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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.

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; EU, 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., 2023). 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

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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. (2023) 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 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 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 3 gives an overview of the methodological approach, and in Section 4, we present the setting of our case study and the analyzed scenarios. Finally, we present our results in Section 5 and draw a conclusion on the insights of our research in Section 6.

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 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 2.2.

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, 2015). 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.

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., 2023). 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 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.

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 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 3.2 and 3.3). Finally, we present our multi-objective optimization model, which identifies the pareto-optimal CMaaS designs (cf. Section 3.4).

Table 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

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.

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 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 1. A detailed view of the used data and respective data sources is provided in the supplementary material.

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 supplementary material. 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. Fig. 1 shows the system boundary of the LCA. Resource extraction, the

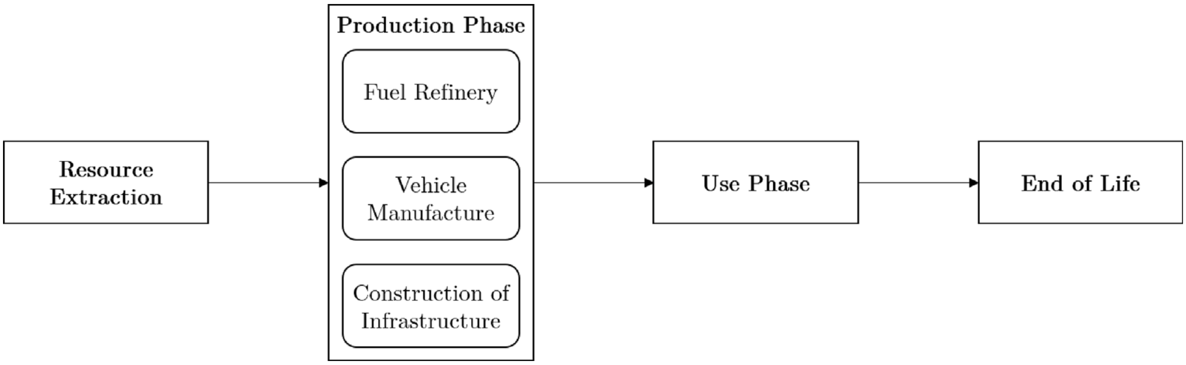

Fig. 1. Scope of the LCA.

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).

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 optimization model previously developed by Frank et al. (2023). 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. Eq. (1)). Fixed system costs, which occur independently of the undertaken trips, consist of the costs per vehicle (c^{veh}_{sv}) within the company-exclusive fleet (x^{E}_{sv}) as well as the costs of memberships (c^{mem}_{sp}) for the selected price tariffs of public mobility services (y_{sp}) (cf. Eq. (2)). Anticipated costs of operation occur in dependence of the mobility behavior and include costs per distance unit (c^{dist}_{isvp}), as well as costs per time unit (c^{time}_{isvp}) and per trip (c^{trip}_{isvp}) as claimed by public mobility service providers (cf. Eq. (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^{w}_{svpi}). The second objective function minimizes the anticipated GHG emissions per passenger kilometer (e^{dist}_{isv}) for each company (cf. Eq. (4)). Like the anticipated costs of operation, the anticipated GHG emissions depend on

Table 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_{svt}^{w}	Set of trips that occupy a vehicle in period t if mobility service s with vehicle class v is used in micromobility setting w
$\mathcal{V}_{si}^{w}$	Set of feasible vehicle classes of mobility service s for trip i in micromobility setting w
Parameters	
c_{sv}^{veh}	Costs per vehicle of company-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
e_{isv}^{dist}	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_{sv}^{E}	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_{svpi}^{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

the employees' willingness to consider micromobility modes and the trip characteristics. Table 2 gives an overview of the model notation of the objective functions. For the comprehensive model notation, compare the supplementary material.

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

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

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

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

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 4.1) and then describe our experimental design (cf. Section 4.2).

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 500 m, trips with transporters and special vehicles, as well as trips by taxi companies. We regard time intervals of 15 min in our analysis. An extract of the driving profiles is presented in Table 3 and the key indicators of the analyzed companies are presented in Table 4.

We regard the mobility services listed in Table 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,

Table 3
Exemplary trip as listed in the driving profiles.

Vehicle ID	Departure					Arrival					Distance
	Year	Month	Day	Hour	Minute	Year	Month	Day	Hour	Minute	
1106000341	2011	7	6	9	35	2011	7	6	11	46	26.19

Table 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]	3424
∅ trip duration per company [min]	19

Table 5
Notation of mobility services.

