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Life cycle engineering of lightweight structures in vehicles for on-demand mobility services

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ABSTRACT

To reduce transport-related environmental impacts, innovative mobility system approaches such as on-demand services are being developed. These can include operating vehicles that differ regarding their characteristics and application profile from privately owned cars in motorized individual transport. Studies on life cycle assessment and life cycle engineering of vehicle lightweight structures are mainly limited to these privately owned cars and the impact category of climate change. In this paper, a method for life cycle assessment-based engineering of lightweight structures in vehicles for various mobility system applications, including on-demand mobility services, is developed. The method enables the holistic life cycle assessment of lightweight structures in different mobility system applications considering parameter changes at the upstream products, component, subsystem, vehicle and mobility system levels, as well as the integration of results into engineering activities. A case study is used to show that the vehicle and mobility system application of lightweight structures can significantly influence their environmental impacts and the selection of ecologically preferable product designs. The application in vehicles for on-demand mobility services can lead to an increase in absolute use stage energy demand and environmental impacts compared to applications in privately owned vehicles for motorized individual transport. However, normalized to the transport performance provided, the lifecycle environmental impacts of structural components in vehicles for on-demand mobility services can be lower than in vehicles for motorized individual transport. The paper contributes methodically and with quantitative results to improved decision making in life cycle engineering activities for lightweight structures in mobility system applications.

1. Introduction

The transport and industrial sector accounted for 30.9 % and 20.3 % of greenhouse gas emissions (GHGE) in the European Union in 2022 (European Environmental Agency, 2023). Transport-related GHGE even show an increasing trend, which is mainly driven by motorized individual transport (MIT) (European Environmental Agency, 2023). So, as in other sectors such as construction (Amin et al., 2023; Qaidi et al., 2022) and energy (Victoria et al., 2020), there is a need to reduce GHGE and further environmental impacts (EI). As the automotive industry contributes to the EI of both the transport and industrial sectors, action by organizations within the automotive value chain is needed to meet the targets and related legislation of the EU Green Deal (Regulation EU, 2021). Various measures such as the electrification of powertrains have been driven forward and implemented to reduce EI of vehicles (Candela et al., 2024; Wellings et al., 2021). Another established approach to reduce EIs in the use stage of vehicles is the implementation of lightweight design strategies, as the use stage energy demand of vehicles depends on their mass (Koffler and Rohde-Brandenburger, 2010). The vehicle energy savings from lightweight design measures can be quantified by the fuel reduction value (FRV) for vehicles with internal combustion engine (ICEVs) and energy reduction value (ERV) for (battery) electric vehicles (BEVs) (Egede, 2017). FRV and ERV depend on the characteristics and driving pattern of a vehicle (Luk et al., 2017). Therefore, the effects of lightweight design measures on the energy demand of vehicles and components in the use stage should be evaluated specifically for different vehicle configurations and their operating conditions.

While electrification and lightweight design can reduce EIs of the use stage, they can result in increased EI of the production and end-of-life (EoL) stages (Herrmann et al., 2018; Kawamoto et al., 2019). To identify and avoid burden shifting between life cycle stages, a holistic assessment of the EI is necessary, considering the entire life cycle of the object under investigation. The life cycle assessment (LCA) method

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based on ISO14040 (ISO International Standardization Organization, 2020a) is an established tool for this purpose. Based on LCA, life cycle engineering (LCE) includes the integration of life cycle thinking into product development activities (Hauschild et al., 2017) and can support decision-making for products with reduced EI, for example by comparing design alternatives with LCA (Kara et al., 2023).

Despite the aforementioned activities, transport-related GHGE are not decreasing worldwide as rising vehicle sales outweigh their mitigating effects (González Palencia et al., 2012; International Energy Agency, 2023). Public transportation has also not been able to exploit its potential for reducing transport emissions (Sörensen et al., 2021). Therefore, innovative system approaches like "shared mobility" are emerging, which allow users "short term access to transportation on demand" as an alternative to private vehicle ownership in MIT (Zhu et al., 2023) and aim to mitigate transport-related EI by intensifying vehicle usage, reducing the number of vehicles while maintaining individual mobility (Arbeláez Vélez, 2024). According to the classification by (Zhu et al., 2023), "shared mobility" modes include ridesharing, carsharing (CS), shared micromobility, shared autonomous vehicles, and the on-demand ride services ridesourcing and ridesplitting, the latter two also known as ride-hailing (RH) (Chalermpong et al., 2023) and ride-pooling (RP) (Zhu and Mo, 2022). The focus of this study is on emerging mobility services with operating vehicles provided by companies on demand and digitally connected to paying customers so that no overlap with private vehicle usage in MIT occurs and vehicle configurations can be developed explicitly for this application. These include business-to-customer carsharing, RH and RP (Neef et al., 2019; Zhu et al., 2023), which are grouped under the term "on-demand mobility services" in this study. CS and RH as individual services according to (Neef et al., 2019) differ in the direction and type of service: CS customers must move to the vehicle location and drive themselves; RH customers order the vehicle to a specified location to be transported individually to a self-defined destination. As in the case of RH, RP customers define their start and destination before an algorithm pools similar routes and assigns them to vehicles that pick up several customers sharing one trip and take them to their destination (Neef et al., 2019). Operating vehicles in on-demand mobility services can exhibit changed geometric and physical characteristics but also changed usage patterns and business models (Friedrich et al., 2019). Emerging vehicle concepts for this purpose range from lightweight vehicles for two passengers to minibuses for up to twenty, which can operate in various configurations such as in platform-based or platooning vehicle concepts (Ostermann et al., 2023a).

