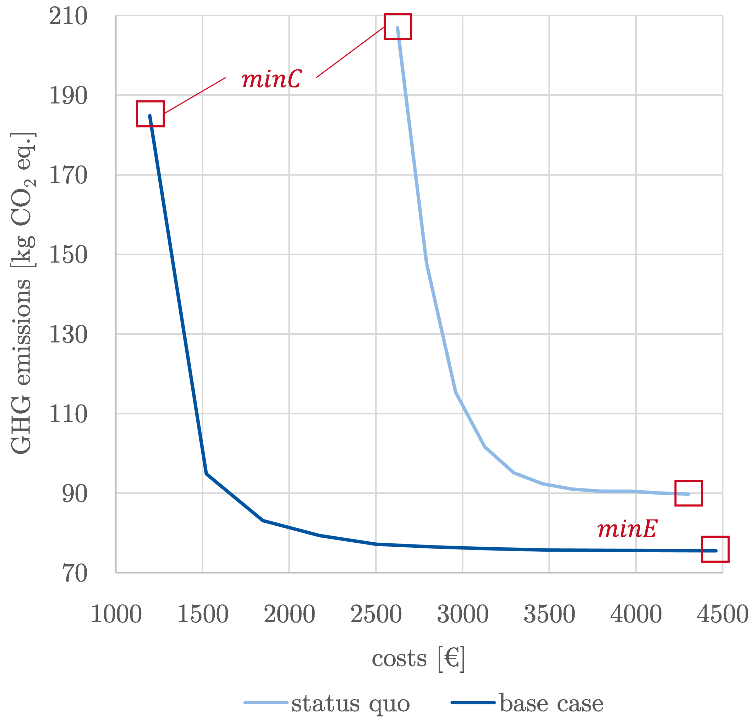

Figure 7-2: Pareto fronts of the exemplary company in the SQ and the BC.

minimum GHG emissions in $minE$ by 8%. At the same time, when applying the minimum amount of costs of the status quo in the base case, companies can reduce their GHG emissions by more than half. Therefore, the introduction of CMaaS allows companies to significantly reduce their costs and GHG emissions, mainly by choosing from a larger set of mobility services to conduct trips. In $minC$, companies benefit from higher efficiency and lower costs of small fleets, while larger company-exclusive fleets are determined to always enable a trip with the mobility service emitting the least in $minE$. Finally, we find that lower GHG emissions can be achieved by the increased use of BEVs, micromobility modes, and public mobility services.

For each analyzed company, Figures 7-4 and 7-5 depict how the objective values change in the base case as compared to the status quo and how these changes relate to the number of trips per company in $minC$ and $minE$. We find that all companies can decrease costs and GHG emissions in $minC$ and $minE$, respectively. Both objectives can be reduced for nearly all companies in $minC$, which illustrates that CMaaS is advantageous for companies and for the environment in the case of cost-minimization. Beyond that, positive environmental effects can be achieved when companies consider GHG emissions in their decision-making. In $minE$, all companies achieve

Table 7-7
Strategic-tactical decisions for the exemplary company.

		company-exclusive: fleet size				public: price tariff			
	mode	car	car	bike	scooter	car	bike	scooter	
	specification	BEV	ICEV	BEV	BEV	shared	shared	shared	taxi
SQ	*minC*	0	8	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	minE	9	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
BC	*minC*	0	2	0	1	active	basic	-	✓
	minE	8	0	8	0	active	-	-	-

n.a. = not available

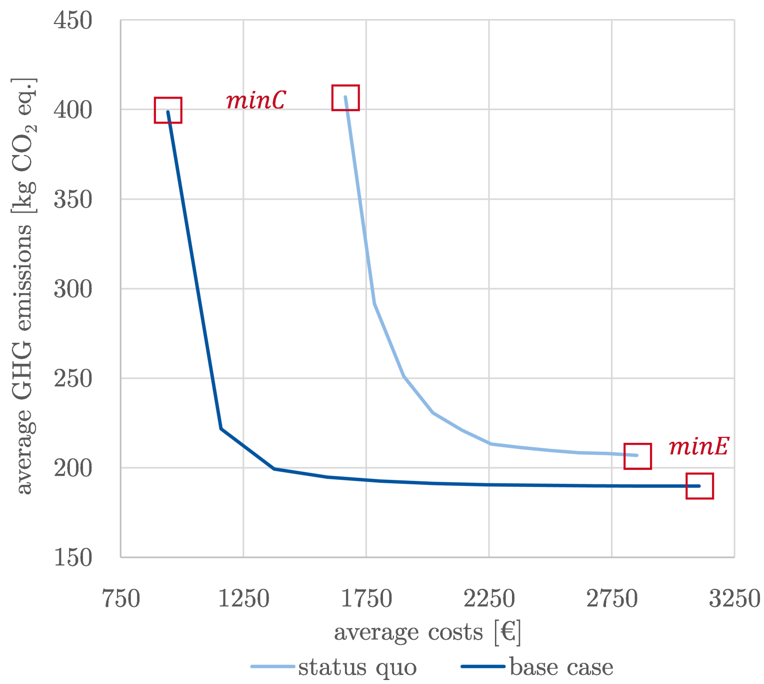

Figure 7-3: Average pareto fronts in the SQ and the BC.

GHG emission reductions, but while mobility costs decrease significantly for some companies with few trips, they increase for most companies. We conducted a comprehensive analysis of further trip and company characteristics, but results do not change considerably when regarding companies with different average trip distances or from certain industrial sectors. Only the total mileage as recorded in the company's driving profiles was found to influence the results (total, costs, and emissions) explicitly.

Table 7-8
Key indicators.

	Status Quo		Base Case	
	minC	*minE*	*minC*	*minE*
∅ mobility costs [€]	1665.41	2852.11	942.66	3102.47
∅ GHG emissions [kg CO_2 eq.]	406.97	206.93	398.66	189.69
∅ company-exclusive fleet size [-]	4.27	5.61	1.44	8.84
trips with BEVs [%]	14.57	99.94	32.79	99.95
trips with micromobility modes [%]	n.a.	n.a.	11.76	20.33
trips with public mobility services [%]	n.a.	n.a.	25.64	37.07

n.a. = not available

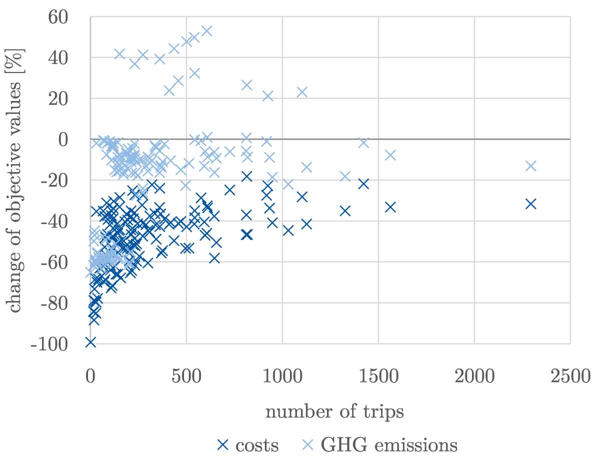

Figure 7-4: Depiction of how the objective values in *minC* change in the BC when compared to the SQ (y-Axis), depending on the number of trips of each company (x-Axis).

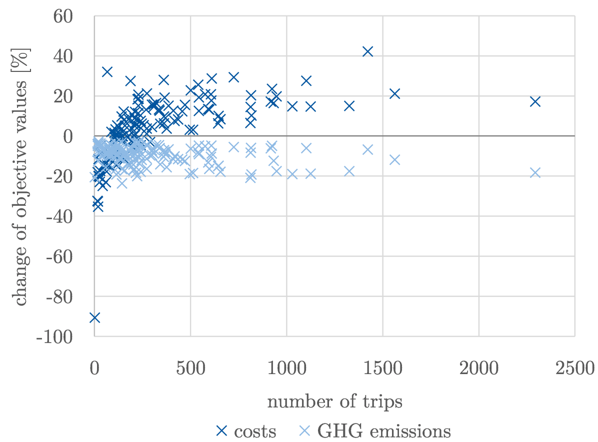

Figure 7-5: Depiction of how the objective values in *minE* change in the BC when compared to the SQ (y-Axis), depending on the number of trips of each company (x-Axis).

In the following, we compare in detail which mobility services must be used by companies to minimize their costs and/or GHG emissions. Figures 7-6 and 7-7 juxtapose *minC* and *minE*, presenting the share of companies that use the different mobility services and price tariffs for at least one trip. In *minC*, most companies use bikesharing with the basic price tariff and leased ICEVs. Carsharing is used equally for shared ICEVs and BEVs, and taxis are used by 64% of the companies, despite the high distance-related costs. In *minE*, nearly all companies use leased electric cars and owned bikes. 83% of the companies use carsharing with the active price tariff, primarily for using electric cars. Further, carsharing is the only mobility service, with which ICEVs are used. Finally, scooters are used by few companies in both, *minC* and *minE*.

The higher variety of used mobility services in *minC* indicates that the cost advantages of the different mobility services are less explicit than the advantages in GHG emissions. Further results show that the availability of shared cars is strongly limited in *minE* of the base case, with shared small BEVs being fully booked in 41% of all considered time intervals (including nights).

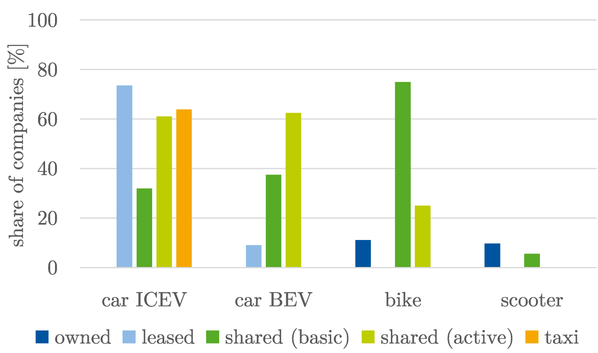

Figure 7-6: Share of the companies that use the mobility services and price tariffs for at least one trip in *minC* of the BC.

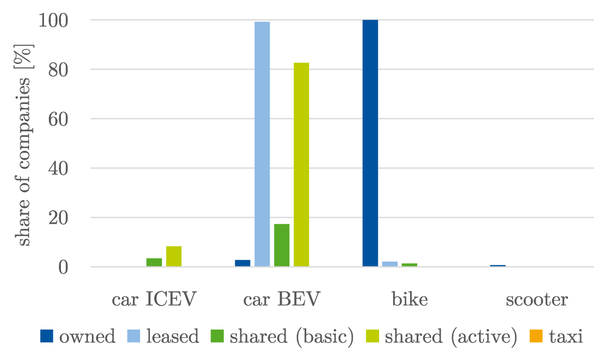

Figure 7-7: Share of the companies that use the mobility services and price tariffs for at least one trip in *minE* of the BC.

Finally, we regard the development of the average share of trips per vehicle class with aggregated vehicle sizes for all pareto-optimal results in the base case (cf. Figure 7-8). We find the most significant changes within the initial 20% of the pareto-optimal solutions from the extreme point *minC*. In this point, GHG emissions are reduced by 50% at the expense of 45% of additional costs. Compared to the status quo, CMaaS systems reduce costs and GHG emissions considerably by 28% and 21%, respectively. Within the initial 20% of the pareto-optimal solutions from *minC*, trips with electric cars and owned bikes increase rapidly, while the use of leased ICEVs, bikesharing, owned scooters, and taxis decreases. After this point, owned bikes account for a consistently high share of trips, while trips with electric carsharing increasingly replace trips with leased electric cars and shared ICEVs.

7.5.2 Scenario Analysis

Figure 7-9 presents the changes in the objective values for all considered scenarios compared to the base case in *minC* and *minE*. For the micromobility scenario (SC1), we regard the case that micromobility modes are considered for each trip ($\gamma^{consMicro} = 1.00$). Under this condition, the micromobility scenario (SC1) is the only scenario that reduces GHG emissions considerably in *minE*, while the sustainable mobility policies (SC2a-b) and the sharing scenarios (SC3a-b)

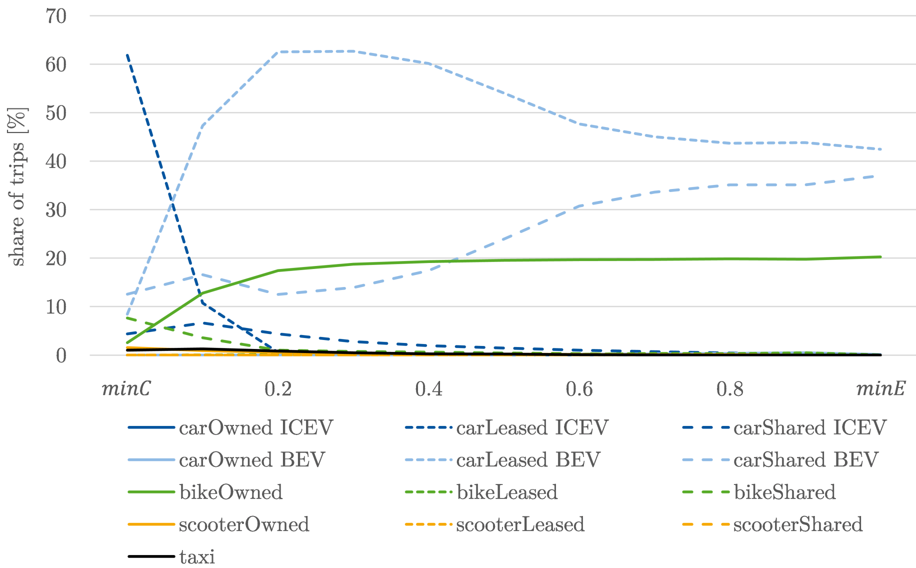

Figure 7-8: Share of trips per mobility service in the BC from *minC* to *minE*, differentiated for drive trains.

have a negligible impact here. In *minC*, GHG emissions can be reduced in all scenarios, especially in the policy scenarios (SC2a-b), which lead to GHG emission reductions of 43% (SC2a) and 11% (SC2b), respectively. The costs are reduced in both, *minC* and *minE*, in the micromobility (SC1), the charging infrastructure (SC2b) and the sharing scenarios (SC3a-b), while the low-emission zone scenario (SC2a) leads to cost increases in *minC*. Thus, when choosing effective measures, policy-makers should consider that improvements of micromobility, charging infrastructure, and sharing services consistently result in improved costs and GHG emissions, whereas increased costs incur when implementing low-emission zones.

In the following, we analyze the changes of the regarded scenarios compared to the base case in further detail to gain insights on how the objective values are achieved. For the micromobility scenario (SC1), we analyze the results varying the consideration of micromobility modes. Figure 7-10 shows that both objectives are negatively correlated with $\gamma^{consMicro}$, illustrating that an increased consideration of micromobility modes allows for substantial cost and GHG emission reductions. Herein, the maximum achievable reduction in both objective values ($\gamma^{consMicro} = 1.00$), compared to the base case ($\gamma^{consMicro} = 0.25$) can be achieved for the objective, which is not optimized primarily. Specifically, costs can be reduced by up to 45% in *minE* compared to 33% in *minC*, and GHG emission by up to 23% in *minC* compared to 15% in *minE*. Although the consideration of micromobility generally allows for cost reductions, costs initially increase in *minE* when $\gamma^{consMicro}$ increases from 0.00 to 0.15, as the cost

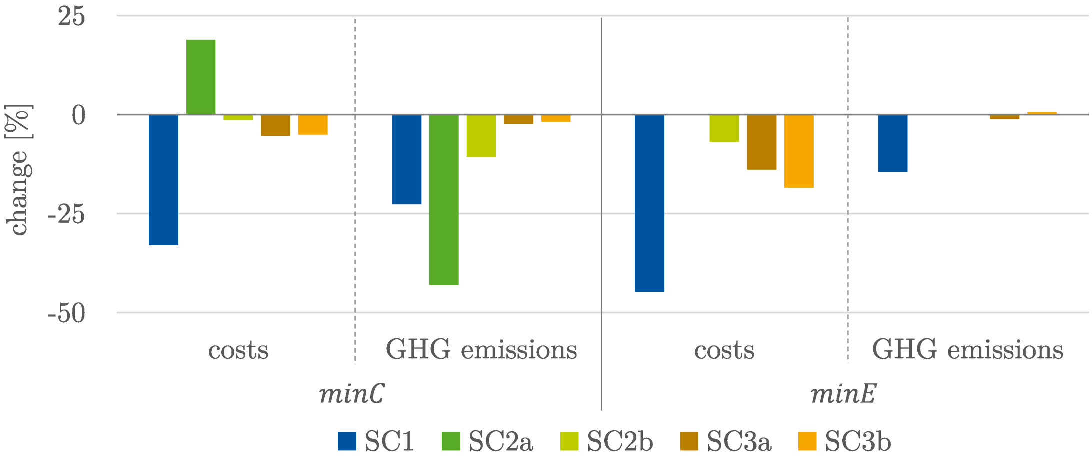

Figure 7-9: Changes in objective values for the analyzed scenarios in comparison to the BC for *minC* and *minE*.

efficiency of the CMaaS system decreases while the shares of micromobility use remain low. For *minC*, we find that trips with micromobility modes primarily replace trips with company-exclusive cars, and that company-exclusive bikes become more cost-efficient than shared bikes from $\gamma^{consMicro} = 0.65$ (cf. Figure 7-11). In *minE*, the share of trips with company-exclusive bikes increases linearly between $\gamma^{consMicro} = 0.00$ and $\gamma^{consMicro} = 1.00$, while the share of trips with cars decreases linearly.