Provision		Company-exclusive		Public	
		Owned	Leased	Shared	Taxi
Mode	Car	*carOwned*	*carLeased*	*carShared*	*taxi*
	Bike	*bikeOwned*	*bikeLeased*	*bikeShared*	–
	Scooter	*scooterOwned*	*scooterLeased*	*scooterShared*	–

Table 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	–	[a,b,c]
	ICEV M			∞	5.5 l	–	[a,b,d]
	BEV S			190	13.0 kWh	11	[a,b,e]
	BEV M			353	15.8 kWh	11	[a,b,f]
Bike	BEV	5	18.5	13	0.35 kWh	0.112	[a,g,h]
Scooter	BEV	5	18.5	2	0.92 kWh	0.056	[a,i,j,k]

[a] Umweltbundesamt (2014).
[b] Cardelino (1998).
[c] ADAC (2023c).
[d] ADAC (2023d).
[e] ADAC (2023a).
[f] ADAC (2023b).
[g] Shimano Inc. (2018).
[h] Cairns et al. (2017).
[i] Cao et al. (2021).
[j] Grover (2021).
[k] Zhu et al. (2020).

we consider the vehicle classes as defined in Table 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 supplementary material.

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 3.2 and 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 supplementary material. 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).

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 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).

5. Results

We present our case study results in the following chapter. Section 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 5.2 how different political measures could encourage companies to implement a more sustainable CMaaS design.

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). Fig. 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

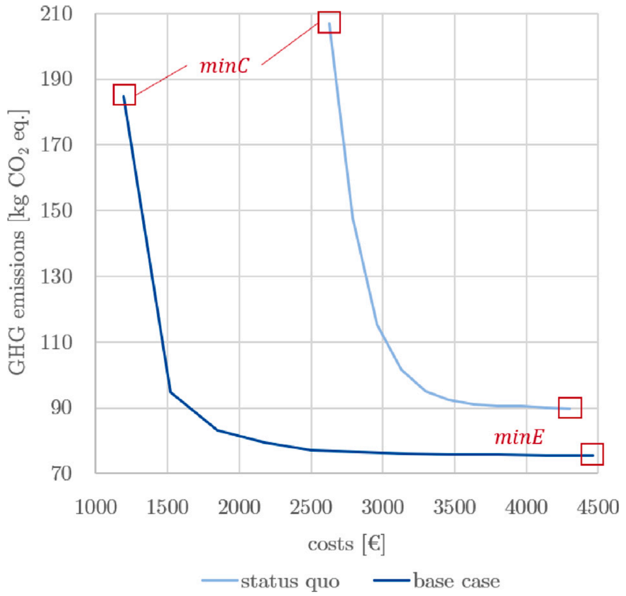

Fig. 2. Pareto fronts of the exemplary company in the SQ and the BC.

Table 7
Strategic-tactical decisions for the exemplary company.

Mode		Company-exclusive: fleet size				Public: price tariff			
specification		Car	Car	Bike	Scooter	Car	Bike	Scooter	Taxi
		BEV	ICEV	BEV	BEV	Shared			
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.

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 Fig. 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 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. Fig. 3 presents the average pareto front for each scenario and Table 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 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, Figs. 4 and 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

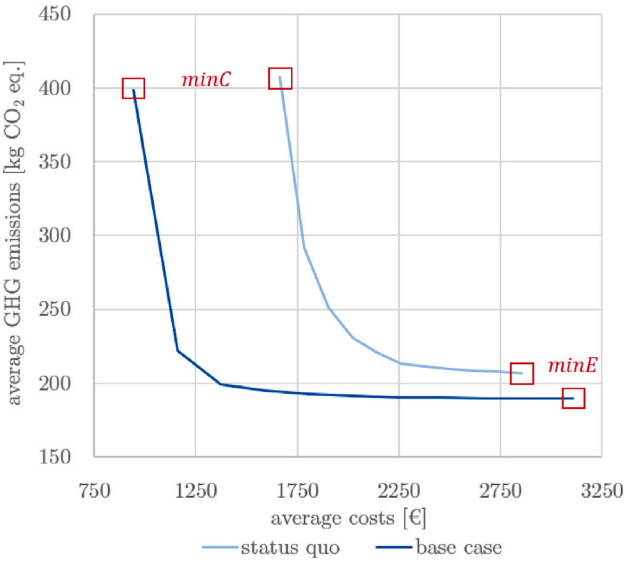

Fig. 3. Average pareto fronts in the SQ and the BC.