In the mid-term, on-demand mobility services are expected to gain market share worldwide (Neef et al., 2019), with vehicles and structural components increasingly being integrated into the product portfolios of vehicle manufacturers (OEMs) and suppliers. To analyze the impact on the achievement of corporate sustainability goals and the fulfillment of sustainability and reporting requirements of customers and further stakeholders, evaluating the EI of structural components in vehicles for on-demand mobility services is necessary. Furthermore, it is the basis for improved decision-making in product and strategy development, as it enables to compare the EI of product design alternatives, to select the design with the least EI for a specific vehicle application, and to align the product portfolio for specific market segments. To assess the EI of these vehicles and their (lightweight) structures by LCA, their use stage must be realistically modelled as it has a major influence on their lifecycle EI (Nordelöf et al., 2014). However, there is a lack of methods and studies to analyze changes in the EI of lightweight structures in vehicles for on-demand mobility services compared to their application in vehicles for MIT, considering LCA parameter changes at component, subsystem, vehicle and mobility system level and ICs beyond the GWP, and to integrate conclusions into product and strategy development (see section 2). The objective of this study is to address this research gap by developing a method that enables the holistic LCA-based LCE of lightweight structures in vehicles for different mobility system applications, including on-demand mobility services. For this purpose, existing approaches for the LCA-based LCE of lightweight structures (Herrmann et al., 2018; Reimer et al., 2020) (section 2.1) and LCA of on-demand mobility services (Gawron et al., 2019; Neef, 2020) (section 2.2) are combined and extended. The mobility system applications are limited to those in which motorized road vehicles with four wheels are used.

In section 2, a literature review on LCA and LCE of lightweight structures and on-demand mobility services is presented. The developed method and a case study to test its practicability are introduced in section 3. In section 4, the results of the case study, including an uncertainty and sensitivity analysis, are presented. In section 5, the conclusions are summarized and discussed.

2. Literature review

2.1. LCE of lightweight structures

In the automotive context, there are numerous LCA studies evaluating the EI of measures such as lightweight design and electrification at vehicle, subsystem, and component level (Cimprich et al., 2023). Based on life cycle thinking and using LCE methods, LCA is increasingly being integrated into development activities of automotive products (Broch, 2017; Hauschild et al., 2017). Since the body structure contributes significantly to the EI of a vehicle (Hirz and Nguyen, 2022), methodical approaches and a general framework for the LCE of lightweight structures have been developed, which is in accordance with the ISO standard 14040 for LCA (Herrmann et al., 2018). These address, for example, the minimization of EI in early concept development (Reimer et al., 2021), and the consideration of prospective scenarios for LCA influencing parameters (Grenz et al., 2023). Studies regarding the eco-efficient development of lightweight vehicle structures already exist on component (Del Pero et al., 2020b; Koffler, 2014; Meng et al., 2017; Witik et al., 2011) and full vehicle level (Raugei et al., 2015), as well as for different powertrain types (Luk et al., 2017; Shanmugam et al., 2019). However, most LCA and LCE studies in the context of vehicle lightweight design are limited to the LCA impact category (IC) of global warming potential (GWP) and neglect other dimensions of environmental sustainability (Cimprich et al., 2023). The used FRVs and ERVs are often based on literature values (Del Pero et al., 2020b; Meng et al., 2017; Witik et al., 2011), which result from model calculations of generic or real vehicles (Luk et al., 2017) and from test data (Carlson et al., 2013). The calculation models such as those from (Del Pero et al., 2017, 2020a; Kim and Wallington, 2016; Koffler and Rohde-Brandenburger, 2010) are often based on standardized driving cycles like the Worldwide harmonized Light Vehicles Test Cycles (WLTC) to ensure comparability of the results (Luk et al., 2017).

So, the approaches for LCA based LCE of vehicle lightweight structures and for model calculations to estimate mass-related changes in vehicle energy demand are limited to conventional vehicles operating in MIT. This is reflected by the assumed vehicle parameters based on conventional series-production cars and the underlying standardized driving cycles. Use stage applications in vehicles for on-demand mobility services, considering the changed vehicle characteristics and usage profiles, as well as comparisons of different mobility system applications are usually excluded. The study by (Reimer et al., 2020) is the only one known to the authors that investigates EI of structural components in vehicles for mobility services, considering individual LCA parameter changes in the use stage, such as the ERV and the mileage. Calculation approaches for estimating these parameters as well as a systematic analysis of further effects on LCA influencing parameters resulting from the vehicle application in mobility services are outside the scope, as are ICs beyond the GWP.