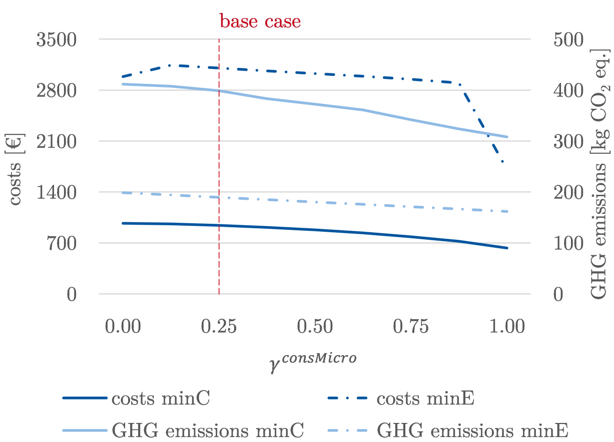

Figure 7-10: Objectives of SC1 in relation to factor $\gamma^{consMicro}$.

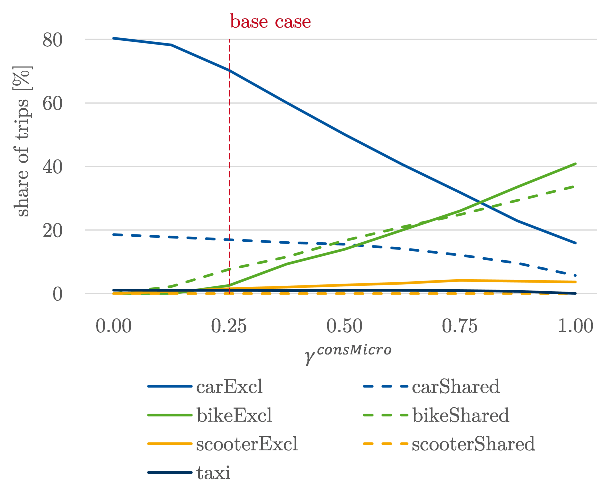

Figure 7-11: Share of trips with different mobility services in *minC* of SC1 in relation to factor $\gamma^{consMicro}$.

Among the regarded scenarios, the low-emission zone scenario with a fee on polluting vehicles (SC2a) allows for the most considerable GHG emission reductions in $minC$, but also increases the costs of $minC$ by 19%. In contrast, the charging infrastructure scenario (SC2b) does not cause cost increases, but neither causes comparable GHG emission reductions in $minC$. Instead, it causes consistent but rather low reductions of both objective values. These impacts are reflected in the pareto curves. The juxtaposition of the pareto fronts with the base case in Figure 7-12 demonstrates that the introduction of low-emission zones significantly reduces the GHG emissions in $minC$. Further analyses of the low-emission zone scenario (SC2a) show that the company-exclusive fleet is restructured, with the comparatively cheap leased ICEVs being substituted by more environmentally friendly mobility services that are not subject to the low-emission zone fee, i.e., leased electric cars, owned bikes, and owned scooters. Improving the charging infrastructure (SC2b) causes an overall shift of the pareto curve to the left, which is accompanied by a reduction of fleet sizes in $minE$ by 14% and an increase of trips made with BEVs in $minC$ by 8%. The implementation of sustainable mobility policies effectively encourages more sustainable CMaaS designs. However, it is essential to critically assess the additional costs of low-emission zones for companies.

The two sharing scenarios (SC3a-b) illustrate the insufficiency of sharing services in the base case. By increasing the availability of shared vehicles (SC3a) and the share of electric cars in carsharing (SC3b), the costs of $minE$ can be reduced by up to 18%. Further effects, like the reductions of GHG emissions in $minC$ and costs in $minC$ are rather small at below 6%. The main impact on the objective values is caused by the increased availability of cars, while the composition of shared cars exclusively influences the costs of $minE$. The change in used mobility services is similar in both sharing scenarios, so that we refer only to scenario SC3b in Figure 7-13 for simplicity. It shows that mainly trips with shared electric cars under the active price tariff increase, while leased electric cars as well as leased and shared ICEVs are substituted. The changed usage structure also leads to an increase in the usage of owned bikes. We therefore find an overall increase in trips with BEVs, especially carsharing, which supports the reduction of GHG emissions.

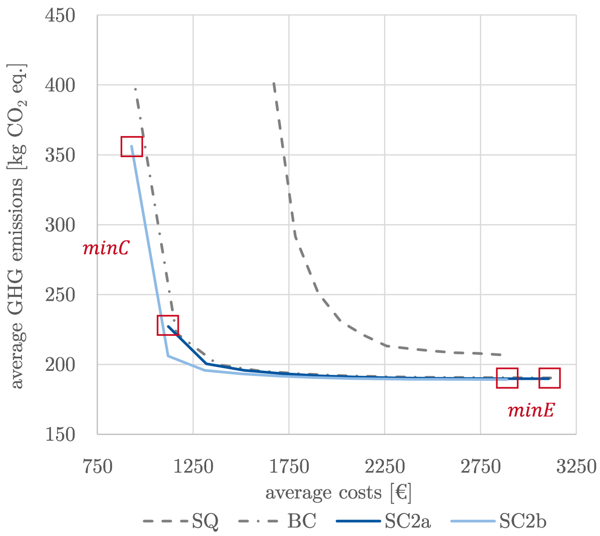

Figure 7-12: Pareto fronts of SQ, BC, SC2a, and SC2b.

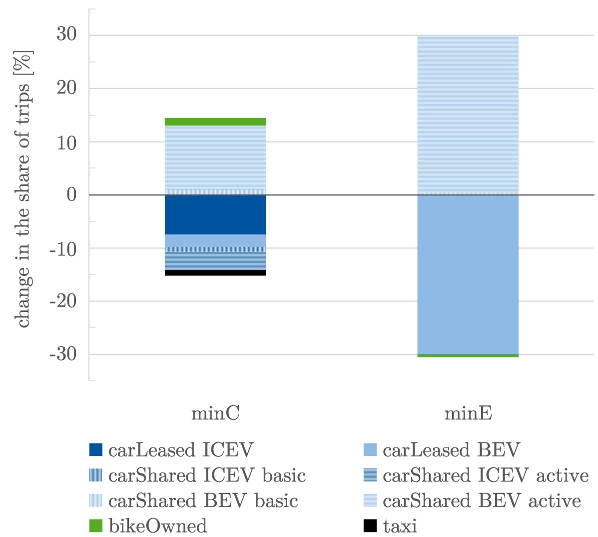

Figure 7-13: Change in the share of trips in SC3b compared to the BC for *minC* and *minE*.

7.6 Conclusion

In our paper, we quantified the potentials of CMaaS to reduce costs and GHG emissions of corporate mobility. We applied a three-step methodology consisting of a cost estimation, an LCA, and a mixed-integer multi-objective optimization model, which identifies the optimal fleet size and composition of company-exclusive mobility services and the optimal choice of price tariffs for public mobility services. By applying our methodology to a comprehensive case study considering more than 46,000 corporate trips, we derive general insights on CMaaS and thereby contribute to the limited literature on its environmental and economic impacts.

The results of our main analysis show that the implementation of CMaaS is generally beneficial for companies and the society. In comparison to traditional fleet management, CMaaS allows all considered companies to decrease their costs and GHG emissions. If we apply the minimum costs of traditional fleet management to a CMaaS system, companies can decrease their GHG emissions considerably. To minimize GHG emissions, we determine larger company-exclusive fleets, as well as a stronger usage of BEVs, micromobility modes, and public mobility services for companies, while minimizing costs requires small and efficient company-exclusive fleets. The usage of mobility services is strongly dependent on the companies' priorities, but bikes and carsharing are a consistently important part of the determined CMaaS systems, due to their low costs and GHG emissions. The scenario analysis gives further insights into how city governments could encourage more sustainable designs of CMaaS, either by improving the settings of the company (SC1 and SC3a-b), or by penalizing the use of highly emitting vehicles (SC2). While penalties can be an efficient tool to reduce GHG emissions, they also lead to increased costs for companies. In contrast, an improvement of the company settings, i.e., a better infrastructure for micromobility modes and higher availability of sharing services, has a positive impact on both objectives.

Our results imply concrete recommendations for corporate and political decision-makers. First, since CMaaS systems are more beneficial for companies and society than traditional fleet management, decision-makers should facilitate the implementation of CMaaS systems in companies. Second, we found that a significant change in mobility usage occurs within the inital 20% of pareto-optimal solutions from the cost-minimal extreme point. Political decision-makers should therefore try to encourage companies to increase their priority for emission reductions by these 20% at least. Here, CMaaS systems decrease costs and emissions considerably in comparison to traditional fleet management and use a very similar mix of mobility services like in the extreme point with minimum emissions. Third, once CMaaS systems are implemented, there are various political measures to encourage their sustainable design, which should be considered to establish a more socially desirable mobility system.

Regarding limitations, we so far applied our model to a data base of corporate trips with information on the conducted trips, the used vehicles, and the respective companies. Conducting a more detailed case study with additional data could give further insights into the quality of our model and the practical implications of introducing CMaaS. Several details, for which we made assumptions in this analysis, depend on the unique circumstances of each company, including the available mobility modes and vehicle classes, the willingness to use micromobility modes, and the number of employees who make a trip. First, we encompass the most prevalent and crucial mobility modes and vehicle classes in our analysis. However, companies might find scooters impractical, but offer mopeds or encourage the usage of public transit. Second, as discussed in Chapter 7.5.2, the willingness of employees to consider micromobility modes has substantial impact on the results. Therefore, it would be valuable to validate our assumptions in this regard with real-world data. Third, we assume that each trip is made by only one employee, since this information is not included in the driving profiles. This assumption presents a limitation to our analysis, because cars are the only regarded mobility mode with a capacity larger than one person. Consequently, our analysis does not account for potential advantages that cars might offer for trips involving more than one employee.

Our methodology could be extended in future research. Commuting trips and the private usage of public mobility services by employees holds further potentials for system improvements due to synergy effects. To facilitate the implementation of CMaaS, future research could analyze the optimal point in time for companies to turn their traditional fleet management into a CMaaS system. Finally, to analyze the environmental impacts of CMaaS in detail, a multi-objective optimization could be conducted of various ecological dimensions as defined by the LCA.

Acknowledgment

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7.A Appendix

7.A.1 Cost Estimation

Table 7A-1
Cost parameters.

mobility service	vehicle class	price tariff	costs in € per vehicle	membership	distance in km	invoice period	trip	references
carOwned	ICEV M	-	459.00	-	0.15	-	-	[1],[2],[3],[4]
carOwned	BEV S	-	547.00	-	0.09	-	-	[1],[2],[3],[4]
carOwned	BEV M	-	614.83	-	0.11	-	-	[1],[2],[3],[4]
carLeased	ICEV M	-	308.71	-	0.11	-	-	[1],[4],[5]
carLeased	BEV S	-	468.95	-	0.06	-	-	[1],[4],[5]
carLeased	BEV M	-	525.71	-	0.07	-	-	[1],[4],[5]
carShared	ICEV S	basic	-	-	0.27	2.35[b]	-	[6]
carShared	ICEV S	active	-	10/+2[a]	0.25	1.35[b]	-	[6]
carShared	ICEV M	basic	-	-	0.27	3.35[b]	-	[6]
carShared	ICEV M	active	-	10/+2[a]	0.26	1.90[b]	-	[6]
carShared	BEV S	basic	-	-	0.27	2.35[b]	-	[6]
carShared	BEV S	active	-	10/+2[a]	0.25	1.35[b]	-	[6]
carShared	BEV M	basic	-	-	0.27	3.35[b]	-	[6]
carShared	BEV M	active	-	10/+2[a]	0.26	1.90[b]	-	[6]
bikeOwned	BEV	-	42.00	-	0.002	-	-	[7],[8],[9],[10]
bikeLeased	BEV	-	75.00	-	0.002	-	-	[11]
bikeShared	BEV	basic	-	-	-	2.00[c]	-	[12],[13]
bikeShared	BEV	active	-	10/4/3/2[a]	-	-	-	[12],[13]
scooterOwned	BEV	-	17.01	-	0.004	-	-	[8],[9],[14]
scooterLeased	BEV	-	40.00	-	0.004	-	-	[15]
scooterShared	BEV	basic	-	-	-	0.19[d]	1.00	[16]
scooterShared	BEV	active	-	5.99	-	0.19[d]	-	[16]
taxi	ICEV M	-	-	-	2.20	-	4.20	[17]

[a]for carsharing, the first employee costs 10 € and every further employee 2 €, costs for bikesharing refer to companies with <50/50-100/101-500/>500 participating employees; [b]per 60 minutes, [c]per 30 minutes, [d]per 1 minute

[1] ADAC 2023a, [2] Generalzolldirektion 2021, [3] De Clerck et al. 2018, [4] ADAC 2021, [5] Sixt Leasing 2021, [6] cambio 2020, [7] Dimpker 2019, [8] CHECK24 2021, [9] BMF 2000, [10] Shimano Inc. 2018, [11] Swapfiets 2023, [12] nextbike 2023b, [13] nextbike 2023a, [14] Segway 2021, [15] Grover 2021, [16] TIER 2021, [17] Rat der Stadt Köln 2021

7.A.2 Life Cycle Assessment

Table 7A-2
Life Cycle Inventory for mobility services with scooters.

flow	unit	scooter excl	scooter shared
inputs			
electric scooter | MaaS[a]	Item(s)	1.52E-04	2.00E-04
electricity, medium voltage[a]	kWh	9.17E-03	1.53E-02
bicycle road construction	m*a	4.40E-05	4.40E-05
transport, freight, lorry 3.5-7.5 metric ton, EURO6[b]	t*km	-	4.08E-03
outputs			
transportation, scooter, electric	p*km	1	1

References: [a]de Bortoli 2021, Moreau et al. 2020, Severengiz et al. 2020; [b]de Bortoli 2021, TGHY 2023

Table 7A-3
Life Cycle Inventory for scooter production.

		scooter	
flow	**unit**	**excl**	**shared**
inputs			
aluminium alloy, AlMg3	kg	5.731	8.528
aluminium, cast alloy	kg	0.256	0.256
battery cell, Li-ion	kg	1.159	3.000
charger, for electric scooter	kg	0.385	0.385
electric motor, for electric scooter	kg	1.187	1.187
electricity, medium voltage	kWh	6.890	10.335
heat, district or industrial, natural gas	MJ	13.6	20.4
heat, district or industrial, other than natural gas	MJ	0.193	0.2895
light emitting diode	kg	0.016	0.016
polycarbonate	kg	0.266	0.266
polycarbonate	kg	0.008	0.008
powder coat, aluminium sheet	m2	0.350	0.350
printed wiring board, mounted mainboard, desktop computer, Pb free	kg	0.059	0.059
steel, low-alloyed	kg	1.349	4.146
synthetic rubber	kg	1.185	1.185
tap water	kg	0.744	0.744
transistor, wired, small size, through-hole mounting	kg	0.062	0.062
welding, arc, aluminium	m	0.750	0.750
transport, freight, train	tkm	126	241.5
outputs			
electric scooter — MaaS	items	1	1
used Li-ion battery	kg	0.849	2.197
municipal solid waste	kg	4.5	6.75
wastewater, average	m3	0.0007	0.0007
water	kg	0.0001	0.0001

References: TGHY 2023, Severengiz et al. 2020, Hollingsworth et al. 2019
Assumptions: shared scooters weigh 18 kg, have the same composition as exclusive scooters and the additional weight is caused by a heavier frame; shared scooters require 1.5 batteries in their lifetime

Table 7A-4
Life Cycle Inventory for mobility services with bikes.

		bike	
flow	**unit**	**excl**	**shared**
inputs			
electric bicycle[a]	Item(s)	6.67E-05	8.00E-05
maintenance, electric bicycle[a]	Item(s)	6.67E-05	8.00E-05
bicycle road construction	m*a	4.40E-05	4.40E-05
electricity, low voltage[b]	kWh	0.0100	0.0103
bikesharing station[c]	items	-	7.00E-06
transport, freight, lorry 3.5-7.5 metric ton, EURO6[d]	tkm	-	2.64E-04
outputs			
transportation, bike, electric	p*km	1	1

References: [a]de Bortoli 2021 (shared), Wernet et al. 2016 (exclusive); [b]Wernet et al. 2016; [c]Velocity 2023, de Bortoli 2021; [d]de Bortoli 2021
Assumption: station lifetime assumed to be 10 years

Table 7A-5
Life Cycle Inventory for electric bike production.

flow	**unit**	**amount**
inputs		
electric bicycle	Item(s)	1
bike dock[a]	Item(s)	0.35
outputs		
electric bicycle, shared	Item	1

References: [a]Velocity 2023

Table 7A-6
Life Cycle Inventory for bike dock production.

flow	**unit**	**amount**
inputs		
aluminum alloy	kg	13.6
electronics for control units	kg	2.72
chromium steel	kg	67.8
outputs		
bike dock	Item	1

References: Luo et al. 2019

Table 7A-7
Life Cycle Inventory for bikesharing station production.

flow	**unit**	**amount**
inputs		
aluminum alloy, AlMg3	kg	38.5
battery, li-ion, rechargeable	kg	81.5
photovoltaic panel, single-Si wafer	m2	1.5
chromium steel 18/8	kg	45.36
flat glass, uncoated	kg	6.8
electronics for control units	kg	10
charger, for electric scooter	kg	3.85
outputs		
bikesharing station	Item	1