Table 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.

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 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.

In the following, we compare in detail which mobility services must be used by companies to minimize their costs and/or GHG emissions. Figs. 6 and 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).

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. Fig. 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.

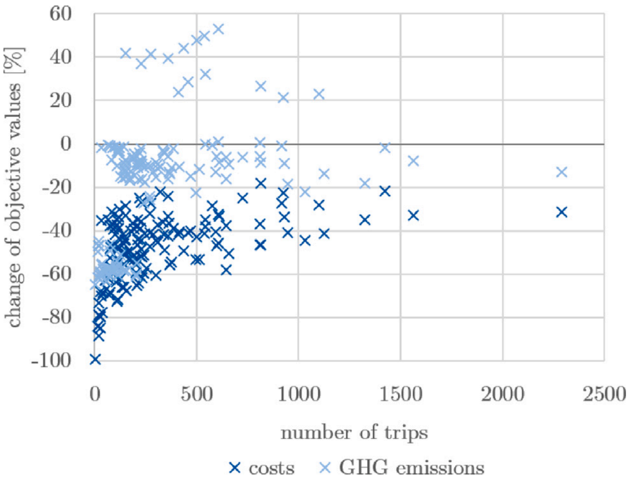

Fig. 4. Depiction of how the objective values in *minC* change in the BC when compared to the SQ (y-Axis), depending on the number of trips of each company (x-Axis).

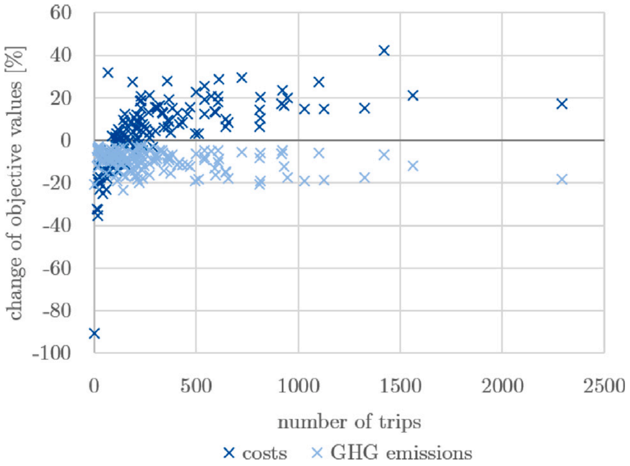

Fig. 5. Depiction of how the objective values in *minE* change in the BC when compared to the SQ (y-Axis), depending on the number of trips of each company (x-Axis).

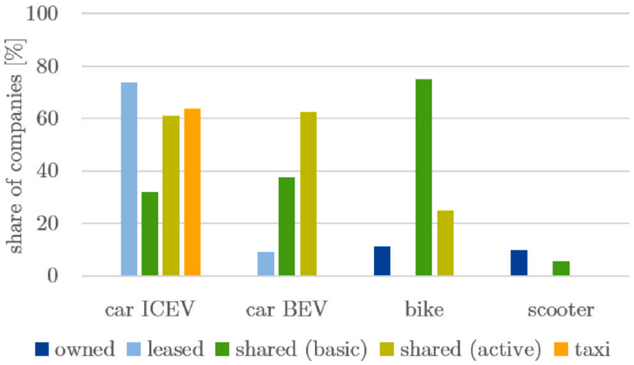

Fig. 6. Share of the companies that use the mobility services and price tariffs for at least one trip in *minC* of the BC.

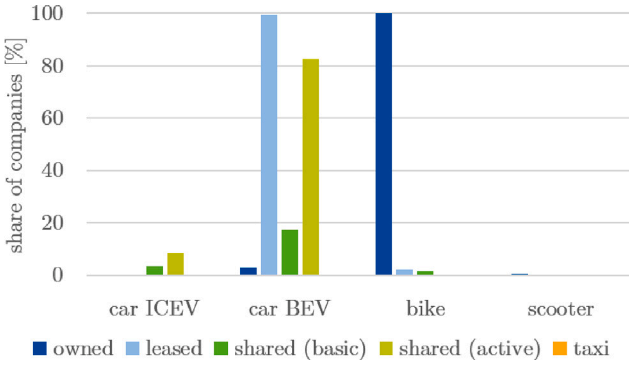

Fig. 7. Share of the companies that use the mobility services and price tariffs for at least one trip in $minE$ of the BC.