2.2. LCA of on-demand mobility services

As shared mobility services are increasingly being integrated into mobility systems, the evaluation of the resulting EI is relevant and can be appropriately addressed using the LCA method (Neef et al., 2019). Several studies review the state of research on the EI of shared mobility services (Zhu et al., 2023), including the on-demand mobility services CS (Arbeláez Vélez, 2024), RH (Tirachini, 2020) and RP (Neef, 2020), and analyze relevant influencing factors. Based on case studies, such as those by (Migliore et al., 2020; Sui et al., 2019; Ward et al., 2019), it is shown that on-demand services often have the potential to reduce the EI of transportation. However, depending on many influencing factors of the service design and specific boundary conditions, on-demand mobility services can also lead to an increase in the EI of transportation (Arbeláez Vélez, 2024; Tirachini, 2020; Zhu et al., 2023). The extent to which on-demand mobility services result in positive or negative environmental effects therefore depends on multiple influencing factors and their interactions, which can be assigned to different system elements and levels. They include the design and management of the services (parking, rebalancing and pricing strategy, fleet size, service life and development of the fleet, pooling, synergies with other mobility services and public transport), the infrastructure (energy mix, charging infrastructure, road utilization), user behavior (mode choice, occupancy rate, travel and driving patterns, induced transport demand), and vehicle characteristics (vehicle size, powertrain technology, mileage, energy demand), whose configuration and interactions result in factors such as the total number of vehicles, empty trips and total vehicle-kilometers travelled (Arbeláez Vélez, 2024; Neef et al., 2019; Neef, 2020; Tirachini, 2020; Zhu et al., 2023). Based on (Gawron et al., 2018), these influencing factors can be assigned to the mobility system level, i.e. the design and management of the service vehicle fleet and the interaction with its surrounding (infrastructure, users, further transport modes) in a mobility system, as well as the vehicle level, i.e. the characteristics of one operating vehicle (e.g. size, powertrain, energy demand) in a mobility system. Some of these influencing factors at both system levels (e.g. energy mix, driving patterns, powertrain type) are also relevant for LCA and LCA-based LCE of lightweight structures, as they affect the use stage energy demand of vehicles in which lightweight structures are installed.

With regard to the methodologies used in LCAs of on-demand mobility services (Neef et al., 2019), conclude that the use of person-kilometers (p-km) as reference unit, and thus the consideration of transport performance, is suitable when comparing the EI of different mobility modes. However, it is evident that few studies perform an LCA taking into account the entire lifecycle, but limit the assessment to the use stage of a vehicle or a vehicle fleet in a mobility system (Zhu et al., 2023). As in the work of (Neef, 2020), the use stage inventory of the vehicles is often based on conventional vehicles in MIT, so that the parameter changes associated with the application of the (emerging) vehicle concepts in on-demand mobility services and their interactions at vehicle and mobility system levels are not considered holistically. In addition most studies are limited to individual EIs like GHGE and energy demand rather than a broad range of ICs (Arbeláez Vélez, 2024).

The studies mentioned show that LCAs for on-demand mobility services are limited in scope and have so far focused on effects and changes in influencing parameters at the mobility system and vehicle level. There is a lack of studies that investigate underlying system elements like subsystems or components and the effect of their application in vehicles for on-demand mobility services on their EI. A study that addresses some of these limitations is by (Gawron et al., 2019), developing a cradle-to-grave LCA framework to evaluate energy demand and GHGE of autonomous vehicle fleets including effects at the subsystem, vehicle and mobility system level. However, conclusions for design and strategy decisions at the subsystem or component level for different use stage applications, considering comprehensive environmental ICs, are excluded. Furthermore, lightweight structures as subsystems or components in vehicles for on-demand mobility services are not within the scope of the study.

3. Materials and methods

3.1. Methodical approach

Fig. 1 shows the developed method for the holistic LCA based LCE of lightweight structures in vehicles for different mobility system applications, including on-demand mobility services.

The procedure of the method is based on the LCE framework for lightweight structures by (Herrmann et al., 2018) and includes five steps, with the first four steps corresponding to ISO 14040 for LCA. The fifth step complements the procedure of the ISO standard with the generation of knowledge and its direct application in engineering activities to improve current and future products and processes (Herrmann et al., 2018). Basic explanations of the individual steps of LCE can be found in (Herrmann et al., 2018). In this section, the focus is on the specific elements for LCA based LCE of lightweight structures in vehicles for on-demand mobility services.