References: Luo et al. 2019

Table 7A-8
Life Cycle Inventory for mobility services with electric cars (BEVs).

		car BEV S		**car BEV M**	
flow	**unit**	**excl**	**shared**	**excl**	**shared**
inputs					
battery, Li-ion, rechargeable, prismatic	kg	0.0012	0.0012	0.0020	0.0020
electricity, low voltage	kWh	0.0872	0.0872	0.1060	0.1060
maintenance, passenger car, electric, without battery	Item(s)	5.76E-06	5.76E-06	5.99E-06	5.99E-06
passenger car, electric, without battery	kg	0.0053	0.0053	0.0055	0.0055
road	m*a	1.07E-04	1.07E-04	1.19E-04	1.19E-04
road maintenance	m*a	1.78E-04	1.78E-04	1.78E-04	1.78E-04
parking area — road-based	m*a	3.23E-04	4.03E-05	3.23E-04	4.03E-05
outputs					
brake wear emissions, passenger car	kg	7.34E-07	7.34E-07	8.23E-07	8.23E-07
road wear emissions, passenger car	kg	8.07E-06	8.07E-06	9.05E-06	9.05E-06
transportation, car, electric	pkm	1	1	1	1
tyre wear emissions, passenger car	kg	4.72E-05	4.72E-05	5.29E-05	5.29E-05

References: Wernet et al. 2016, ADAC 2023b, ADAC 2023c, Assumption: BEVs have significantly lower brake wear emissions due to regenerative braking than ICEVs, while road/tyre wear emissions depend on the vehicle weight (cf. Group 2019)

Table 7A-9
Life Cycle Inventory for mobility services with fossil-fueled cars (ICEVs).

		car ICEV S		car ICEV M		
flow	**unit**	**excl**	**shared**	**excl**	**shared**	**taxi**
inputs						
passenger car maintenance	Item(s)	3.30E-06	3.30E-06	4.34E-06	4.34E-06	7.27E-06
passenger car, petrol/natural gas	kg	0.0041	0.0041	0.0054	0.0054	0.0090
petrol, low-sulfur	kg	0.0206	0.0206	0.0277	0.0277	0.0463
road	m*a	7.14E-05	7.14E-05	9.40E-05	9.40E-05	9.40E-05
road maintenance	m*a	1.78E-04	1.78E-04	1.78E-04	1.78E-04	1.78E-04
parking area — road-based	m*a	3.23E-04	4.03E-05	3.23E-04	4.03E-05	3.23E-04
outputs						
1-Pentene	kg	8.17E-09	8.17E-09	1.10E-08	1.10E-08	1.83E-08
2-Methyl pentane	kg	2.47E-06	2.47E-06	3.31E-06	3.31E-06	5.54E-06
Acetaldehyde	kg	5.57E-08	5.57E-08	7.47E-08	7.47E-08	1.25E-07
Acetone	kg	4.53E-08	4.53E-08	6.08E-08	6.08E-08	1.02E-07
Acrolein	kg	1.41E-08	1.41E-08	1.89E-08	1.89E-08	3.17E-08
Ammonia	kg	6.19E-07	6.19E-07	8.31E-07	8.31E-07	1.39E-06
Benzaldehyde	kg	1.63E-08	1.63E-08	2.19E-08	2.19E-08	3.67E-08
Benzene	kg	1.24E-06	1.24E-06	1.66E-06	1.66E-06	2.77E-06
brake wear emissions, passenger car	kg	1.94E-06	1.94E-06	2.56E-06	2.56E-06	4.28E-06
Butane	kg	2.45E-06	2.45E-06	3.29E-06	3.29E-06	5.50E-06
Cadmium	kg	2.06E-10	2.06E-10	2.77E-10	2.77E-10	4.63E-10
Carbon dioxide, fossil	kg	6.56E-02	6.56E-02	8.80E-02	8.80E-02	1.47E-01
Carbon monoxide, fossil	kg	1.29E-04	1.29E-04	1.72E-04	1.72E-04	2.89E-04
Chromium	kg	1.03E-09	1.03E-09	1.38E-09	1.38E-09	2.32E-09
Chromium IV	kg	2.06E-12	2.06E-12	2.77E-12	2.77E-12	4.63E-12
Copper	kg	3.51E-08	3.51E-08	4.71E-08	4.71E-08	7.88E-08
Cyclohexane (for all cycloalkanes)	kg	8.47E-08	8.47E-08	1.14E-07	1.14E-07	1.90E-07
Dinitrogen monoxide	kg	2.68E-06	2.68E-06	3.60E-06	3.60E-06	6.03E-06
Ethane	kg	3.42E-07	3.42E-07	4.59E-07	4.59E-07	7.69E-07
Ethene	kg	8.79E-09	8.79E-09	1.18E-08	1.18E-08	1.98E-08
Ethylene oxide	kg	5.42E-07	5.42E-07	7.27E-07	7.27E-07	1.22E-06
Formaldehyde	kg	1.26E-07	1.26E-07	1.69E-07	1.69E-07	2.84E-07
Heptane	kg	5.50E-08	5.50E-08	7.37E-08	7.37E-08	1.23E-07
Hexane	kg	1.20E-07	1.20E-07	1.60E-07	1.60E-07	2.69E-07
Lead	kg	3.10E-11	3.10E-11	4.15E-11	4.15E-11	6.95E-11
m-Xylene	kg	1.05E-06	1.05E-06	1.41E-06	1.41E-06	2.37E-06
Mercury	kg	1.44E-12	1.44E-12	1.94E-12	1.94E-12	3.24E-12
Methane	kg	5.28E-06	5.28E-06	7.08E-06	7.08E-06	1.19E-05
Methyl ethyl ketone	kg	3.71E-09	3.71E-09	4.98E-09	4.98E-09	8.34E-09
Nickel	kg	1.44E-09	1.44E-09	1.94E-09	1.94E-09	3.24E-09
Nitrogen oxides	kg	1.03E-05	1.03E-05	1.38E-05	1.38E-05	2.32E-05
NMVOC	kg	2.21E-05	2.21E-05	2.97E-05	2.97E-05	4.97E-05
...						

Table 7A-9
Life Cycle Inventory for mobility services with fossil-fueled cars (ICEVs) (continued).

flow	unit	car ICEV S excl	car ICEV S shared	car ICEV M excl	car ICEV M shared	taxi
...						
outputs						
o-Xylene	kg	2.46E-07	2.46E-07	3.29E-07	3.29E-07	5.52E-07
PAH, polycyclic aromatic hydrocarbons	kg	7.18E-10	7.18E-10	9.63E-10	9.63E-10	1.61E-09
Particulates, <2.5 um	kg	3.40E-07	3.40E-07	4.56E-07	4.56E-07	7.63E-07
Pentane	kg	2.88E-06	2.88E-06	3.86E-06	3.86E-06	6.46E-06
Propane	kg	1.86E-06	1.86E-06	2.50E-06	2.50E-06	4.18E-06
Propene	kg	4.92E-08	4.92E-08	6.61E-08	6.61E-08	1.11E-07
Propylene oxide	kg	2.84E-07	2.84E-07	3.81E-07	3.81E-07	6.37E-07
road wear emissions, passenger car	kg	5.41E-06	5.41E-06	7.12E-06	7.12E-06	1.19E-05
Selenium	kg	2.06E-10	2.06E-10	2.77E-10	2.77E-10	4.63E-10
Styrene	kg	7.50E-08	7.50E-08	1.01E-07	1.01E-07	1.68E-07
Sulfur dioxide	kg	4.13E-07	4.13E-07	5.54E-07	5.54E-07	9.27E-07
Toluene	kg	2.44E-06	2.44E-06	3.27E-06	3.27E-06	5.48E-06
transportation, car, fossil-fueled	pkm	1	1	1	1	1
tyre wear emissions, passenger car	kg	3.16E-05	3.16E-05	4.16E-05	4.16E-05	6.97E-05
Zinc	kg	2.06E-08	2.06E-08	2.77E-08	2.77E-08	4.63E-08

References: Wernet et al. (2016), ADAC 2023d, ADAC 2023e
Assumption: exhaust emissions are directly related to fuel consumption and non-exhaust emissions are directly related to vehicle weight (cf. Group (2019), Fontaras et al. (2017))

Table 7A-10
Results of the Life Cycle Assessment for mobility services with micromobility modes.

name	unit	scooter excl	scooter shared	bike excl	bike shared
natural land transformation	m2	4.03E-06	7.16E-06	3.51E-06	7.49E-06
ionising radiation	kg U235-Eq	0.0026	0.00427	0.00119	0.0032
climate change	**kg CO2-Eq**	**0.02318**	**0.04093**	**0.01719**	**0.03686**
terrestrial acidification	kg SO2-Eq	0.00012	0.0002	0.00011	0.00023
metal depletion	kg Fe-Eq	0.02206	0.03098	0.01777	0.04522
photochemical oxidant formation	kg NMVOC	9.26E-05	0.00016	7.82E-05	0.00017
human toxicity	kg 1,4-DCB-Eq	1.25036	1.85577	1.08694	2.53629
fossil depletion	kg oil-Eq	0.00686	0.01204	0.00525	0.01119
terrestrial ecotoxicity	kg 1,4-DCB-Eq	2.70E-05	5.15E-05	7.92E-05	0.00016
urban land occupation	m2a	0.00064	0.00104	0.00061	0.00122
particulate matter formation	kg PM10-Eq	5.99E-05	0.0001	5.63E-05	0.00013
freshwater ecotoxicity	kg 1,4-DCB-Eq	0.0061	0.00957	0.0055	0.01209
ozone depletion	kg CFC-11-Eq	1.47E-09	2.78E-09	1.17E-09	2.70E-09
freshwater eutrophication	kg P-Eq	2.20E-05	3.42E-05	1.41E-05	3.29E-05
agricultural land occupation	m2a	0.00082	0.00133	0.00066	0.00172
marine ecotoxicity	kg 1,4-DCB-Eq	3.63488	6.12802	2.30774	5.2659
marine eutrophication	kg N-Eq	3.75E-05	6.18E-05	2.71E-05	5.59E-05
water depletion	m3	0.00014	0.00022	0.00011	0.00028

Table 7A-11
Results of the Life Cycle Assessment for mobility services with electric cars (BEVs).

		car BEV S		car BEV M	
name	**unit**	**excl**	**shared**	**excl**	**shared**
natural land transformation	m2	1.49E-05	1.29E-05	1.73E-05	1.52E-05
ionising radiation	kg U235-Eq	0.00687	0.00627	0.00772	0.00712
climate change	**kg CO2-Eq**	**0.05719**	**0.05491**	**0.06533**	**0.06304**
terrestrial acidification	kg SO2-Eq	0.00032	0.0003	0.00038	0.00037
metal depletion	kg Fe-Eq	0.05293	0.05265	0.07113	0.07085
photochemical oxidant formation	kg NMVOC	0.00067	0.00064	0.00073	0.0007
human toxicity	kg 1,4-DCB-Eq	3.89417	3.87338	4.90426	4.88347
fossil depletion	kg oil-Eq	0.0199	0.01815	0.0226	0.02085
terrestrial ecotoxicity	kg 1,4-DCB-Eq	0.00025	0.00025	0.00028	0.00028
urban land occupation	m2a	0.00518	0.0029	0.00568	0.00341
particulate matter formation	kg PM10-Eq	0.00019	0.00018	0.00022	0.00021
freshwater ecotoxicity	kg 1,4-DCB-Eq	0.0204	0.02033	0.02573	0.02566
ozone depletion	kg CFC-11-Eq	4.89E-09	4.05E-09	5.55E-09	4.71E-09
freshwater eutrophication	kg P-Eq	4.90E-05	4.87E-05	6.10E-05	6.07E-05
agricultural land occupation	m2a	0.00257	0.00249	0.00295	0.00287
marine ecotoxicity	kg 1,4-DCB-Eq	8.22428	8.18885	10.32864	10.29321
marine eutrophication	kg N-Eq	9.73E-05	9.06E-05	1.10E-04	1.10E-04
water depletion	m3	0.00039	0.00039	0.00047	0.00039

Table 7A-12
Results of the Life Cycle Assessment for mobility services with fossil-fueled cars (ICEVs).

		car ICEV S		car ICEV M	
name	**unit**	**excl**	**shared**	**excl**	**shared**
natural land transformation	m2	3.49E-05	3.28E-05	4.58E-05	4.38E-05
ionising radiation	kg U235-Eq	0.009	0.0084	0.01151	0.01091
climate change	**kg CO2-Eq**	**0.10888**	**0.10659**	**0.14436**	**0.14211**
terrestrial acidification	kg SO2-Eq	0.00028	0.00026	0.00036	0.00034
metal depletion	kg Fe-Eq	0.01322	0.01294	0.01735	0.01707
photochemical oxidant formation	kg NMVOC	0.0003	0.00027	0.00039	0.00035
human toxicity	kg 1,4-DCB-Eq	1.27734	1.25655	1.67663	1.65587
fossil depletion	kg oil-Eq	0.03855	0.0368	0.05079	0.04904
terrestrial ecotoxicity	kg 1,4-DCB-Eq	0.00019	0.00018	0.00025	0.00024
urban land occupation	m2a	0.00383	0.00156	0.00423	0.00195
particulate matter formation	kg PM10-Eq	0.00013	0.00012	0.00017	0.00015
freshwater ecotoxicity	kg 1,4-DCB-Eq	0.00692	0.00686	0.00911	0.00904
ozone depletion	kg CFC-11-Eq	1.64E-08	1.56E-08	2.17E-08	2.08E-08
freshwater eutrophication	kg P-Eq	1.72E-05	1.69E-05	2.25E-05	2.21E-05
agricultural land occupation	m2a	0.00153	0.00145	0.00195	0.00188
marine ecotoxicity	kg 1,4-DCB-Eq	2.78889	2.75346	3.66493	3.62949
marine eutrophication	kg N-Eq	6.66E-05	5.98E-05	8.56E-05	7.88E-05
water depletion	m3	0.00018	0.00018	0.00024	0.00023

Table 7A-13
Results of the Life Cycle Assessment for the regarded taxi service.

name	unit	taxi
natural land transformation	m2	7.45E-05
ionising radiation	kg U235-Eq	0.01810
climate change	**kg CO2-Eq**	**0.23848**
terrestrial acidification	kg SO2-Eq	0.00058
metal depletion	kg Fe-Eq	0.02861
photochemical oxidant formation	kg NMVOC	0.00061
human toxicity	kg 1,4-DCB-Eq	2.77000
fossil depletion	kg oil-Eq	0.08302
terrestrial ecotoxicity	kg 1,4-DCB-Eq	0.00041
urban land occupation	m2a	0.00480
particulate matter formation	kg PM10-Eq	0.00027
freshwater ecotoxicity	kg 1,4-DCB-Eq	0.01510
ozone depletion	kg CFC-11-Eq	3.54E-08
freshwater eutrophication	kg P-Eq	3.69E-05
agricultural land occupation	m2a	0.00310
marine ecotoxicity	kg 1,4-DCB-Eq	6.06529
marine eutrophication	kg N-Eq	1.40E-04
water depletion	m3	0.00039

7.A.3 Optimization Model

$$\min \quad Z_1 = C^{\text{system}} + C^{\text{operation}} \tag{7A-1}$$

$$C^{\text{system}} = \sum_{s\in\mathcal{S}^{\text{E}}}\sum_{v\in\mathcal{V}_s} c^{\text{veh}}_{sv} x^{\text{E}}_{sv} + \sum_{s\in\mathcal{S}\setminus\mathcal{S}^{\text{E}}}\sum_{p\in\mathcal{P}_s} c^{\text{mem}}_{sp} y_{sp} \tag{7A-2}$$

$$C^{\text{operation}} = \sum_{w\in\mathcal{W}}\sum_{s\in\mathcal{S}}\sum_{i\in I}\sum_{v\in\mathcal{V}^w_{si}}\sum_{p\in\mathcal{P}_s} (c^{\text{trip}}_{isvp} + c^{\text{dist}}_{isvp} + c^{\text{time}}_{isvp})\gamma^w a^w_{svpi} \tag{7A-3}$$

$$\min \quad Z_2 = \sum_{w\in\mathcal{W}}\sum_{s\in\mathcal{S}}\sum_{i\in I}\sum_{v\in\mathcal{V}^w_{si}}\sum_{p\in\mathcal{P}_s} e^{\text{dist}}_{isv}\gamma^w a^w_{svpi} \tag{7A-4}$$

$$s.t. \quad \sum_{s\in\mathcal{S}}\sum_{v\in\mathcal{V}^w_{si}}\sum_{p\in\mathcal{P}_s} a^w_{svpi} = 1 \qquad \forall w\in\mathcal{W}, i\in I \tag{7A-5}$$

$$\sum_{i\in I^w_{svt}} f_{svi} a^w_{svpi} = b^w_{svpt} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, v\in\mathcal{V}_s, p\in\mathcal{P}_s, t\in\mathcal{T} \tag{7A-6}$$

$$\sum_{p\in\mathcal{P}_s} b^w_{svpt} \le x^{\text{E}}_{sv} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}^{\text{E}}, v\in\mathcal{V}_s, t\in\mathcal{T} \tag{7A-7}$$

$$\sum_{p\in\mathcal{P}_s} b^w_{svpt} \le N_{svt} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, v\in\mathcal{V}_s, t\in\mathcal{T} \tag{7A-8}$$

$$\sum_{w\in\mathcal{W}}\sum_{i\in I}\sum_{v\in\mathcal{V}^w_{si}} a^w_{svpi} \le M y_{sp} \qquad \forall s\in\mathcal{S}\setminus\mathcal{S}^{\text{E}}, p\in\mathcal{P}_s \tag{7A-9}$$

$$\sum_{p\in\mathcal{P}_s} y_{sp} \le 1 \qquad \forall s\in\mathcal{S}\setminus\mathcal{S}^{\text{E}} \tag{7A-10}$$

$$x^{\text{E}}_{sv} \in \mathbb{N} \qquad \forall s\in\mathcal{S}^{\text{E}}, v\in\mathcal{V}_s \tag{7A-11}$$

$$y_{sp} \in \{0;1\} \qquad \forall s\in\mathcal{S}\setminus\mathcal{S}^{\text{E}}, p\in\mathcal{P}_s \tag{7A-12}$$

$$a^w_{svpi} \in \{0;1\} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, i\in I, v\in\mathcal{V}^w_{si}, p\in\mathcal{P}_s \tag{7A-13}$$

$$b^w_{svpt} \in \mathbb{N} \qquad \forall w\in\mathcal{W}, s\in\mathcal{S}, v\in\mathcal{V}_s, p\in\mathcal{P}_s, t\in\mathcal{T} \tag{7A-14}$$

Table 7A-14
Model notation.