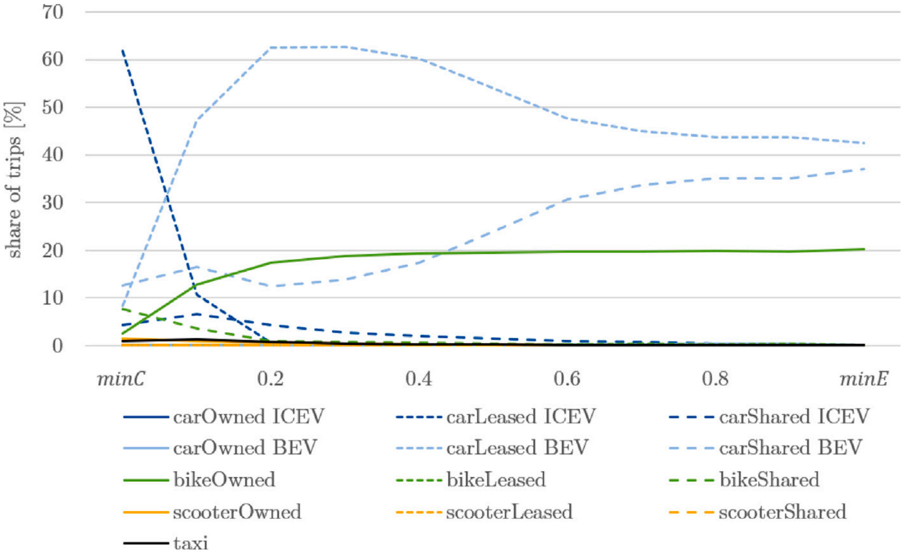

Fig. 8. Share of trips per mobility service in the BC from $minC$ to $minE$, differentiated for drive trains.

5.2. Scenario analysis

Fig. 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) 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. Fig. 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 efficiency of the CMaaS system decreases while the shares of micromobility use remain low. For $minC$, we find that trips with micromobility modes primarily

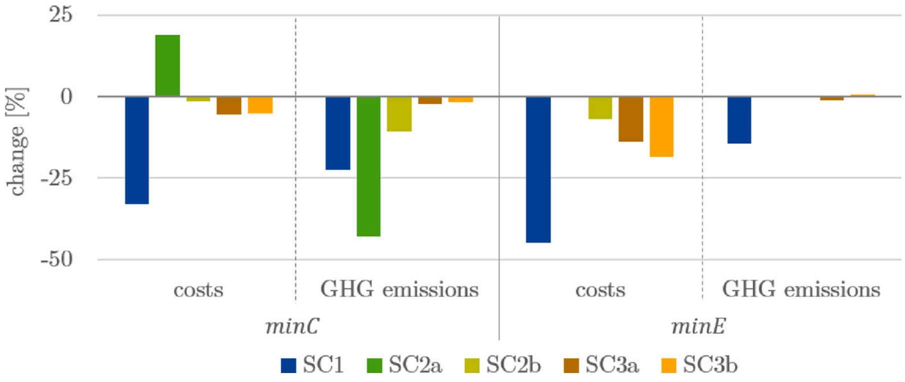

Fig. 9. Changes in objective values for the analyzed scenarios in comparison to the BC for $minC$ and $minE$.

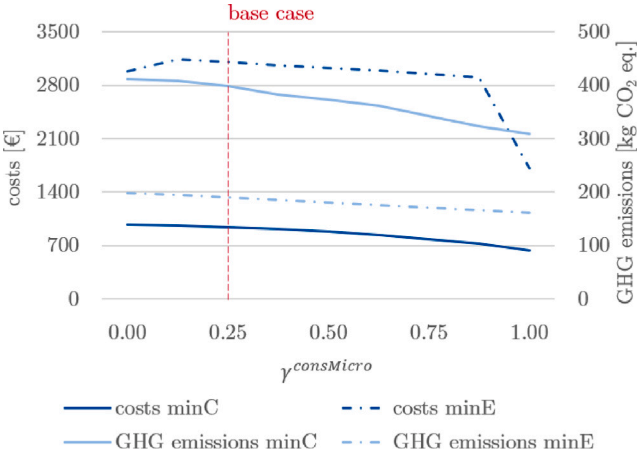

Fig. 10. Objectives of SC1 in relation to factor $\gamma^{consMicro}$.

replace trips with company-exclusive cars, and that company-exclusive bikes become more cost-efficient than shared bikes from $\gamma^{consMicro} = 0.65$ (cf. Fig. 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.