Within the goal and scope definition (1), the structural component as product to be investigated is regarded as a part of an overall system with various interdependencies on several system levels that can be classified in the automotive value chain. In this way, structural components are functional elements of vehicles that enable transportation of people and goods in a mobility system. The requirements for products in this system can usually be broken down from higher levels to those below and provide the basis for product development (Kaluza et al., 2017). In turn, the properties of the products on a certain level determine the characteristics of the products on the higher levels. Based on the characteristics of the system elements on these levels, the relevant parameters for a component LCA can be derived. Based on the studies analyzed in section 2 (Del Pero et al., 2020a; Gawron et al., 2019; Luk et al., 2017; Ostermann et al., 2023b), these parameters are presented in Fig. 1 and assigned to the system levels to consider their changes and interactions in LCA of lightweight structures in different applications. In addition to the parameters listed in Fig. 1, there are those that are related to the surroundings of the mobility system and include, for example, climatic conditions (Egede et al., 2015). Based on the knowledge of the system parameters and their interactions, the product model for the LCA (Herrmann et al., 2018) can be generated. In addition, the generation of a vehicle model is an essential part of the method, which is described at the end of this section. For the determination of the functional unit as part of the goal and scope definition, based on (Neef et al., 2019) the use of p-km as a reference unit is suitable when comparing different modes of transport to take their transport performance into account.

In the second step, life cycle inventory (LCI) (2) data must be acquired to generate an LCI model. The quantity and quality of LCI data in LCE activities depend on data availability and sharing along the value chain. For example, an OEM usually has more information on use stage data at vehicle level than suppliers. Consequently, a component manufacturer's LCI quality depends on the extent of data shared by the OEM during development.

For the steps life cycle impact assessment (3), interpretation and visualization (4) as well as knowledge generation and direct application (5), there are no significant differences compared to the LCE framework.

A central element of the developed method is a dynamic vehicle simulation model for estimating energy demand and ERV in different mobility system applications as relevant parameters in LCE of lightweight structures. The model is designed to estimate these values at various development stages and levels of detail regarding the available information on the vehicle and its usage profile. Consequently, a modular model approach in MATLAB-Simulink (The MathWorksInc., 2023) was chosen to allow detailing of the three main modules driver, vehicle, and longitudinal dynamics with increasing information in the development process (Fig. 2). Following existing models for calculating