Sets	
$\mathcal{T}$	set of time periods
$\mathcal{S}$	set of mobility services
$\mathcal{S}^{\mathrm{E}}$	set of company-exclusive mobility services
$\mathcal{V}_s$	set of vehicle classes of mobility service s
$\mathcal{P}_s$	set of price tariffs of mobility service s
$\mathcal{W}$	set of micromobility settings
I	set of trips
I^w_{svt}	set of trips that occupy a vehicle in period t if mobility service s with vehicle class v is used in micromobility setting w
$\mathcal{V}^w_{si}$	set of feasible vehicle classes of mobility service s for trip i in micromobility setting w
Parameters	
c^{veh}_{sv}	costs per vehicle of company-exclusive mobility service s in vehicle class v
c^{mem}_{sp}	total membership costs of public mobility service s in price tariff p
c^{trip}_{isvp}	basic trip costs of trip i with mobility service s in vehicle class v and price tariff p
c^{dist}_{isvp}	distance costs of trip i with mobility service s in vehicle class v and price tariff p
c^{time}_{isvp}	time costs of trip i with mobility service s in vehicle class v and price tariff p
N_{svt}	vehicle capacity of mobility service s in vehicle class v in period t
γ^w	probability of micromobility setting w
f_{svi}	number of required vehicles if mobility service s with vehicle class v is used for trip i
M	big M: large positive value
Decision variables	
x^{E}_{sv}	integer: fleet size of company-exclusive mobility service s in vehicle class v
y_{sp}	binary: 1 if price tariff p is selected for public mobility service s, 0 otherwise
a^w_{svpi}	binary: 1 if mobility service s with vehicle class v and price tariff p is selected for trip i in micromobility setting w, 0 otherwise
b^w_{svpt}	integer: number of occupied vehicles of mobility service s in vehicle class v and price tariff p in period t and micromobility setting w

We refer to Frank et al. 2024 for a detailed derivation of the model. For an explanation of the objective functions (Equations 7A-1 to 7A-4), please compare Section 7.3.4 of the corresponding article. Equations 7A-5-7A-14 of our model describe the following contraints: Equations 7A-5 ensure that exactly one mobility service with one vehicle class and one price tariff is selected to perform trip i if micromobility setting w occurs. Equations 7A-6 determine the number of occupied vehicles of mobility service s in vehicle class v and price tariff p in period t if micromobility setting w occurs. Herein, the number of occupied vehicles in period t depends on the number of booked trips and their respective vehicle demand f_{svi}. For mobility services with BEVs, the number of occupied vehicles additionally depends on the number of vehicles that require recharging in the respective period. Equations 7A-7 determine the fleet size of company-exclusive mobility services as the maximum value of occupied vehicles over all periods and both micromobility settings. Thus, the fleet sizes are reliable with regard to the uncertainty of the micromobility use. Equations 7A-8 guarantee that in period t no more vehicles of class v of mobility service s are used than are actually available N_{svt}. Equations 7A-9 indicate if the company uses mobility service s with price tariff p. Equations 7A-10 ensure that no more than one price tariff p is selected per mobility service s. More precisely, if the company does not use the mobility service, no price tariff is selected (=0) and, vice versa, exactly one price tariff is selected (=1) if the company uses the mobility service. Equations 7A-11 to 7A-14 define integer and binary variables.

7.A.4 Sensitivity Analysis

Energy prices are highly volatile and introduce a degree of uncertainty regarding the reliability of our results. We conduct a sensitivity analysis of the fuel and electricity prices to quantify the impact of such changes. We analyze two energy price scenarios for 2030 which are defined as follows.

Scenario 1 (Sens1):

The wholesale price of electricity will decrease according to the "upper price path" as defined by vbw & Prognos (2023). Taxes, levies, and network charges are assumed to remain constant (BDEW 2023, Bundesnetzagentur 2021). The expected final electricity costs of the companies amount to 0.1745€/kWh.

The prices of gasoline will change according to the expected prices of crude oil (EY 2023b, August 2020) and the increase in the CO_2 price as required by the EU ETS (EY 2023a). The expected final gasoline price amounts to 2.09€/liter.

Scenario 2 (Sens2):

The wholesale price of electricity will decrease according to the "lower price path" as defined by vbw & Prognos (2023). Other price components are treated as in Scenario 1, so that the expected final electricity costs of the companies amount to 0.1375€/kWh. The expected final gasoline price amounts to 2.09€/liter as in Scenario 1.

Results show that the influence of changes in the fuel and electricity prices is limited to *minC* (cf. Figure 7A-1). Herein, emissions are reduced by 18% (Sens1) and 19% (Sens2), while the costs are reduced by 2% (Sens1) and 3% (Sens2). These changes are induced by an increased share of trips made with BEVs by 15% (Sens1) and 16% (Sens2). In *minE*, emissions and the share of trips made with BEVs does not change in Sens1 and Sens2 compared with the base case, while costs are reduced by 1.5% (Sens1) and 1.7% (Sens2).

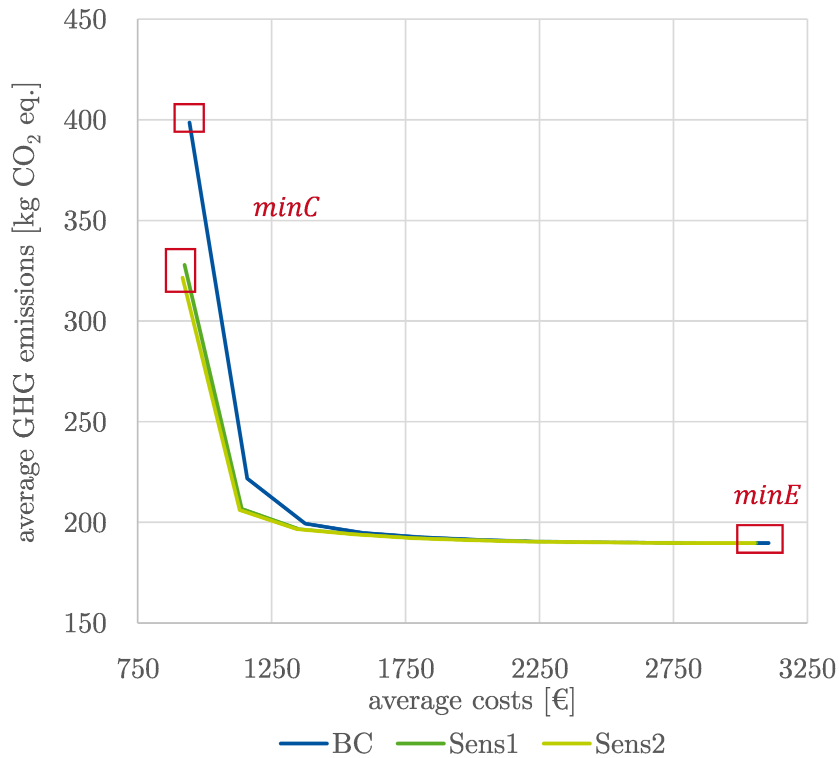

Figure 7A-1: Pareto fronts of the base case, as well as Scenario 1 and 2 of the sensitivity analysis.

In conclusion, the expected prices for the year 2030 impact the optimal CMaaS designs of the companies particularly when cost minimization is the primary objective ($minC$). Herein, the expected prices cause emission reductions and increased BEV shares in $minC$, inducing that the optimal CMaaS configurations of $minC$ approximate the optimal CMaaS configurations of $minE$, where minimization of emissions is the primary objective and trips are exclusively made with BEVs. Importantly, the overall curve progressions of the pareto fronts remain consistent so that the price fluctuations do not narrow the general insights we generate.

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Chapter 8

Social Costs of Corporate Mobility as a Service (CMaaS)

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Abstract

Corporate Mobility as a Service (CMaaS) can be implemented to complement a company's car-based fleet with other exclusive mobility modes, e.g., bikes and scooters, as well as public mobility services, e.g., shared vehicles and taxis. Prior research indicates that CMaaS can be an important component of the sustainable transition of corporate mobility, but detailed analyses of the potentials of CMaaS are lacking. Against this background, we quantify the social costs of CMaaS. Herein, we conduct an external cost assessment, an estimation of internal costs, and we apply a strategic-tactical optimization model to identify the optimal system configurations among thirteen mobility services. We produce general insights about the potentials of CMaaS by implementing our approach for 144 companies with 428 driving profiles. Our results suggest that CMaaS can reduce the social costs of corporate mobility by up to 20% on average.

8.1 Introduction

Within the Green Deal, the European Union defines its strategy to create a sustainable mobility system until 2050 and proposes key elements to frame the transition. So far, this is mainly aiming at private mobility demand, e.g., zero-emission vehicles, vehicle sharing, and Mobility as a Service (MaaS) (cf. European Commission 2021). However, a sustainable mobility transition requires additional elements that specifically target corporate mobility, since every second new car in Germany is registered by companies (cf. KBA 2024b). Corporate Mobility as a Service (CMaaS) can be implemented in companies to meet the corporate mobility demand, complementing the unimodal, car-based fleets with public mobility services, e.g., shared vehicles or taxis, and with low-emission mobility modes, e.g., electric bikes and scooters (cf. Klopfer et al. 2023, Hesselgren et al. 2020). First studies show that implementing CMaaS can reduce the internal mobility costs as well as CO_2 emissions of companies (cf. Klopfer et al. 2023). By transforming corporate mobility to a multimodal mobility system, CMaaS might be a key element for the sustainable mobility transition.

A holistic assessment of the potentials of CMaaS to contribute to a more sustainable mobility system requires the consideration of not only economic and environmental, but also social impacts. An established way to measure the social burden of mobility is to quantify the social costs (cf. van Essen et al. 2019). The social costs of mobility comprise all costs incurred by society through the provision and use of the mobility system, including internal costs, which are borne by the individual users of the mobility system, and external costs, which are caused by the activities of individual users but are imposed on society (cf. van Essen et al. 2019). Causes of external costs are for instance the fatalities and injuries caused by accidents, illnesses due to air pollution and noise emissions, damages caused by climate change, as well as delays due to congested roads. Additionally, the external costs of the space consumption by car parking became an increasingly present topic in recent years (cf. Agora Verkehrswende 2022). Quantifying the social costs of mobility services in a common framework can therefore yield comprehensive insights into the absolute social burden of a certain mobility service, as well as the relative social burden as compared with other mobility services.

To the best of our knowledge, social cost assessments of CMaaS do not exist so far. Related studies analyze the external costs of private urban mobility, but disregard taxis, sharing and/or electric mobility services (cf. Maier et al. 2023, Schröder et al. 2023, Pisoni et al. 2022). Previous assessments of CMaaS suggest that it can be an important component of the sustainable transition of corporate mobility, but respective studies so far focus on economic and environmental impacts. Klopfer et al. (2023) and Frank et al. (2024) analyze the potentials of CMaaS to reduce the internal costs and GHG emissions from corporate mobility and find that both can be reduced considerably. Surveys in the context of real-world trials confirm that CMaaS can decrease the internal costs of corporate mobility and find positive attitudes of employees towards the introduction of new mobility modes and the implemented CMaaS system (cf. Günther et al. 2020, Hesselgren et al. 2020, Vaddadi et al. 2020). However, integrated assessments of the internal and external costs of CMaaS are lacking and related social cost assessments do not regard the relevant characteristics of corporate mobility (cf. Maier et al. 2023, Gössling et al. 2019), which illustrates the need for further research in the context of CMaaS.

We address this research gap by quantifying the potentials of CMaaS to reduce the social costs of corporate mobility. Herein, we juxtapose the internal and external costs of CMaaS. To deduce general insights about the potentials of CMaaS, we analyze 144 companies and regard thirteen different mobility services, deriving general insights about the social costs of corporate mobility. Since some of the external costs of mobility are directly influenced by the regional setting of the company, we differentiate between cities, towns, and rural areas. By providing insights about the potentials of CMaaS to contribute to a sustainable mobility system and achieve minimum social impacts of corporate mobility, our research addresses policy-makers who want to design sustainable mobility systems.

We first quantify the external costs per kilometer for each mobility service individually. Herein, we analyze six external cost dimensions of corporate mobility, i.e., accidents, air pollution, climate change, congestion, noise, and parking. Second, we quantify the internal cost factors for the mobility services using a framework established in prior studies (cf. Frank et al. 2024, Klopfer et al. 2023). Third, we apply a strategic-tactical optimization model to determine the optimal CMaaS configurations for the 144 regarded companies, choosing among the available mobility services. The model minimizes either internal, external, or social costs using separate objective functions. The optimal CMaaS configuration includes decisions about the optimal fleet size and composition of exclusive mobility services and the optimal price tariffs for the use of public mobility services. For each company in our data set, we quantify and evaluate the social costs of CMaaS.

The following work is structured as follows. In Chapter 8.2, we give an overview of prior studies regarding social cost assessments in the context of CMaaS and present the optimization models that are related to our model. In Chapter 8.3, we present our methodological approach and in Chapter 8.4 the specifications of our case study. In Chapter 8.5, we analyze our results. Finally, we discuss the implications of our results and the limitations in Chapter 8.6 and conclude our work in Chapter 8.7.

8.2 Literature Review

MaaS provides a smooth and personalized transportation service, combining all mobility options within a specific area into a single digital platform and providing an integrated interface for planning, booking, and payment (cf. Enoch and Potter 2023, Ho et al. 2018, Jittrapirom et al. 2017, Hietanen 2014). Accordingly, CMaaS refers to such an integrated multimodal mobility system, which is under corporate control and which allows company members to meet their mobility demand by utilizing the versatile mobility services that are accessible (cf. Hesselgren et al. 2020). Within our literature review, we present existing approaches to assess the social costs of CMaaS and other passenger mobility systems (cf. Section 8.2.1). We further introduce the optimization models that are related to our methodological approach, which include strategic fleet size and composition models for heterogeneous corporate or public mobility systems (cf. Section 8.2.2).

8.2.1 Social Costs of Heterogeneous Passenger Mobility Systems

Social costs of mobility are the total costs to society that result from mobility-related activities, including both internal and external costs (cf. van Essen et al. 2019). Internal costs are the costs which are paid for by the entity (e.g., person, group, or organization) which uses the mobility system, e.g., the costs of purchasing vehicles or the fare of a taxi ride. External costs of mobility are the monetized impacts that are caused by the mobility-related activities of one entity on other entities and which are not accounted for by the first entity (cf. van Essen et al. 2019). Examples are the illnesses that are caused by mobility-induced noise, where treatment costs are not born by the specific emitters, but paid for by society (cf. WHO 2011). Externalities can be quantified as average or marginal external costs, where average costs reflect the costs that occur per driven kilometer, and marginal costs reflect the costs for an additional kilometer driven with a vehicle (cf. van Essen et al. 2019). Policy-makers consider external costs to shape internalization policies, e.g., taxes or fees, in order to reallocate these costs to the emitters (cf. Santos et al. 2010).

To the best of our knowledge, neither external, nor social cost assessments of CMaaS exist. Related studies include external cost assessments of public mobility systems. Table 8-1 gives an overview of the mobility services considered in these studies, where ”exclusive” indicates that vehicles are owned or leased by companies or individuals. In contrast, shared vehicles and taxis are accessible via public service providers. Further, internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) are distinguished. A first assessment evaluates the heterogeneous mobility system in Munich, covering a broad range of mobility services, including shared vehicles, motorized individual transport, public transport, conventional and electric bikes, as well as walking, but does not regard shared electric bikes and taxi services (cf. Schröder et al. 2023). The authors find the lowest average external costs per kilometer for active mobility, public transport, and moped sharing. Other studies that analyze the external costs of heterogeneous mobility systems do not regard shared vehicles and either focus on urban mobility (cf. Maier et al. 2023, Pisoni et al. 2022) or neglect electric mobility modes (cf. Matthey and Bünger 2020, Gössling et al. 2019, van Essen et al. 2019). Herein, some mobility services that are relevant for companies, i.e., taxis, exclusive and shared electric bikes (rather than conventional bikes), and/or exclusive and shared electric scooters are not regarded. Table 8-1 shows that most studies assess the average external costs and the dimensions accidents, air pollution, climate change, congestion, and noise. In some works, the external costs of parking are regarded implicitly within the land use or habitat damage by infrastructure (cf. Gössling et al. 2019). Only two assessments explicitly regard the external costs that occur when parking fees are lower than the land value and the costs of parking space maintenance (cf. Letmathe and Paegert 2024, Schröder et al. 2023).