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 Fig. 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 Fig. 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.

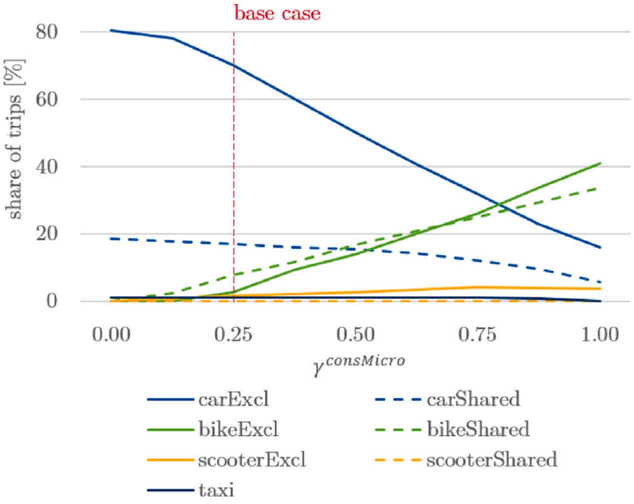

Fig. 11. Share of trips with different mobility services in *minC* of SC1 in relation to factor $\gamma^{consMicro}$.

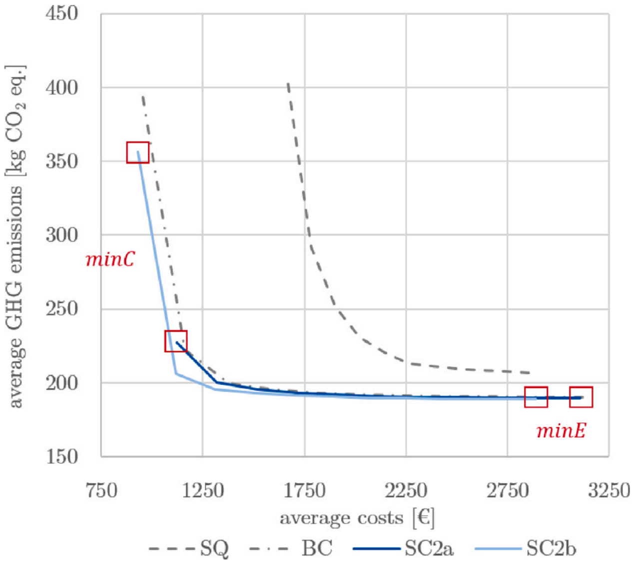

Fig. 12. Pareto fronts of SQ, BC, SC2a, and SC2b.

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

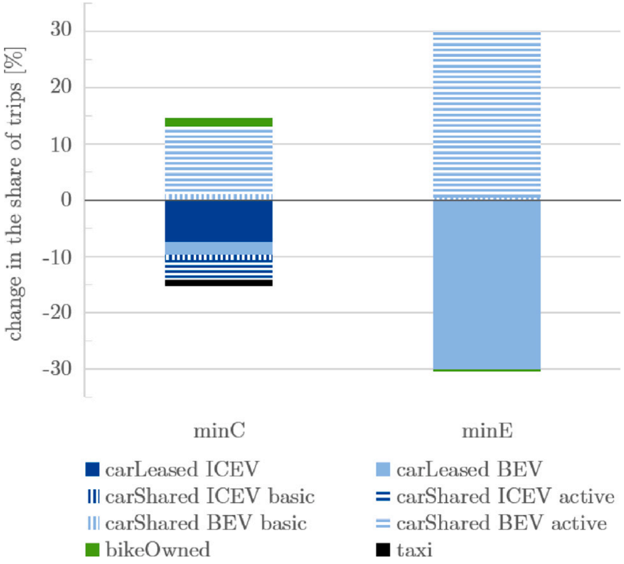

Fig. 13. Change in the share of trips in SC3b compared to the BC for $minC$ and $minE$.

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 initial 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 Section 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.

CRediT authorship contribution statement

Antonia Klopfer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Laura Frank:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Grit Walther:** Resources, Writing – review & editing, Project administration, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.trd.2023.103985.

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