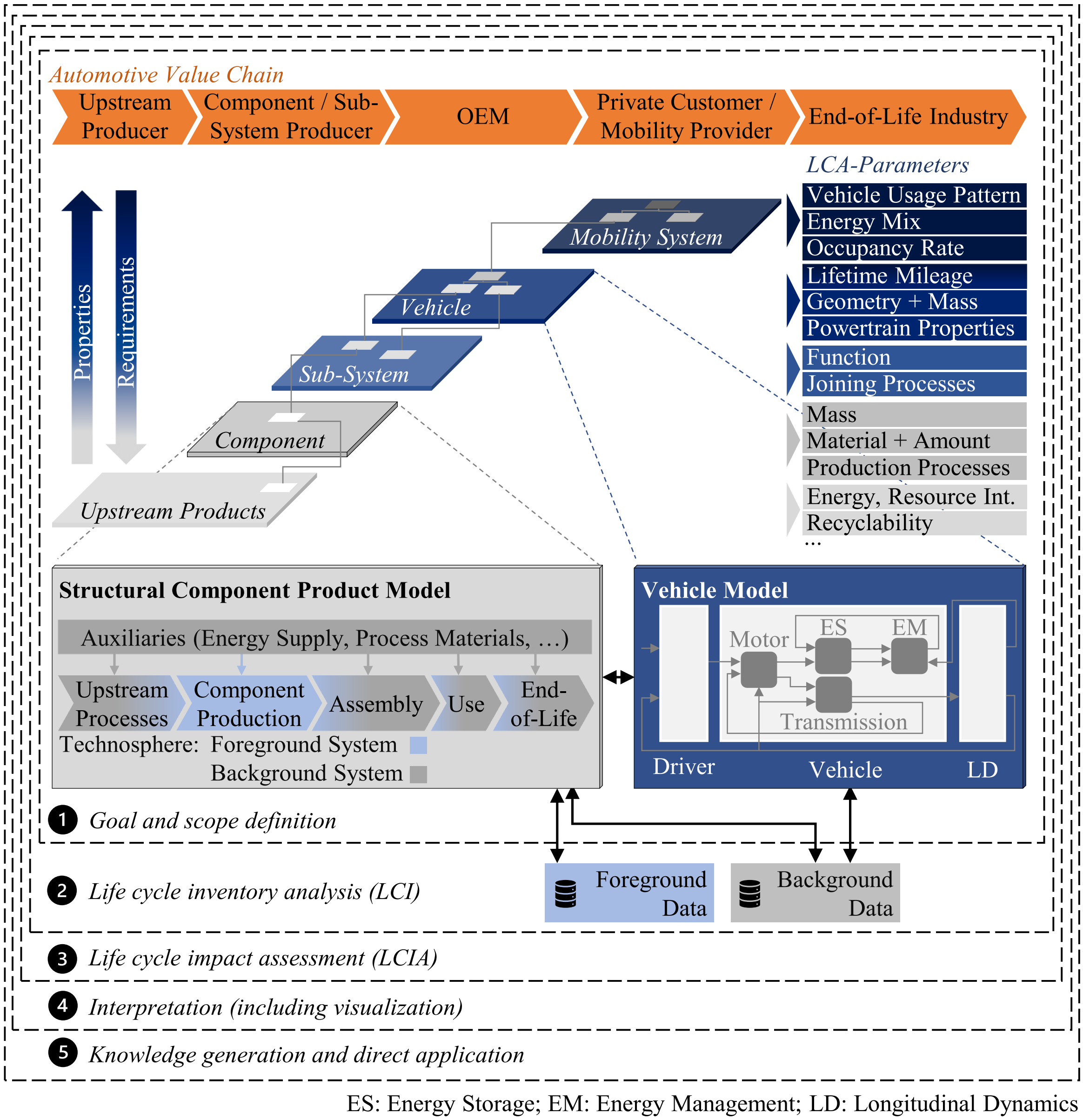


Fig. 1. Method for LCA based LCE of lightweight structures in vehicles for on-demand mobility services based on the contributions by (Reimer et al., 2020; Neef, 2020; Gawron et al., 2019), ISO 14040 for LCA (ISO International Standardization Organization, 2020a), and the LCE framework by (Herrmann et al., 2018).

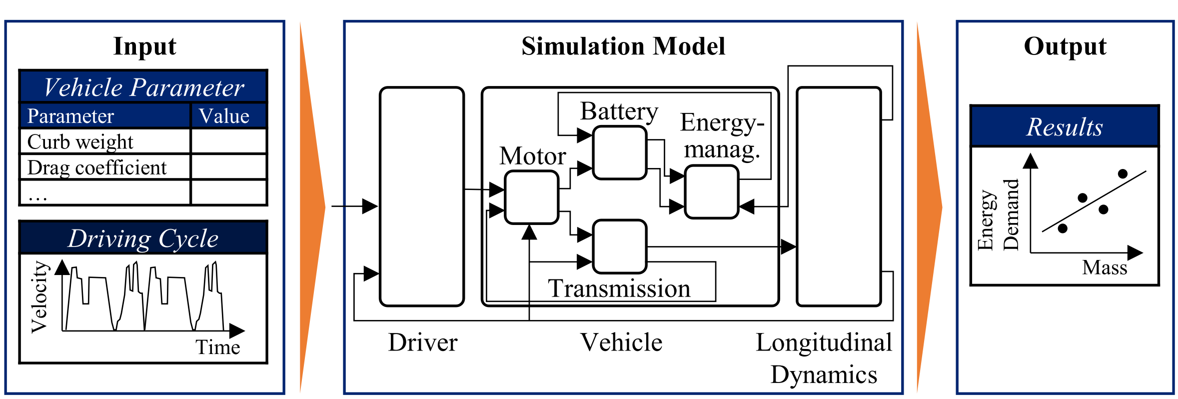


Fig. 2. Structure of the vehicle simulation model for estimating energy demand and ERV.

the energy demand of vehicles, it is reduced to longitudinal dynamics. Since emerging vehicles for on-demand mobility services almost exclusively rely on BEVs, the model is limited to this powertrain type (Ostermann et al., 2023a). Based on the input of consumption-relevant vehicle parameters and its driving profile in a mobility system, the model calculates the energy demand of a reference vehicle and for a user-specified number of mass changes. Based on (Del Pero et al., 2020a), the ERV is then determined using a linear regression analysis of energy demand and vehicle masses.

The driver module includes an automatic proportional-integral-derivative (PID) controller to calculate and adjust the required traction or braking torque, ensuring the vehicle follows the given driving profile. The vehicle module uses the required torque as an input to calculate the force at the tire, considering its subsystems (motor, transmission, battery, and energy management) and losses. To calculate the vehicle energy demand, the battery power is integrated over time and related to the distance travelled. Based on the force at the tires, the distance travelled and speed are calculated in the longitudinal dynamic module, considering aerodynamic drag, rolling, acceleration and gradient resistance (Formula 1) (Breuer and Rohrbach-Kerl, 2015).

$$\ddot{x} = \frac{1}{\lambda \cdot m} \cdot \left(F_T - m \cdot g \cdot f_R \cdot \cos\alpha - \frac{1}{2} \cdot \rho_A \cdot c_d \cdot A_V \cdot {v_r}^2 - m \cdot g \cdot \sin\alpha \right) \qquad (1)$$

The model was validated using three real vehicles (Smart forfour (Pfeffer, 2020), Hyundai Kona (Ruhdorfer, 2018), Volkswagen ID3 (Ruhdorfer, 2020)) for which many of the required input parameters and the energy demands for a specific driving cycle were available. The deviations between the model calculations and manufacturer's specifications were about 6.5 % and can be attributed to the fact that, assumptions still must be made for individual input parameters like the efficiency of the engines and transmission.

3.2. Case study

To validate the practicability of the method presented, it is applied to a case study of a seat crossmember section as a component of a vehicle body-in-white. The function of the component is to absorb the operational loads that occur during driving and contribute to the stiffness over the service life of a vehicle without plastic deformation. Based on a steel reference, lightweight variants of the seat crossmember were derived by material substitution with aluminum, carbon fiber-reinforced plastic (CFRP) and a hybrid variant of steel and CFRP using finite element simulations of three load cases to ensure their functional equality. Fig. 3 presents a seat crossmember as part of a vehicle body as well as the thickness and mass data of the design variants.