Existing studies on CMaaS analyze the improvements of internal costs and other key performance indicators from the corporate perspective. Some studies analyze the changes in internal costs when meeting the corporate mobility demand with a CMaaS system instead of exclusive car fleets. Studies on CMaaS design find an internal cost reduction potential of 33-57% for optimized CMaaS systems (cf. Frank et al. 2024, Klopfer et al. 2023). Trial studies like Günther et al. (2020) analyze the internal cost reductions during a CMaaS trial in a German company and find that the costs of all analyzed groups of mobility services can be reduced by 22-26%. Other studies that analyze real-world CMaaS trials find that providing more mobility services, especially electric bikes, leads to an improvement of environmental indicators (cf. Amaral et al. 2020, Hesselgren et al. 2020). Related studies further show that a lack of knowledge on CMaaS hinders the shift from private cars to CMaaS (cf. Vaddadi et al. 2020), and that the complexity of CMaaS is one important factor that impedes the realization of cost advantages of CMaaS (cf. Zhao et al. 2020).

Table 8-1
Overview of external cost assessments in the passenger mobility sector.

		regarded passenger mobility services										regarded external cost dimensions						
	external costs	car ICEV exclusive	car BEV exclusive	car ICEV shared	car BEV shared	taxi	e-bike exclusive	e-bike shared	e-scooter exclusive	e-scooter shared	others	accidents	air pollution	climate change	congestion	noise	parking	others
I	average	X	X	X	X	-	X	-	-	X	1-6	X	X	X	X	X	-	B,H,L[a]
II	average	X	-	-	-	-	-	-	-	-	1,2,5,6	X	X	X	X	X	-	D,W
III	average	X	X	-	-	-	X	-	-	-	1,6	X	X	X	X	X	-	B,D,H,W
IV	average	X	X	-	-	-	-	-	-	-	3,5,6	-	X	X	-	-	-	L
V	average/ marginal	X	-	-	-	-	-	-	-	-	1,2	X	X	X	X	X	-	H,M,Q,S,W
VI	average	X	-	-	-	-	-	-	-	-	5,6	X	X	X	X	X	-	D,W
VII	marginal	-	X	-	-	-	-	-	-	-	7	X	X	-	X	X	X	W
VIII	marginal	X	X	X	X	X	X	X	X	X	-	X	X	X	X	X	X	[b]

I = Schröder et al. (2023), II = Pisoni et al. (2022), III = Maier et al. (2023), IV = Matthey and Bünger (2020), V = Gössling et al. (2019), VI = van Essen et al. (2019), VII = Letmathe and Paegert (2024), VIII = this work
1 = walking, 2 = conventional bike, 3 = moped (exclusive), 4 = moped (shared), 5 = motorcycle, 6 = public transport, 7 = autonomous electric vehicle (shared)
B = barrier effects, D = habitat damage, H = health benefits, L = land use, M = traffic infrastructure maintenance, Q = quality of life, S = perceived safety, W = well-to-tank emissions
[a]parking is included in the dimension land use, [b]W is included in the dimensions air pollution and climate change

8.2.2 Strategic Planning of Heterogeneous Corporate or Public Fleets

To handle the complexity of CMaaS systems, optimization models can be applied. Related models build on Gould (1969) and Dantzig and Fulkerson (1954) who optimize the fleet size and composition of heterogeneous vehicle fleets while minimizing internal mobility costs. Many strategic models so far focus on shared unimodal vehicle fleets with heterogeneous vehicle characteristics, analyzing station-based (cf. Ahani et al. 2023, Lemme et al. 2019, Yoon and Cherry 2018, Hu and Liu 2016, Boyacı et al. 2015, George and Xia 2011) and free-floating carsharing (cf. Weikl and Bogenberger 2013), bikesharing (cf. Luo et al. 2020, Maggioni et al. 2019, Frade and Ribeiro 2015), or ridesharing fleets (cf. Wallar et al. 2019). Several studies base their calculations on historic driving profiles to approximate the real mobility demand (cf. Luo et al. 2020, Maggioni et al. 2019, Wallar et al. 2019, Yoon and Cherry 2018, Frade and Ribeiro 2015). Only two existing publications identify the optimal CMaaS configurations of a corporate mobility system. However, these studies minimize only internal mobility costs (cf. Frank et al. 2024) or add GHG emissions as a second objective (cf. Klopfer et al. 2023).

The current literature suggests that CMaaS has the potential to reduce the impacts of corporate mobility, but also illustrates the need for further insights on the potentials of CMaaS (cf. Section 8.2.1). Few studies assess the social costs of heterogeneous mobility systems and so far, none regards the specific requirements of corporate mobility. Likewise, the marginal external costs of parking have not been regarded in a multimodal setting. To close this research gap, we integrate social costs into an optimization model, that determines the optimal fleet size and composition of CMaaS systems (cf. Frank et al. 2024, Klopfer et al. 2023).

8.3 Methodological Approach

We apply an optimization model that identifies the optimal CMaaS configurations for companies, minimizing their internal, external, or social costs. The following sections will first explain the requirements for modeling CMaaS and the main features of the optimization model (cf. Section 8.3.1). Further, we present the frameworks for quantifying the social costs of mobility (cf. Section 8.3.2). The approach of our analysis is presented in Figure 8-1.

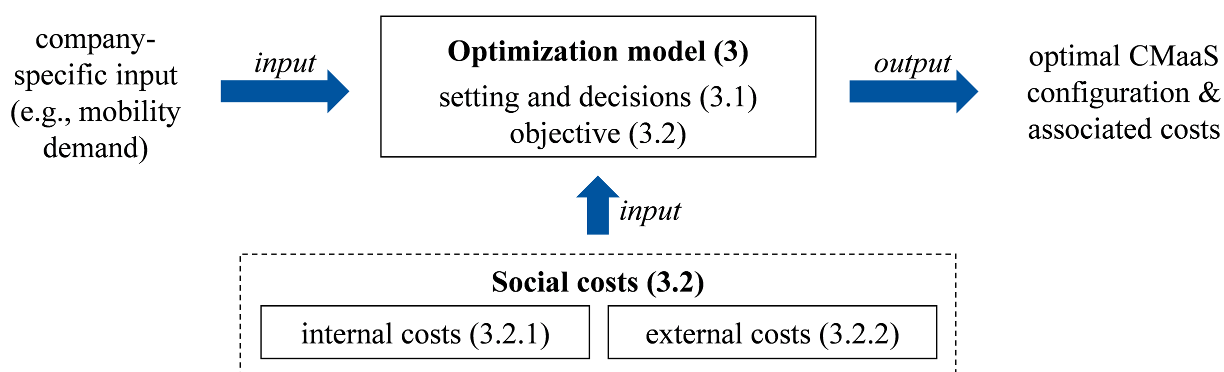

Figure 8-1: Approach of our analysis.

8.3.1 Modeling Corporate Mobility as a Service

When designing a CMaaS system, corporate mobility managers must strategically combine the available mobility services to meet the corporate mobility demand effectively. We define a mobility service as the combination of a vehicle class and a type of provision. We specify each vehicle class by the mobility mode, e.g., car, bike, or scooter, and the respective drive train, e.g., BEV and ICEV. The type of provision describes how a vehicle is made accessible to the company, e.g., being owned, leased, or shared. Mobility services are categorized into two groups: exclusive mobility services, which are available only to company members, and public mobility services, which are accessible to the public.

Exclusive and public mobility services require different decisions, as illustrated in Figure 8-2. For exclusive mobility services, the fleet size and composition must be determined, i.e., how many vehicles from a certain vehicle class are used via which type of provision. When including public mobility services, corporate mobility managers must choose among the different price tariffs from various providers, often distinguished as a basic price tariff and an active price tariff. Within the basic price tariff, users pay certain fees per trip, per time unit, and/or per distance unit. Within the active price tariff, these variable fees are lower, but additionally, a membership fee incurs. These two decisions about the fleet size and composition of exclusive mobility services and the price tariffs of public mobility services directly influence the social costs caused by the corporate mobility system.

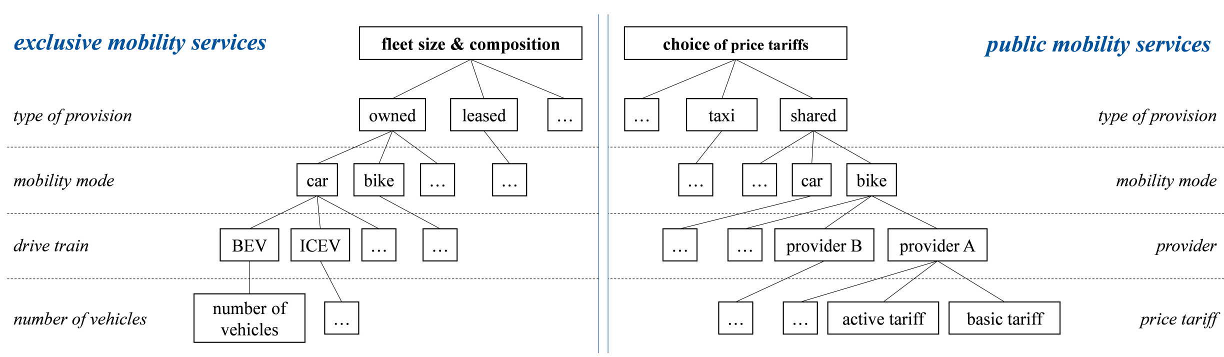

Figure 8-2: Illustration of decisions for designing a CMaaS system.

To model these decisions and thereby design the optimal CMaaS systems, we build on a strategic-tactical optimization model developed by Frank et al. (2024) to define the optimal CMaaS design for each company. The model determines the optimal fleet size and composition of the exclusive mobility services and the optimal price tariffs of the public mobility services, while meeting the mobility demand of the company. To define the corporate mobility demand, a representative set of trips, e.g., from records of the travel management department, is required as model input. The model allocates these trips to available mobility services, creating the CMaaS system from these choices. The model constraints account for the feasibility of the technical characteristics of the vehicles and the availability of public mobility services, which are limited by bookings of users who are no company members. Further, the model considers that some mobility services, e.g., bikes or scooters, can not be used for every trip, e.g., due to the weather conditions. All model constraints and the model notation can be found in the appendix (cf. Equations 8A-1 to 8A-10 and Table 8A-1).

8.3.2 Social Costs

The following sections describe how we quantify internal (Section 8.3.2.1) and external costs (Section 8.3.2.2) and explain the objective functions of our model. Besides minimizing internal and external costs individually, we minimize the social costs of corporate mobility as the sum of internal and external costs.

8.3.2.1 Internal Costs

Internal mobility costs of a company occur when conducting trips to meet the corporate mobility demand. Thus, they depend on the exact usage pattern of mobility services. We evaluate the internal costs for a representative time period, using a framework applied in previous CMaaS studies (cf. Frank et al. 2024, Klopfer et al. 2023), which considers the specific cost structures of exclusive and public mobility services (cf. Section 8.3.1). We regard costs that occur per vehicle, e.g., purchase prices and insurance, per distance unit, e.g., energy costs and maintenance, as well as costs that occur per time unit, per trip, and for memberships, as defined by the tariffs of public mobility service providers. Hence, our objective function for internal cost minimization sums all these cost types according to Equation 1 (cf. Table 8-2 for model notation).

$$\begin{aligned}\text{min internal costs} = &\sum_{s\in\mathcal{S}^{\mathrm{E}}}\sum_{v\in\mathcal{V}_s} c^{\mathrm{veh}}_{sv} x^{\mathrm{E}}_{sv} + \sum_{s\in\mathcal{S}\setminus\mathcal{S}^{\mathrm{E}}}\sum_{p\in\mathcal{P}_s} c^{\mathrm{mem}}_{sp} y_{sp} \\ &+ \sum_{w\in\mathcal{W}}\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}}\sum_{v\in\mathcal{V}^w_{si}}\sum_{p\in\mathcal{P}_s} (c^{\mathrm{dist}}_{isvp} + c^{\mathrm{time}}_{isvp} + c^{\mathrm{trip}}_{isvp})\gamma^w a^w_{isvp}\end{aligned} \tag{1}$$

8.3.2.2 External Costs

We measure the external costs of corporate mobility in Euro-cent per vehicle kilometer, and analyze the marginal external costs, i.e., the costs for transitioning from car fleets to CMaaS. We regard the external costs from well to wheel, including electricity generation, petrol production,

Table 8-2
Model notation.

Sets	
$\mathcal{S}$	set of mobility services
$\mathcal{S}^{\mathrm{E}}$	set of exclusive mobility services
$\mathcal{V}_s$	set of vehicle classes of mobility service s
$\mathcal{P}_s$	set of price tariffs of mobility service s
$\mathcal{W}$	set of micromobility settings
$\mathcal{I}$	set of trips
$\mathcal{V}_{si}^{w}$	set of feasible vehicle classes of mobility service s for trip i in micromobility setting w
Parameters	
c_{sv}^{veh}	costs per vehicle of exclusive mobility service s in vehicle class v
c_{sp}^{mem}	total membership costs of public mobility service s in price tariff p
c_{isvp}^{trip}	basic trip costs of trip i with mobility service s in vehicle class v and price tariff p
c_{isvp}^{dist}	distance costs of trip i with mobility service s in vehicle class v and price tariff p
c_{isvp}^{time}	time costs of trip i with mobility service s in vehicle class v and price tariff p
ex_{isv}^{dist}	external costs of trip i with mobility service s in vehicle class v
γ^{w}	factor determining the occurrence of micromobility setting w ($\sum_{w\in\mathcal{W}} \gamma^{w} = 1$)
Decision variables	
x_{sv}^{E}	integer: fleet size of exclusive mobility service s in vehicle class v
y_{sp}	binary: 1 if price tariff p is selected for public mobility service s, 0 otherwise
a_{isvp}^{w}	binary: 1 if mobility service s with vehicle class v and price tariff p is selected for trip i in micromobility setting w, 0 otherwise

vehicle manufacture, and the use phase. The evaluation of CMaaS requires us to take a system perspective in which we aggregate the external costs of various mobility services in proportion to the driven kilometers. We further distinguish between different regional settings of the analyzed companies, considering the structural differences in cities, towns, and rural areas. To generate comparable results, we follow the latest recommendations for external cost assessments of the European Commission (cf. van Essen et al. 2019) and the German Federal Environmental Agency (cf. Matthey and Bünger 2020), where possible.

We regard external costs of accidents, air pollution, climate change, congestion, noise, and parking as defined by Equations 2 to 7. For better readability, the equations include the units of the parameters, and Table 8-3 gives an explanation of the sets and parameters. To calculate the external costs of accidents, the accident costs caused by a certain mobility service are divided by its mileage and adjusted by the risk elasticity and the risk internalization factor. The risk elasticity describes how much the accident costs change with one additional vehicle on the road, while the risk internalization factor quantifies the degree to which risk is internalized by traffic participants using the different mobility services (cf. van Essen et al. 2019). The dimensions air pollution, climate change, congestion, and noise are calculated via the cost factors of the respective impacts, emission factors, mileage shares to account for different regions and road types, and/or additional factors that are specific to the respective dimension. In addition to these well established dimensions (cf. Matthey and Bünger 2020, van Essen et al. 2019), we regard the external costs that are caused by parking. Herein, we regard the land value, as well as costs and incomes that incur for the required space, e.g., costs of surveillance and incomes from parking fees.

$$EC_s^{\text{accidents}} = \sum_{r \in \mathcal{R}} SM_r \ [\%] \ * \ \frac{\sum_{f \in \mathcal{F}} AC_{fs} \ [\text{-}] * UR_{fs} \ [\%] * CF_f \ [€]}{MI_s \ [km]} \\ * \ (1 + \sum_{j \in \mathcal{J}} (RE_{js} \ [\text{-}] * SM_{jrs} \ [\%]) - RI_s \ [\%]) \tag{2}$$

$$EC_s^{\text{air pollution}} = \sum_{r \in \mathcal{R}} SM_r \ [\%] \ * (\sum_{a \in \mathcal{A}} \sum_{u \in \mathcal{U}} EP_{asu} \ \left[\frac{kg}{km}\right] * CA_{au} \ \left[\frac{€}{kg}\right] * SM_{rsu} \ [\%]) \tag{3}$$

$$EC_s^{\text{climate change}} = \sum_{g \in \mathcal{G}} EG_{gs} \ \left[\frac{kg}{km}\right] \ * CG_g \ \left[\frac{€}{kg}\right] \tag{4}$$

$$EC_s^{\text{congestion}} = DC \ [\%] \ * \ \sum_{j \in \mathcal{J}} CC_j \ \left[\frac{€}{km}\right] \ * SM_{jrs} \ [\%] \tag{5}$$

$$EC_s^{\text{noise}} = \sum_{r \in \mathcal{R}} SM_r \ [\%] * (\sum_{d \in \mathcal{D}} \sum_{u \in \mathcal{U}} SD_{du} \ [\%] * CN_{du} \ \left[\frac{€}{km}\right] * SM_{rsu} \ [\%]) \tag{6}$$

$$EC_s^{\text{parking}} = \sum_{r \in \mathcal{R}} SM_r \ [\%] * (CP_r \ \left[\frac{€}{m^2}\right] + EX_s \ \left[\frac{€}{m^2}\right] - IN_{rs} \ \left[\frac{€}{m^2}\right]) * (SR_{rs} \ [m^2] \ / \ MI_{rs} \ [km])$$
$$with \quad CP_r \ \left[\frac{€}{m^2}\right] = LV_r \left[\frac{€}{m^2}\right] / \ PF \ [\text{-}] \tag{7}$$

Aggregating all external cost dimensions, we minimize the external costs that are caused by the mobility demand of each company according to Equation 8. We minimize the social costs according to Equation 9.

$$\text{min external costs} = \sum_{w \in \mathcal{W}} \sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}} \sum_{v \in \mathcal{V}_{si}^w} \sum_{p \in \mathcal{P}_s} ex_{isv}^{dist} \gamma^w a_{isvp}^w$$
$$with \quad ex_{isv}^{dist} = \sum_{e \in \mathcal{E}} EC_s^e * MI_{isv}^w \qquad \forall i \in \mathcal{I}, s \in \mathcal{S}, v \in \mathcal{V}_{si}^w, w \in \mathcal{W} \tag{8}$$

$$\text{min social costs} = \text{internal costs} + \text{external costs} \tag{9}$$

Table 8-3
Notation of the external cost equations.