4. Results

This section presents the results of applying the method presented in section 3.1 to the case study. The structure is derived from the five steps of the developed method (Fig. 1) and the requirements for an LCA report according to ISO 14040 and 14044.

Table 1
Scenarios for the seat crossmember use stage in different vehicle and mobility system applications (MIT: Motorized individual transport; RH: Ride-hailing; RP: Ride-pooling).

	Mobility system	Vehicle type	Powertrain type
Scenario 1	MIT	Midsize passenger car (Class M1, Segment C)	ICEV
Scenario 2	MIT	Small passenger car (Class M1, Segment A)	BEV
Scenario 3	RH	Small passenger car (Class M1, Segment A)	BEV
Scenario 4	MIT	Midsize passenger car (Class M1, Segment C)	BEV
Scenario 5	RH	Midsize passenger car (Class M1, Segment C)	BEV
Scenario 6	RP	Minibus (Class M2)	BEV
Scenario 7	RH	LEV (Class L7e)	BEV
Scenario 8	RP	LEV platoon (Class L7e)	BEV

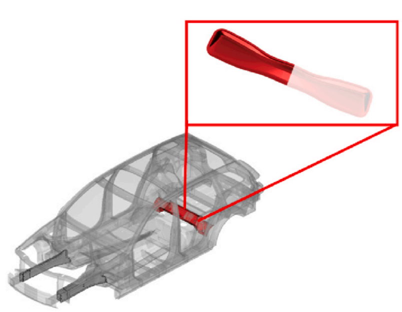
4.1. Goal and scope definition

The goal of the study is to evaluate the lifecycle EI of four material designs of a seat crossmember, considering the use stage scenarios from Table 1, to validate the practicability of the developed method for the target group of LCA practitioners in the mobility sector.

For this purpose, the functional unit of a seat crossmember absorbing the occurring loads as part of the vehicle body over one service life of a vehicle, is investigated according to the method presented in section 3.1 and following the ISO 14040 and ISO 14044 standards for LCA (ISO International Standardization Organization, 2020a; 2020b).

The scope of the study covers the lifecycle of the seat crossmember designs described in section 3.2, from raw material extraction to component production, the use stage as part of a vehicle until EoL processing. The scope, system boundary and process modules of the study are shown in Figure A.1. Accordingly, all vehicle subsystems other than the seat crossmember remain outside the scope of the study and are not considered. It is assumed that production, use, and EoL of the seat crossmember designs take place in Europe. Depending on the material properties and the associated processing technologies, the production routes differ between the material variants and are shown in Figure A.1. Thereby, the effects of the component material characteristics on the coating and joining operations with the rest of the vehicle body as subsystem are considered.

The main assumptions for the study and their potential effects on the results are summarized in Table A.1. For the use stage, different scenarios regarding the application of the seat crossmember in vehicles and mobility systems are investigated. These are listed in Table 1, whereby the classification of the vehicles was made according to the specifications of the European Union (Regulation (EC), 2002, Regulation (EU), 2013, Regulation (EU), 2018). In line with the objective of this study, the



	Steel	Hybrid (St.-CFRP)	Al.	CFRP
Thickness in mm	1.45	1.90	3.30	5.10
Mass in kg	1.99	1.60	1.54	1.35
Relative mass change in %	0	− 19.60	− 22.61	− 32.16

Fig. 3. Seat crossmember in a vehicle body (left) and masses of the design alternatives (right).

scenarios were chosen to investigate the influences of the vehicle type, its powertrain, and its application in different mobility systems, including on-demand mobility services, on the EI of vehicle lightweight structures. There are further on-demand mobility services and vehicle concepts, such as carsharing and vehicle concepts with interchangeable cabin modules (Friedrich et al., 2019), which could be considered as use stage scenarios. However, as these are mainly combined forms of the scenarios examined and the focus of the case study is on testing the practicability of the method, no additional conclusions are expected from their inclusion. The RP service in scenario 8, using platoons of light electric vehicles (LEV), is based on the emerging on demand-mobility concept NeMo.bil presented in a previous study by the authors (Ostermann et al., 2023a). This concept envisages LEVs operating the first and last mile individually and forming a platoon at higher speeds for further distances. The platoon is towed by a larger vehicle with sufficient power and energy capacity. By dividing the driving operation between two vehicle types, LEVs for the first and last mile at low speeds and platoons consisting of LEVs and a towing vehicle for longer distances at higher speeds, considerable energy saving potentials are expected (Ostermann et al., 2023a).

Within the use stage, the study is limited to the energy-related EI resulting from the supply of the required energy and direct emissions from fuel combustion in the case of ICEV. Seat crossmembers as components of the vehicle body-in-white are not maintained regularly, but are repaired, if at all, in the event of structural damage after a crash (He and Chang, 2014). As the associated repair measures and their implementation depend on many uncertain factors (e.g. severity of the crash, the repair costs and the economic residual value of the vehicle), and studies at the overall vehicle level show that maintenance activities have a minor influence on the life cycle EI (Hawkins et al., 2013), these are not considered in this case study. As fully autonomous on-demand services are not yet widely used, this study is limited to non-autonomous vehicles. The scope of a use stage scenario always includes one component in one vehicle. Thus, rebound effects associated with the introduction of on-demand mobility services on vehicle fleet and mobility system level, for example induced mobility demand, are not within the scope of the study. The effect of empty trips of on-demand service vehicles is considered by the different occupancy rates.

For the EoL stage, a cut-off modeling approach is chosen, considering two alternative processing routes for the EoL treatment (Figure A.1). First, based on (Rosa and Terzi, 2016), a shredding process of the component after the use and dismantling of the vehicle is investigated, which corresponds to the current standard treatment of EoL vehicles in the European Union (Directive 2000/53/EC, 2000) (Case 1). As ongoing legislative revisions aim to enhance circularity by promoting higher secondary material content and design for easier dismantling and recycling (European Commission, 2025), a second case is considered. In this more optimistic case, it is assumed that the seat crossmember is dismantled for reuse or recycling. Following the cut-off modeling approach, EIs from primary material production and recycling processes are allocated to the product where the respective material is used, no credits are accounted for avoiding primary material production by using secondary material and EIs from waste treatment are allocated to the product generating the waste (Hermansson et al., 2022). For steel and aluminum material shares, the EoL treatment is considered until they are separated, sorted and can enter the reuse or recycling industry (after shredding in case 1; after dismantling in case 2). Since the recycling of CFRP is not yet as established as for steel and aluminum, the treatment of CFRP material fractions is considered until their final disposal in Case 1.

In accordance with the goal of the study, which focuses on validating the developed method and not on estimating the ES of the seat crossmember designs as precisely as possible, the requirements for data quality are comparatively low. The data used should be technologically representative of the process modules within the system boundary shown in Figure A.1 and geographically representative of their application in Europe. If available, primary data is preferable to literature and database data for the foreground processes. If literature data is used, it should not be older than 10 years to ensure temporal representativeness.

Finally, the information contained in this section 4 should fulfill the requirements for an LCA report intended for publication in accordance with ISO 14040 (ISO International Standardization Organization, 2020a) and ISO 14044 (ISO International Standardization Organization, 2020b).

4.2. Life cycle inventory analysis

The data sources and data collection methods used to generate the LCI for the case study are provided in Table A.2, together with an assessment of conformity with the data quality requirements. In addition, mass or energy balances of the process modules were carried out to validate the life cycle inventory data. The data validation shows that individual data sets used do not meet the defined data quality requirements (see section 4.1) due to their geographical representativeness (see Table A.2). As this non-fulfillment only applies to the geographical representativeness of individual data sets, it is acceptable against the background of the study's goal. The remainder of this section focuses on the calculation methods and results as part of the LCI, determined by applying the developed method and the associated vehicle simulation model.

Using the incremental allocation method introduced by (Eberle and Franze, 1998), the mass-induced energy demand of a vehicle is allocated to a component according to Formula 2 for ICEVs as well as Formula 3 for BEVs (Reimer et al., 2020).

$$FC_C = FRV_{V,A} \cdot m_C \cdot d_{V,A} \tag{2}$$

$$ED_C = \frac{ERV_{V,A} \cdot m_C \cdot d_{V,A}}{\eta_{charge_V}} \tag{3}$$

For the vehicles listed in Table 1, exemplary vehicles, and their parameters, which are required for the vehicle model to calculate the ERV, were recorded and listed in Table A.3. The assumed driving profiles for the mobility system applications are shown in Table A.4. Since RH services have been predominantly used in cities so far, the Hyzem Urban cycle as a common European city cycle is used (Zaccardi and Le Berr, 2013). As RP services intend several trips to be bundled and people to board, the Braunschweig city cycle is used, which is characterized by many start-stop phases and speeds below 60 km/h (Trajkovic et al., 2010).

For the ERV calculation of scenario 8, the individual trip of the LEV at low speed for the first- and last mile and its trip in a platoon need to be distinguished. For the single trip, the Hyzem urban cycle is considered. Since the trips of the platoon are planned to be made also outside cities and at higher speeds, for example on rural roads, the Hyzem road cycle is used. The combined ERV of the two driving situations of the LEV in the RP service ($ERV_{LEV,RP}$) is determined by weighting the shares of individual and platoon trips in the total distance travelled (Formula 4). Based on a use case scenario of the NeMo.blil system for connecting rural regions to cities described in (Ostermann et al., 2023a), these shares are determined to be 20 % individual to 80 % platoon trips.

$$ERV_{LEV,RP} = \frac{ERV_i \cdot s_i + ERV_p \cdot s_p}{s_{total}} \tag{4}$$

The ERVs and FRVs determined by the vehicle simulation model for scenarios 2–8 and by literature values for scenario 1 are shown in Table 2. In addition to the mean values, minimum and maximum values are provided, considering the variations in vehicle parameters within a vehicle category, occupancy rates and associated vehicle loads as well as potential deviations of the assumed driving cycles from real-world driving (see Table A.5). The increased ERVs of the vehicles applications in RH services compared to MIT (mean values:31 % for small BEV,

Table 2
FRV and ERV for the use stage scenarios (FRV in l/(100 km*100 kg); ERV in kWh/(100 km*100 kg)). Mean, minimum and maximum values are based on the data in Table A.5.