Sets		External cost parameters	
$\mathcal{A}$	set of air pollutants	EC_s^e	external costs of dimension e and mobility service s
$\mathcal{D}$	set of traffic densities	*accidents*	
$\mathcal{E}$	set of external cost dimensions	AC_{fs}	incidents of casualty f in accidents caused by mobility service s
		CF_f	cost factor of casualty f
$\mathcal{F}$	set of casualties	MI_s	total mileage of mobility service s
$\mathcal{G}$	set of greenhouse gases	RE_{js}	risk elasticity of mobility service s on road type j, i.e., the extent to which the accident risk increases with a traffic increase of 1%
$\mathcal{J}$	set of road types		
$\mathcal{R}$	set of regional settings	RI_s	risk internalization factor of mobility service s, calculated as the proportion of fatalities with s out of all fatalities including s
$\mathcal{S}$	set of mobility services		
$\mathcal{U}$	set of traveled regions	SM_{jrs}	share of mileage of mobility service s from region r on road type j
		SM_r	share of mileage by companies from region r
		UR_{fs}	underreporting factor for casualty f of mobility service s
		air pollution	
		CA_{au}	cost factor of pollutant a in region u
		EP_{asu}	emission factor of pollutant a by mobility service s in region u
		SM_r	share of mileage by companies from region r
		SM_{rsu}	share of mileage traveled in region u by mobility service s from region r
		climate change	
		CG_g	cost factor of greenhouse gas g
		EG_{gs}	emission factor of greenhouse gas g by mobility service s
		congestion	
		CC_j	cost factor of congestion of road type j
		DC	delay because of congestion as share of total travel time
		SM_{jrs}	share of mileage of mobility service s from region r on road type j
		noise	
		CN_{du}	cost factor of traffic density d in region u
		SD_{du}	share of traffic densities d in region u
		SM_r	share of mileage by companies from region r
		SM_{rsu}	share of mileage traveled in region u by mobility service s from region r
		parking	
		CP_r	cost factor of land use in region r
		EX_s	parking expenditures for mobility service s
		IN_{rs}	parking incomes in region r for mobility service s
		LV_r	average land value in region r
		MI_{rs}	total mileage of mobility service s from region r
		PF	purchase price factor
		SM_r	share of mileage by companies from region r
		SR_{rs}	space requirements of mobility service s in region r

8.4 Case Study

To generate general insights on the external costs of CMaaS, we apply our methodology to a comprehensive data base of companies. The following sections present the underlying data, sources, and assumptions of our case study (cf. Section 8.4.1) as well as our experimental design (cf. Section 8.4.2). The basic data sources and assumptions in our case study correspond to the setting in previous studies on CMaaS design, but are updated and adjusted to match the focus of our analysis (cf. Frank et al. 2024, Frank 2023, Klopfer et al. 2023).

8.4.1 Setting

We regard 144 companies from the REM 2030 driving profiles data base, which contains all corporate trips made with commercially licensed passenger cars over the course of four weeks (cf. Fraunhofer 2021). Each driving profile reflects the trips of a specific car, providing detailed information about the performed trips, i.e., time stamps of departure and arrival, performed distance, and maximum distance from the company site. The data base further provides details about the used vehicles, i.e., type and size, and the company, i.e., number of employees, economic sector, and city size. Among the trips provided in the database, we neglect trips below 500 m, trips with transporters and special vehicles, as well as trips by taxi companies. The key indicators of the analyzed companies and an extract of the driving profiles are presented in Tables 8A-2 and 8A-3 of the appendix.

In our analysis, the optimal CMaaS system of each company can consist of thirteen different mobility services. We regard four vehicle classes, i.e., fossil-fueled cars (ICEVs), electric cars (BEVs), as well as electric bikes and electric scooters, which can be used via three types of provision, i.e., they can be owned, leased, or shared. Additionally, ICEVs can be used via a taxi service (cf. Table 8-4). All technical details of the regarded vehicle classes are defined according to one mid-range vehicle model and listed in Table 8A-4. To define realistic driving distances by bike and scooter, we refer to the average distances per trip as surveyed in recent studies (cf. Cao et al. 2021, Cairns et al. 2017), while the maximum driving distance of BEVs is defined by the battery range.

We assume that all mobility services are available to each company and that shared vehicles are accessible in all regions and within a reasonable distance from the company location. The availability of shared vehicles is listed in Table 8A-4, but we consider that bookings of other users limits the number of available vehicles (cf. Boldrini et al. 2016). When a vehicle serves a trip, the duration of occupancy is defined by a fixed access time, the travel time, and the charging duration of electric vehicles. The access time includes for instance the search for parking spaces and (un-)locking vehicles, i.e., the time needed for accessing and exiting the vehicle. We determine the travel time considering the vehicle speed as well as the trip distance, and include the duration of the appointment for most mobility services. Taxis are an exception, since they are universally available and only have to be booked during the drive to the appointment and back. The charging duration of electric vehicles is determined by the consumption (kWh) and charging capacity (kW) of the vehicle. For simplicity, we consider AC charging stations, disregard charging losses, and assume an average plug-in time of three minutes. Further, we regard that the willingness to use bikes and scooters depends on external determinant, e.g., weather conditions, and internal determinants, e.g., individual preferences (cf. Lopez-Carreiro et al. 2021, Zhu et al. 2020). We make the conservative assumption that employees consider micromobility modes for 25% of the feasible trips, i.e., trips within the driving distances defined in Table 8A-4 (cf. Frank et al. 2024, Klopfer et al. 2023).

Table 8-4
Regarded mobility services.

vehicle class		**type of provision**	
mobility mode	drive train	exclusive	public
car	ICEV	**owned, leased**	**shared, taxi**
	BEV		**shared**
bike	electric		
scooter	electric		

To approximate the patterns of corporate trips in different regional settings, we distinguish companies from cities, i.e., municipalities with 100,000 inhabitants or more, towns, i.e., municipalities with 20,000 to 100,000 inhabitants, and rural areas, i.e., municipalities with less than 20,000 inhabitants. For car usage, we define the share of mileage by companies from each region (SM_r) and the share of mileage traveled in each region with a certain mobility service (SM_{rsu}) based on the information given in the driving profiles data base (cf. Fraunhofer 2021). We assume that the share of mileage traveled within the region of the company's location can be approximated by the share of mileage traveled in trips with a distance up to 10km in cities and towns, and up to 20km in rural areas. We divide the remaining share of mileage equally between the other two regions. We take the share of mileage on the different road types (SM_{jrs}) from Matthey and Bünger (2020) (cf. Table 8-5). Due to the low maximum driving distances of bikes and scooters, we assume that these modes do not leave the regional setting of the company and exclusively use urban roads, not motorways or other roads.

Table 8-5: Company characteristics and assumptions for car usage in the different regions.

	companies[a]			**mileage in region** $[SM_{rsu}]^a$			**mileage on road type** $[SM_{jrs}]^b$		
region	companies	trips	mileage $[SM_r]$	cities	towns	rural	urban roads	other roads	motorways
cities	23.6%	20.1%	24.2%	55.0%	22.5%	22.5%	26.0%	41.0%	33.0%
towns	29.9%	37.8%	31.2%	20.0%	60.0%	20.0%			
rural	46.5%	42.2%	44.6%	22.5%	22.5%	55.0%	10.0%	57.0%	33.0%

[a]deduced from data base (cf. Fraunhofer 2021)
[b]cf. Matthey and Bünger (2020), deviation for rural companies: own assumption

The applied external cost factors are listed in Table 8-6 and mostly correspond to the values recommended by van Essen et al. (2019) and Matthey and Bünger (2020), adjusted for the year 2023 according to the consumer price index (cf. Statistisches Bundesamt 2024a). Note that Matthey and Bünger (2020) define the regional settings according to the population density, not the total population as in this work. Since the average density of the regions defined in our work corresponds to the regions defined in Matthey and Bünger (2020), we apply the values without adjustment. All data sources and the values for each parameter are presented in Tables 8A-5 to 8A-7. Where possible, the data is retrieved for 2023, otherwise applying the most recent data available. We apply the average fuel and electricity prices for 2023 as reported by en2x (2024) and BDEW (2024). Due to the unavailability of some data, we base our external cost assessment on the following assumptions.

- Accidents: The presence of an additional bike or scooter on the road has risk increasing effects, i.e., a higher probability of being involved in an accident, and risk decreasing effects, e.g., by causing a higher sensitivity of other traffic participants for micromobility modes and the slowing down of traffic (cf. van Essen et al. 2019). We assume that the risk decreasing effects are higher for scooters than for bikes, because scooters are relatively new traffic participants so that the current sensitivity for these vehicles and their behavior in traffic is expected to be lower than for bikes. We therefore assume that the risk elasticity (RE_{is}) ranges between -0.1 and +0.1 for bikes and between -0.15 and +0.05 for scooters. In our main analysis, we assume the more conservative risk elasticity values of +0.1 for bikes and +0.05 for scooters.

- Congestion and Noise: We follow the insights of prior studies and neglect congestion and noise externalities of micromobility (cf. Huang et al. 2022, Koning and Conway 2016). We further assume that the share of car mileage in dense traffic is comparable to the share of mileage during peak times.

- Parking: Since there are no representative prices of public space usage by sharing service providers in towns and rural municipalities, we assume that they are the same as in cities, but adjusted by the land value of the respective region. Further, the limited availability of data on parking forces us to focus exclusively on parking lots, ignoring for instance roadside parking. Accordingly, we ignore the space consumption caused by bikes and scooters, which are usually parked on the sidewalk.

- Taxi: We base the calculations for taxis on the assumption that 40% of the mileage is made without passengers (cf. Schaller 2021).

Table 8-6: External cost factors.

dimension	**externality**	**unit**	**cost factor**	**dimension**	**externality**	**unit**	**cost factor**
accidents[a]	fatality	€/cas	4,008,008	climate change[b]	CO_2 equivalents	€/kg	0.215
(CF_f)	serious injury	€/cas	625,641	(CG_g)			
	slight injury	€/cas	48,326	congestion[a]	trunk road	ct/vkm	28.77
air pollution[b]	SO_2	€/kg	18.07	(CC_j)	other urban road	ct/vkm	67.63
(CA_{au})	NO_X	€/kg	21.49		motorways	ct/vkm	26.45
	$PM_{2.5}$ (c)	€/kg	281.34		other road	ct/vkm	46.17
	$PM_{2.5}$ (t)	€/kg	81.11	noise[a] (CN_{du})	dense traffic (c)	ct/vkm	0.771
	$PM_{2.5}$ (r)	€/kg	47.61		thin traffic (c)	ct/vkm	1.984
	PM_{10} (c)	€/kg	33.06		dense traffic (t)	ct/vkm	0.044
	PM_{10} (t)	€/kg	9.37		thin traffic (t)	ct/vkm	0.132
	PM_{10} (r)	€/kg	5.40		dense traffic (r)	ct/vkm	0.011
	PM_{coarse}	€/kg	1.10		thin traffic (r)	ct/vkm	0.011
	NH_3	€/kg	38.68	parking[c] (CP_r)	space (c)	€/m^2	20.96
	$NMVOC$	€/kg	2.42		space (t)	€/m^2	5.67
					space (r)	€/m^2	1.03

cas = casualty, c = cities, t = towns, r = rural areas
[a]van Essen et al. (2019)
[b]Matthey and Bünger (2020)
[c]own calculations

8.4.2 Research Design

We determine the social costs of traditional fleet management, where companies meet their mobility demand by using exclusive cars only (BEVs and ICEVs), minimizing their internal mobility costs (IntT). We then compare the results with a CMaaS setting, in which each company designs its individual CMaaS system as described in Section 8.4.1. Within the CMaaS setting, we regard three different scenarios that define the priorities under which the CMaaS system is designed. We consider that the companies minimize the internal mobility costs (IntC), the external mobility costs (ExtC), or the overall social costs (SocC) that are caused by their mobility behavior (cf. Table 8-7).

Table 8-7: Research design.

			objective		
			companies minimize their...		
		fleet design	internal costs[a]	external costs[b]	social costs[c]
setting	traditional fleet management	only exclusive cars (BEVs and ICEVs)	**IntT**	-	-
	CMaaS	all mobility services	**IntC**	**ExtC**	**SocC**

[a]cf. Section 8.3.2.1
[b]cf. Section 8.3.2.2
[c]social costs = internal costs + external costs

8.5 Results

We present the results of our analysis in the following. In Section 8.5.1, we present the results of our external and internal cost assessment. In Section 8.5.2, we introduce two exemplary companies and present how their internal, external and social costs change when using CMaaS instead of traditional fleet management. To deduce general insights about the potentials of CMaaS, we present average results for 144 analyzed companies in Section 8.5.3.

8.5.1 Cost Analysis

The results of the external cost assessment are presented in Figure 8-3 and illustrate that the external costs caused by the different mobility services vary in amount and composition. Since the external costs of owned and leased vehicles are identical for each vehicle class, we will not differentiate between the exclusive mobility services in the following analysis. With 24 cents per kilometer, taxis cause the highest external costs per kilometer, due to high contributions to climate change and congestion. The external costs of the other car-based mobility services range between 16 and 20 cents per kilometer and consist of all regarded dimensions. In addition to climate change and congestion, we find that parking has a substantial impact, causing 20-31% of the external costs. With 6 cents of external costs per kilometer, exclusive bikes have the lowest impacts. The external costs of scooters are more than twice as high, and amount to approximately 14 cents per kilometer. For bike- and scooter-based mobility services, the dominant dimension is accidents, constituting 88-96% of the external costs. In contrast to shared cars, shared bikes and scooters have higher external costs than exclusive bikes and scooters, due to the CO_2 emissions that are caused during the relocation of vehicles.

Figure 8-4 illustrates the regional differences in external costs for car-based mobility services. In general, mobility in cities causes higher external costs, because more people are affected by the emissions and congestion. We find that the external costs per kilometer differ less for taxis than for exclusive and shared cars. The main driver of regional differences is parking. Since taxis do not require conventional parking spaces, the differences between the regions are lower. We do not regard regional differences for bikes and scooters, since the caused accidents and emitted carbon emissions do not depend on the regional setting.

The internal mobility costs for each mobility service as well as the respective data sources are listed in Table 8A-8 of the appendix. Exclusive mobility services cause costs per vehicle and per distance unit, while public mobility services, i.e., shared mobility services and taxis, are associated with different combinations of costs for memberships, per distance unit, per invoice period, and per trip, depending on the price tariff.

8.5.2 Company Examples

We first illustrate our approach of analyzing the external costs of CMaaS using the example of two companies with different key characteristics. Company 1 is a manufacturing company, has between ten and 50 employees, and is based in a city. Company 2 is active in the field of human health and social work activities, has between 51 and 250 employees, and is based in a

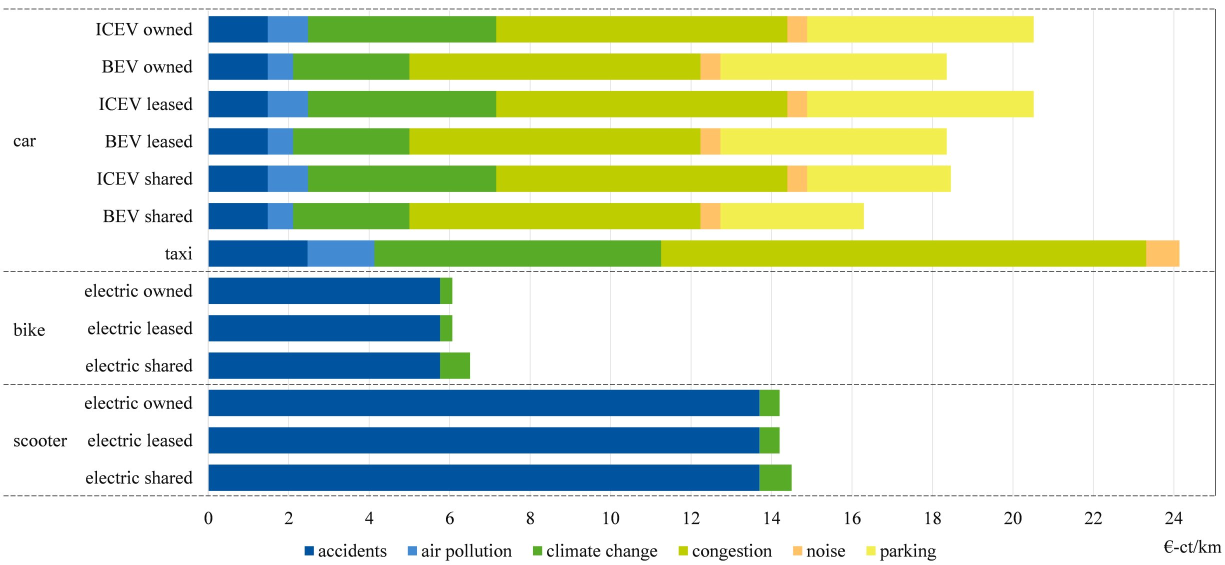

Figure 8-3: Average external costs per kilometer of each regarded mobility service.

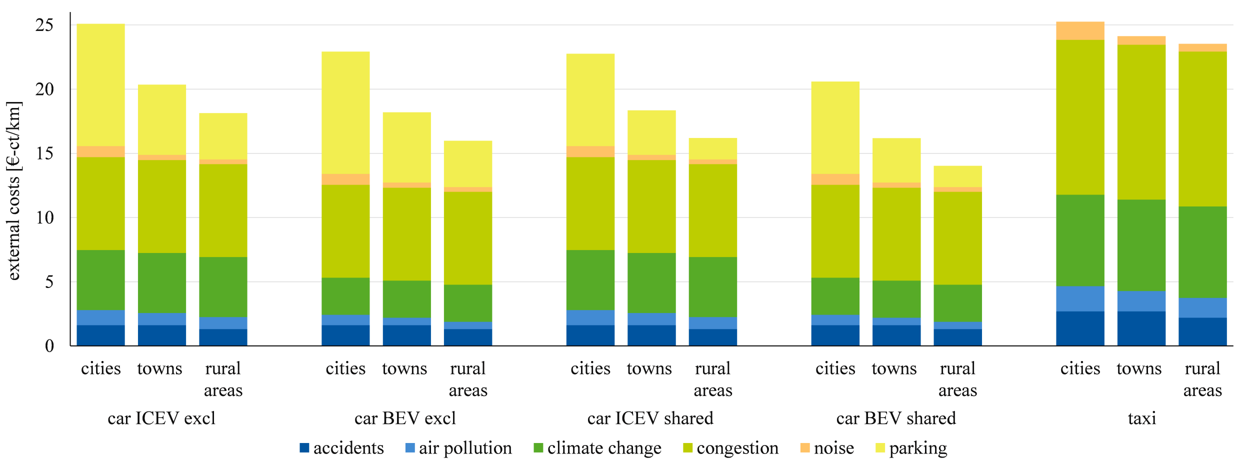

Figure 8-4: Comparison of the external costs per kilometer of the mobility services that vary with the regional setting.

town. The mileage of company 1 is twice as high as the mileage of company 2, but their internal mobility costs are comparable, because fewer but considerably longer trips allow company 1 to use their vehicles more efficiently. With traditional fleet management (IntT), both companies use six fossil-fueled cars to meet their demand. The external costs of corporate mobility amount to 89,000€ in the case of company 1, while company 2 causes 33,000€ of external costs with traditional fleet management. Table 8-8 and Figure 8-5 present the key indicators of both companies, as well as the social costs in all regarded scenarios. The pie charts depict the share of mileage for different clusters of mobility services.

Minimizing internal mobility costs by implementing CMaaS (IntC), company 1 can reduce their internal costs by 37% and the external costs by 9%, while company 2 can reduce the internal and external costs by 28% and 14%, respectively (cf. Figure 8-5). Overall, the companies reduce the social costs by 10% (company 1) and 15% (company 2). Herein, the two companies can reduce their exclusive car fleets and instead use shared cars and bikes. When minimizing external costs (ExtC), company 1 can decrease external costs by 23% and company 2 by 32% compared with IntT. However, internal costs increase by 160% (company 1) and 219% (company 2). The social costs can be decreased by 20% for company 1 and by 25% for company 2. Both companies only use exclusive BEVs, shared cars, and exclusive bikes in this scenario. When minimizing social costs (SocC), the social costs can be reduced by 23% (company 1) and 29% (company 2). For company 1 and company 2, the internal costs are 8% and 19% higher than in IntT, but external costs are 23% and 31% lower, respectively. These changes are caused by a predominant use of shared cars, exclusive and shared bikes, as well as exclusive BEVs. Additionally, the companies use taxis to a small extent.

Table 8-8: Key indicators, internal and external mobility costs, as well as used mobility services for the two exemplary companies.

	company 1	company 2		company 1	company 2
industry	carpentry	social work	*- used mobility services*[c] *-*		
employees	10-50	51-250	TFM	4 owned cars (ICEV)	5 owned cars (ICEV)
location in GER	RP[a]	BW[b]		2 leased cars (ICEV)	1 leased car (ICEV)
regional setting	city	town	IntC	1 leased car (ICEV)	1 owned car (ICEV)
mileage [km]	3,529.40	1,633.00		CS(A), BS(A), T	1 leased car (ICEV)
- internal mobility costs [€] -					1 owned bike
IntT	1,689.69	1,509.78			1 owned scooter
IntC	1,072.22	1,088.75			CS(A), BS(B), T
ExtC	4,399.51	3,474.27	ExtC	4 leased cars (BEV)	3 owned cars (BEV)
SocC	1,832.47	1,790.57		5 leased bikes	2 leased cars (BEV)
- external mobility costs [€] -				CS(A)	6 owned bikes
IntT	88,551.94	33,240.33			CS(A)
IntC	80,182.57	28,536.71	SocC	2 owned bikes	2 owned cars (BEV)
ExtC	67,770.29	22,676.19		CS(A), BS(B), T	3 owned bikes
SocC	67,745.40	22,869.01			CS(A), BS(B), T

[a]RP = Rhineland-Palatinate,
[b]BW = Baden-Wuerttemberg,
[c]CS = shared cars, BS = shared bikes, T = taxi, A = active price tariff, B = basic price tariff

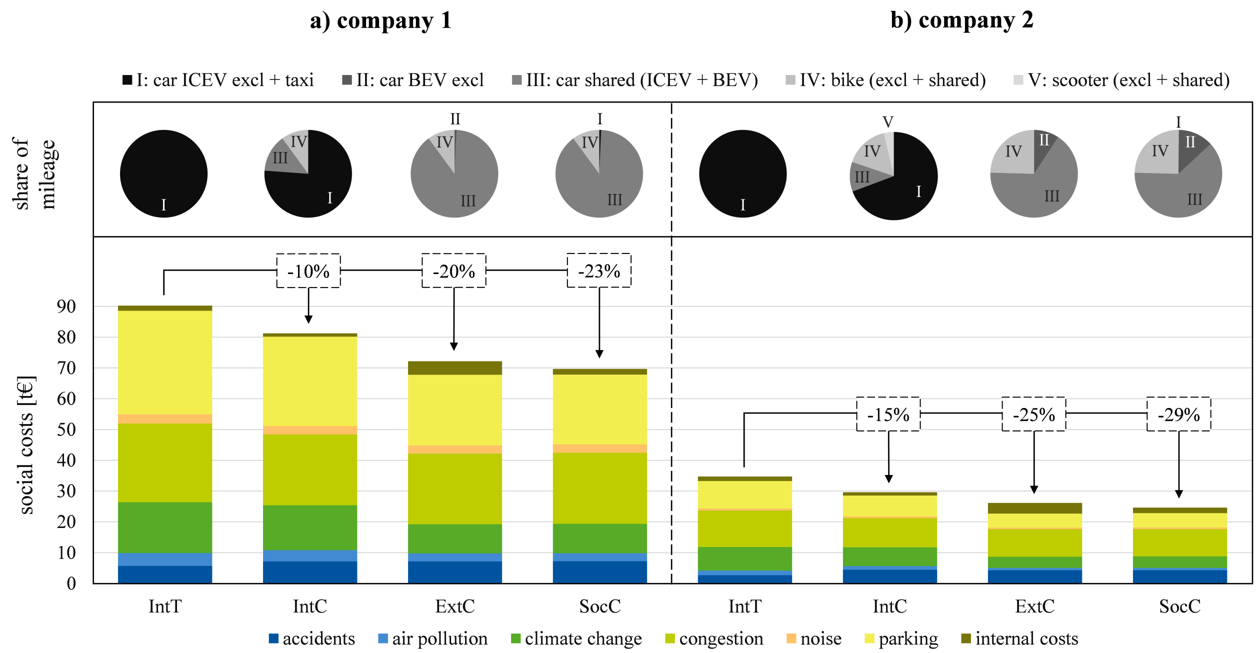

Figure 8-5: Social costs of the exemplary companies in all regarded scenarios and the respective shares of mileage with different mobility services.

8.5.3 Average Results

Analyzing results over all 144 analyzed companies, we find that the internal costs can be reduced on average by 28% and the external costs by 4% compared with traditional fleet management (IntT) when implementing CMaaS and minimizing internal costs (IntC) (cf. Figure 8-6). Herein, especially the external costs of parking are reduced by shifting 14% of the mileage from exclusive ICEVs and BEVs to shared vehicles, bikes, and scooters. While external costs can be decreased in most dimensions, we find an increase in the external costs of accidents due to the higher share of bikes and scooters. The social costs are reduced by 5% compared with traditional fleet management (IntT).

When minimizing external costs (ExtC), the overall potentials of CMaaS to decrease external costs are considerably higher. On average, the minimum external costs are 21% lower than the external costs of traditional fleet management (IntT). Only exclusive BEVs and shared cars as well as exclusive bikes are used. The highest relative external cost decreases can be achieved in the dimensions parking (37%), climate change (36%), and air pollution (35%), while the increased usage of micromobility modes again leads to increases in the external costs of accidents (20%). While external costs can be decreased considerably in this scenario, internal costs are more than twice as high than with traditional fleet management, so that the social costs are

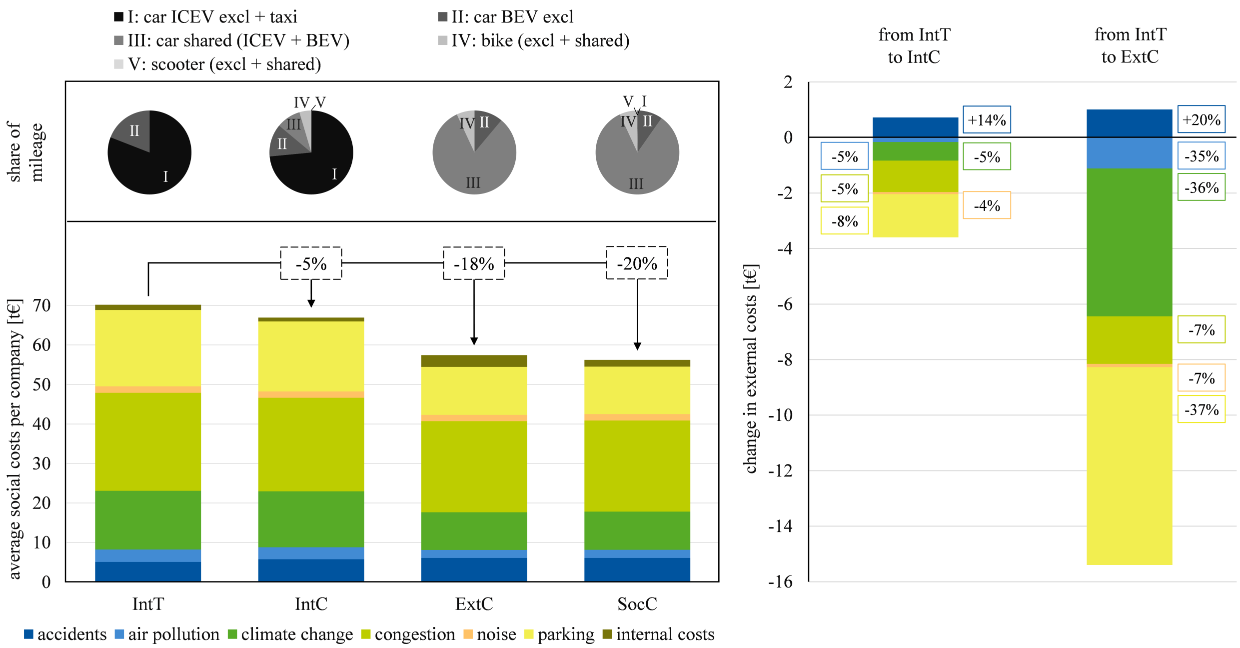

Figure 8-6: Average social costs per company (left) and change in the structure of external costs (right).

reduced by 18% on average.

Minimizing the social costs of mobility (SocC), external costs can be reduced by 21% on average, while internal costs are 25% higher than with traditional fleet management (IntT). Accordingly, the external costs are comparable to ExtC, while the internal costs are 73% higher than in IntC. The social costs can be decreased by 20% on average. Herein, companies conduct on average 82% of their mileage with shared BEVs, further using bikes (10%), exclusive BEVs (4%), shared ICEVs (4%), as well as exclusive ICEVs and taxis (below 1%).

In all scenarios, taxis and scooters serve less than 0.2% of the mileage (IntC and SocC), or are not used at all (ExtC). Minimizing external costs requires on average a larger exclusive fleet than with traditional fleet management, mainly consisting of BEVs and electric bikes. In IntC and SocC, the car fleet can be reduced by 69% and 80% compared with traditional fleet management, respectively. Adding exclusive bikes and scooters to the corporate fleet leads to reductions of the total fleet size, i.e., including cars, bikes, and scooters, of 63% (IntC) and 46% (SocC). Most companies use the active tariff for shared cars in all scenarios, indicating that shared cars are consistently an important part of corporate mobility, independent of the considered objective. In contrast, the basic price tariff is used by most companies in IntC and SocC for shared bikes and scooters; in ExtC, shared bikes and scooters are not used at all.

Since the external costs of some dimensions depend on the regional setting (cf. Section 8.5.1), the external costs per kilometer differ significantly between the companies from different regions. Figure 8-7 shows that in all regarded scenarios, the external costs per kilometer are on average 26-31% lower in rural areas than in cities. The deviation of the external costs per kilometer among companies is low with traditional fleet management (IntT) because of the low variety of suitable mobility modes. In the CMaaS scenarios, the high deviation among companies reflects that companies use different mobility services to meet their mobility demand.

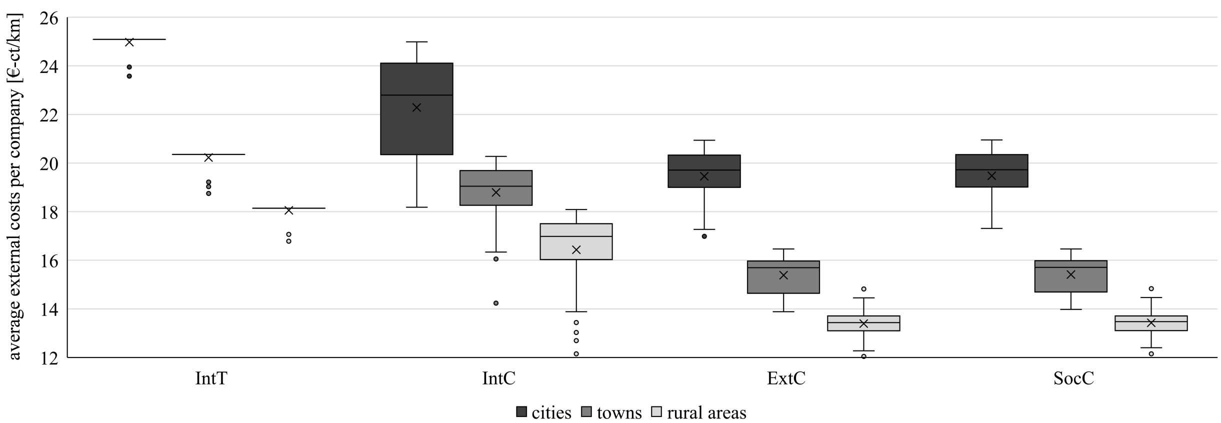

Figure 8-7: Average external costs in Euro-cent per kilometer for companies from cities, towns, and rural areas.

8.6 Discussion

In the following, we reflect the insights about CMaaS that can be derived from our study. We first explain the implications of our results in Section 8.6.1, and then discuss the main limitations as well as the need for further research in Section 8.6.2.

8.6.1 Implications

Our results show that CMaaS enables companies to reduce the social costs of their mobility by up to 20% on average, suggesting that CMaaS is an effective tool to reduce the social impacts of corporate mobility and drive the sustainable mobility transformation. We show that external costs are significantly higher than internal costs, highlighting that most costs are not covered by individual users but are borne by society instead. To realize the maximum potential of CMaaS to decrease the social costs of corporate mobility, the existing mode choice bias in favor of owned or leased cars must be overcome and instead, mobility services with lower external costs per kilometer, like bike-based services and shared cars, should be used where possible. Our results show that bikes and shared cars would also be used in a setting with minimum internal costs, further emphasizing their value to corporate fleets. Policy-makers should therefore prioritize to make the usage of bikes and shared cars accessible to all companies, e.g., by providing a safe road infrastructure and supporting the installation of further carsharing stations or reserved parking spots. Our results further reveal regional differences in the impacts of corporate mobility, indicating a specifically high potential in cities, since the external costs per kilometer are higher in cities than in towns and rural areas.

8.6.2 Limitations and Future Research

In the following, we discuss four main limitations of our work in further detail to illustrate the need for subsequent research. Due to the limited number of related external cost assessments, especially of studies quantifying the marginal external costs of passenger mobility (cf. Section 8.2.1), we cannot verify the results of our external cost assessment comprehensively. Two studies previously quantified the marginal external costs of exclusive ICEVs (cf. van Essen et al. 2019) and exclusive BEVs (cf. Letmathe and Paegert 2024). van Essen et al. (2019) provide the country-based external cost factors that serve as an input for our analysis, but do not quantify the further parameters needed so that a verification of our results is impossible. Letmathe and Paegert (2024) exclusively focus on the external costs of BEVs in cities, which is to some degree comparable with the results for companies from cities in our study. However, we consider that companies in cities do not exclusively drive in cities, but also in towns and rural areas. This is the major reason for the external costs of BEVs from cities being in total 16% lower in our study than in Letmathe and Paegert (2024). In the future, more external cost assessments in the context of passenger mobility should be realized to enable a direct comparison of the different approaches and results.

We propose an approach to quantify the external costs of parking for mobility services. Due to a lack of the required data, parking lots can be regarded exclusively, omitting roadside or sidewalk parking. Therefore, only a share of the impacts can be regarded and we expect the real external costs of parking to be higher than the external costs identified in this study. Accordingly, we cannot consider the external costs of parking of shared bikes and scooters, which consume space on sidewalks and at the roadside, and falsely parked vehicles might additionally cause obstruction or accidents. Accordingly, there is a need for research that surveys the areas used for roadside and sidewalk parking, and that specifies the respective land value as well as the damage caused by falsely parked vehicles.

In accordance with prior studies, we find that taxis are associated with the highest impacts per kilometer because of the necessary empty rides (cf. de Bortoli and Christoforou 2020). However, taxis have a positive inclusion effect, since it might be the only mobility service that can be used by people with physical limitations, or without a driving license for certain trips. Further, we could not consider the benefits of job creation from taxi usage. Future research should try to monetize these effects to allow its consideration in subsequent external cost assessments.

Finally, we want to emphasize that data on the usage of bikes and scooters is still lacking. For cars and car usage, valuable data is provided by German government agencies, but corresponding data for micromobility is scarce. A better insight into the travel behavior with bikes and scooters would help research to identify pathways for the carbon-neutral mobility transition. Continual research could further assess how the use of bike-based and shared services could be encouraged, since they can be important drivers of internal and external cost reductions.

8.7 Conclusion

We analyzed the potentials of CMaaS to reduce the social impacts of corporate mobility by quantifying the social costs in different scenarios. We applied a strategic-tactical optimization model to identify the optimal CMaaS design for a company's individual circumstances, considering the company-specific regional setting and mobility demand. To create general insights, we juxtaposed the social costs of CMaaS and traditional fleet management for 144 companies, considering thirteen different mobility services. Our results show that CMaaS has the potential to reduce the external costs of corporate mobility significantly, but that further incentives might be needed to reduce the mode choice bias and increase consideration of bikes and shared cars for corporate trips.

Acknowledgment

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8.A Appendix

Equations 8A-1 to 8A-10: Model constraints of the applied optimization model, cf. Frank et al. (2024).

$$\sum_{s \in \mathcal{S}} \sum_{v \in \mathcal{V}_{si}^{w}} \sum_{p \in \mathcal{P}_s} a_{isvp}^{w} = 1 \qquad \forall w \in \mathcal{W}, i \in \mathcal{I} \quad \text{(8A-1)}$$

$$\sum_{i \in \mathcal{I}_{svt}^{w}} f_{isv} a_{isvp}^{w} = b_{svpt}^{w} \qquad \forall w \in \mathcal{W}, s \in \mathcal{S}, v \in \mathcal{V}_s, p \in \mathcal{P}_s, t \in \mathcal{T} \quad \text{(8A-2)}$$

$$\sum_{p \in \mathcal{P}_s} b_{svpt}^{w} \leq x_{sv}^{\mathrm{E}} \qquad \forall w \in \mathcal{W}, s \in \mathcal{S}^{\mathrm{E}}, v \in \mathcal{V}_s, t \in \mathcal{T} \quad \text{(8A-3)}$$

$$\sum_{p \in \mathcal{P}_s} b_{svpt}^{w} \leq N_{svt} \qquad \forall w \in \mathcal{W}, s \in \mathcal{S}, v \in \mathcal{V}_s, t \in \mathcal{T} \quad \text{(8A-4)}$$

$$\sum_{w \in \mathcal{W}} \sum_{i \in \mathcal{I}} \sum_{v \in \mathcal{V}_{si}^{w}} a_{isvp}^{w} \leq M y_{sp} \qquad \forall s \in \mathcal{S} \setminus \mathcal{S}^{\mathrm{E}}, p \in \mathcal{P}_s \quad \text{(8A-5)}$$

$$\sum_{p \in \mathcal{P}_s} y_{sp} \leq 1 \qquad \forall s \in \mathcal{S} \setminus \mathcal{S}^{\mathrm{E}} \quad \text{(8A-6)}$$

$$x_{sv}^{\mathrm{E}} \in \mathbb{N} \qquad \forall s \in \mathcal{S}^{\mathrm{E}}, v \in \mathcal{V}_s \quad \text{(8A-7)}$$

$$y_{sp} \in \{0; 1\} \qquad \forall s \in \mathcal{S} \setminus \mathcal{S}^{\mathrm{E}}, p \in \mathcal{P}_s \quad \text{(8A-8)}$$

$$a_{isvp}^{w} \in \{0; 1\} \qquad \forall w \in \mathcal{W}, s \in \mathcal{S}, i \in \mathcal{I}, v \in \mathcal{V}_{si}^{w}, p \in \mathcal{P}_s \quad \text{(8A-9)}$$

$$b_{svpt}^{w} \in \mathbb{N} \qquad \forall w \in \mathcal{W}, s \in \mathcal{S}, v \in \mathcal{V}_s, p \in \mathcal{P}_s, t \in \mathcal{T} \quad \text{(8A-10)}$$

Table 8A-1: Model notation.

Sets	
$\mathcal{S}$	set of mobility services
$\mathcal{S}^{\mathrm{E}}$	set of exclusive mobility services
$\mathcal{V}_s$	set of vehicle classes of mobility service s
$\mathcal{P}_s$	set of price tariffs of mobility service s
$\mathcal{W}$	set of micromobility settings
$\mathcal{I}$	set of trips
$\mathcal{I}^w_{svt}$	set of trips that occupy a vehicle in period t if mobility service s with vehicle class v is used in micromobility setting w
$\mathcal{V}^w_{si}$	set of feasible vehicle classes of mobility service s for trip i in micromobility setting w
Parameters	
c^{veh}_{sv}	costs per vehicle of exclusive mobility service s in vehicle class v
c^{mem}_{sp}	total membership costs of public mobility service s in price tariff p
c^{trip}_{isvp}	basic trip costs of trip i with mobility service s in vehicle class v and price tariff p
c^{dist}_{isvp}	distance costs of trip i with mobility service s in vehicle class v and price tariff p
c^{time}_{isvp}	time costs of trip i with mobility service s in vehicle class v and price tariff p
ex^{dist}_{isv}	external costs of trip i with mobility service s in vehicle class v
N_{svt}	vehicle capacity of mobility service s in vehicle class v in period t
f_{isv}	number of required vehicles if mobility service s with vehicle class v is used for trip i
M	big M: large positive value
γ^w	factor determining the occurrence of micromobility setting w ($\sum_{w\in\mathcal{W}} \gamma^w = 1$)
Decision variables	
x^{E}_{sv}	integer: fleet size of exclusive mobility service s in vehicle class v
y_{sp}	binary: 1 if price tariff p is selected for public mobility service s, 0 otherwise
a^w_{isvp}	binary: 1 if mobility service s with vehicle class v and price tariff p is selected for trip i in micromobility setting w, 0 otherwise
b^w_{svpt}	integer: number of occupied vehicles of mobility service s in vehicle class v and price tariff p in period t and micromobility setting w

Table 8A-2: Excerpt from the REM 2030 driving profiles data base.

	departure					arrival					
vehicle ID	year	month	day	hour	minute	year	month	day	hour	minute	distance
1106000341	2011	7	6	9	35	2011	7	6	11	46	26.19
1106000341	2011	7	6	13	36	2011	7	6	15	35	24.98
...	...	...	...	...	...	...	...	...	...	...	...

Table 8A-3: Key indicators of the analyzed driving profiles.

	data base
number of companies [-]	144
number of driving profiles [-]	428
∅ number of trips per company [-]	322
∅ trip distance per company [km]	13
∅ company mileage [km]	3,424
∅ trip duration per company [min]	19

Table 8A-4: Technical details of vehicle classes.

mobility mode	**car**		**bike**	**scooter**
drive train	**ICEV**	**BEV**	**electric**	**electric**
access time [min]	11		5	5
speed [km/h]	24.1		18.5	18.5
max. distance [km]	∞	472	13	2
consumption per 100km	5.4 l	16.3 kWh	0.27 kWh	0.84 kWh
charging capacity [kW]	-	11	0.1	0.075
max. number of available shared vehicles	5	5	12	6
references	ADAC 2024b	ADAC 2024c	Swapfiets 2024, Cairns et al. 2017	Segway Europe BV 2024, Cao et al. 2021

Table 8A-5: Values and data sources for the external costs of car-based mobility services.

dimension	parameter	condition	value	data sources
cars				
accidents	AC_{fs} [-]	f = fatalities	1331	Statistisches Bundesamt 2024b
		f = serious injuries	27,708	
		f = slight injuries	174,679	
	MI_s	-	600.6 bn	BaSt 2024
	RE_{js} [-]	j = urban roads	0	van Essen et al. 2019
		j = other roads	-0.25	
		j = motorways	-0.25	
	RI_s [%]	-	0.63	own calculations[a]
	UR_{fs} [%]	f = fatalities	1.00	van Essen et al. 2019
		f = serious injuries	1.25	
		f = slight injuries	2.00	
climate change	EG_{gs} [kg/km]	g = CO_2 equivalents		Lauf et al. 2023[b]
		and $s \in$ ICEV	0.2057	
		and $s \in$ BEV	0.1269	
		and s = taxi	0.3131	
congestion	DC [%]	-	0.17	Letmathe and Paegert 2024
noise	SD_{du} [%]	d = dense	0.46	own calculations[c]
		d = thin	0.54	
parking	EX_s [€/m^2]	$s \in$ excl	51	Agora Verkehrswende 2022,
		$s \in$ shared	18	Bergk and Schreiner 2022
	IN_{rs} [€/m^2]	$s \in$ excl		Rat der Stadt Bonn 2022,
		and r = cities	0.90	Bundesstadt Bonn 2024a
		and r = towns	0	
		and r = rural	0	
		$s \in$ shared		Bundesstadt Bonn 2024b
		and r = cities	40.00	
		and r = towns	10.82	
		and r = rural	2.62	
	LV_r [€/m^2]	r = cities	7320	BORIS-NRW 2024
		r = towns	1980	
		r = rural	480	
	MI_{rs} [km]	r = cities	1.81 bn	own calculations[d]
		r = towns	0.32 bn	
		r = rural	0.11 bn	
	PF [-]	-	29.10	Daube and Krivenkov 2023
	SR_{rs} [m^2/veh.]	r = cities	3.67	average values for parking areas
		r = towns	5.12	as surveyed by
		r = rural	6.24	Bezirksregierung Köln 2023

[a]following van Essen et al. 2019,
[b]supplemented by ADAC 2024b, ADAC 2024c (vehicle consumption), Wernet et al. 2016 (shares of PM sizes, energy transformation losses), Bundesnetzagentur 2024 (energy mix), Klopfer et al. 2023 (vehicle production)
[c]approximated by share of mileage during (= dense traffic) or outside (= thin traffic) peak times acc. to data base
[d]based on the average number of vehicles in each region as surveyed by KBA 2024a (approx. by regional data from the federal state of North Rhine-Westphalia) and the average distance per vehicle as surveyed by BaSt 2024

Table 8A-6: Values and data sources for the external costs of mobility services with bikes and scooters.

dimension	parameter	condition	value	data sources
bikes				
accidents	AC_{fs} [-]	f = fatalities	348	Statistisches Bundesamt 2024b
		f = serious injuries	11,227	
		f = slight injuries	44,778	
	MI_s [km]	-	40.880 bn	Nobis and Kuhnimhof 2018
	RE_{js} [-]	j = urban roads	0.1	own assumptions (cf. Section 8.4)
		j = other roads	0.1	
		j = motorways	0	
	RI_s [%]	-	0.97	own calculations[a]
	UR_{fs} [%]	f = fatalities	1.00	van Essen et al. 2019
		f = serious injuries	1.55	
		f = slight injuries	3.20	
climate change	EG_{gs} [kg/km]	g = CO_2 equivalents		Lauf et al. 2023[b]
		and s = excl	0.0134	
		and s = shared	0.0328	
scooters				
accidents	AC_{fs} [-]	f = fatalities	42	Statistisches Bundesamt 2024b
		f = serious injuries	1,358	
		f = slight injuries	6,171	
	MI_s [km]	-	1.382 bn	Krauss et al. 2024, GDV 2023, DLR 2020
	RE_{js} [-]	j = urban roads	0.05	own assumptions
		j = other roads	0.05	
		j = motorways	0	
	RI_s [%]	-	1.00	own calculations[a]
	UR_{fs} [%]	f = fatalities	1.00	van Essen et al. 2019
		f = serious injuries	1.55	
		f = slight injuries	3.20	
climate change	EG_{gs} [kg/km]	g = CO_2 equivalents		Lauf et al. 2023[b]
		and s = excl	0.0218	
		and s = shared	0.0351	

[a]following van Essen et al. 2019 and based on data from Statistisches Bundesamt 2024b,
[b]supplemented by Swapfiets 2024, Segway Europe BV 2024 (vehicle consumption), Wernet et al. 2016 (shares of PM sizes, energy transformation losses), Bundesnetzagentur 2024 (energy mix)

Table 8A-7: Emission factors of air pollutants (EP_{asu}) in mg/km.

		SO_2	NO_X	$PM_{2.5}$	PM_{10}	PM_{coarse}	NMVOC	NH_3
vehicle classes	car ICEV	51.3086	137.6222	25.6108	66.3547	138.5057	367.7918	10.6854
	car BEV	28.4670	65.0854	22.9608	71.4899	3.6899	4.8259	2.8212
	bike electric	0.4796	1.0964	0.0094	0.0975	0.0622	0.0813	0.0475
	scooter electric	1.4607	3.3396	0.0288	0.2971	0.1893	0.2476	0.1448

Table 8A-8: Cost factors of all considered mobility services and vehicle classes.

mobility service	price tariff	costs in € per vehicle	membership[a]	distance in km	invoice period	trip	references
car ICEV owned	-	159.83	-	0.57	-	-	[1],[2]
car BEV owned	-	190.33	-	0.56	-	-	[1],[2],[3],[4]
car ICEV leased	-	332.00	-	0.10	-	-	[1],[2],[5]
car BEV leased	-	594.42	-	0.04	-	-	[1],[2],[5]
car ICEV shared	basic	-	-	0.31	4.30[c]	-	[6]
car ICEV shared	active	-	20/+3[b]	0.29	2.25[c]	-	[6]
car BEV shared	basic	-	-	0.31	4.30[c]	-	[6]
car BEV shared	active	-	20/+3[b]	0.29	2.25[c]	-	[6]
taxi ICEV	-	-	-	2.60	-	4.90	[17]
bike electric owned	-	42.32	-	0.0007	-	-	[7],[8],[9],[10]
bike electric leased	-	85.52	-	0.0007	-	-	[11]
bike electric shared	basic	-	-	-	2.00[d]	-	[12],[13]
bike electric shared	active	-	10/4/3/2[b]	-	-	-	[12],[13]
scooter electric owned	-	16.77	-	0.002	-	-	[8],[9],[14]
scooter electric leased	-	32.90	-	0.002	-	-	[14],[15]
scooter electric shared	basic	-	-	-	0.24[e]	1.20	[16]
scooter electric shared	active	-	2.99	-	0.24[e]	-	[16]

[a]We assume that membership fees are paid for 20% of the employees of each company, if an active price tariff is selected. [b]For carsharing, the first employee costs 20 € and every further employee 3 €, but not more than 50 € per company. Costs for public bikesharing refer to companies with <50/50-100/101-500/>500 participating employees, respectively. [c]per 60 minutes, [d]per 30 minutes, [e]per 1 minute [1] ADAC 2024a, [2] ADAC 2021, [3] Generalzolldirektion 2024, [4] De Clerck et al. 2018, [5] Sixt Leasing 2024, [6] cambio 2024, [7] Dimpker 2024, [8] CHECK24 2024, [9] BMF 2000, [10] Shimano Inc. 2024, [11] Swapfiets 2024, [12] nextbike 2024, [13] nextbike 2021, [14] Segway Europe BV 2024, [15] Grover 2024, [16] TIER 2024, [17] Stadt Köln 2022

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