	Value	S1	S2	S3	S4	S5	S6	S7	S8
FRV (S1) and ERV (S2-S8)	Minimum	0.16	0.40	0.52	0.48	0.56	0.88	0.45	0.48
	Mean	0.17	0.57	0.75	0.60	0.82	1.07	0.56	0.52
	Maximum	0.23	0.80	0.94	0.84	1.04	1.56	0.69	0.71

38 % for midsize BEV) can be attributed to the more dynamic driving cycle, which leads to an increased mass dependence of the energy demand (Del Pero et al., 2020a). Due to the higher mass and motor power as well as the vehicle geometry and the underlying driving cycle, the highest ERV results for the minibus in the RP application (S6). The application of the LEV in an RP service with platooning (S8) can result in a reduction of the ERV compared to its application in the RH service (S7). This can be attributed to the partial driving of the LEV in a platoon, for which a less dynamic driving cycle is assumed.

Applying Formulas 2-4, the absolute use stage energy demands for the eight scenarios, which are proportional to the component mass, the FRV or ERV, and the vehicle mileage, can be calculated and related to the scenario specific mileage (in v-km) and transportation performance (in p-km) of the vehicles (Fig. 4). Based on the mentioned variations of the FRVs and ERVs and additionally considering the variations of mileages and occupancy rates from Table A.4 as well as an assumed variation of the component masses by ± 10 % of the mean values from Fig. 3, minimum and maximum values for the energy demands are shown in addition to the mean values. The partially large variation of these influencing parameters results in a wide range for the energy demands in the individual scenarios. The consideration of these variations in input data and resulting energy demands as elements of the life cycle inventory is the basis for the uncertainty and sensitivity analysis in section 4.4.

The steel variant shows the highest energy demand within all use stage scenarios, followed by the hybrid, the aluminum and the CFRP design. This order and the energy demand ratio between the design variants result from the component masses and the mass proportionality of the energy demand (Formulas 2-3). Comparing the absolute mean energy demands between the use stage scenarios shows that the higher ERVs and mileages of the vehicles in the on-demand mobility services (scenarios 3, 5, 6, 7, 8) result in most cases in higher absolute usage energy demands compared to the application in MIT vehicles (scenarios 1, 2, 4). Exceptions are the lower absolute energy demands in scenarios 7 (LEV in RH) and 8 (LEV platoon in RH service) compared to scenario 1 (ICEV in MIT), which can be attributed to the lower energy efficiency of the ICEV compared to the BEV and the comparatively low ERVs in scenarios 7 and 8. Relating the absolute energy demands to the transportation performance provided by the vehicles, in which the components are installed, can result in lower values for the applications in on-demand service vehicles compared to those in MIT. This applies to all on-demand service vehicle scenarios (3, 5, 6, 7, 8) compared to the ICEV in MIT scenario 1. Comparing the on-demand service vehicles with the BEVs in MIT scenarios (2, 4), only scenario 8 shows a lower mean energy demand per p-km. Thus, for component applications in on-demand service vehicles to result in lower energy demands per p-km compared to vehicle applications in MIT, either the FRVs/ERVs must be lower (e.g. by higher energy efficiency of the vehicle) or the occupancy rate of the vehicles needs to be high enough to balance the increased FRVs/ERVs. It is important to emphasize that it cannot be concluded from these ratios that MIT is more energy efficient in terms of transport performance than on-demand mobility services, as the underlying vehicle operation and driving profiles are not comparable.

4.3. Life cycle impact assessment

For the life cycle impact assessment, the CML-IA baseline method developed by the University of Leiden (version 2016) is used, including its predefined impact categories, impact indicators, characterization models and factors (Guinée et al., 2002). This method is internationally recognized and widely adopted in scientific and industrial contexts, including automotive applications, ensuring reproducible results with high transparency and comparability (Dolganova et al., 2020; Eltohamy et al., 2024). Based on the life cycle inventory results, all of the following eleven midpoint ICs of the CML-IA method are examined for this study, enabling a comprehensive assessment of EIs critical for informed decision-making (Guinée et al., 2002): elementary (ADP elements) and fossil (ADP fossil) abiotic resource depletion, acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), global warming potential 100 years (GWP100), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), terrestrial ecotoxicity potential (TETP).

In line with ISO 14040 and 14044, endpoint-level areas of protection (e.g., human health, ecosystems) are excluded, as the study focuses on comparing design variants at the midpoint level, which aligns with the

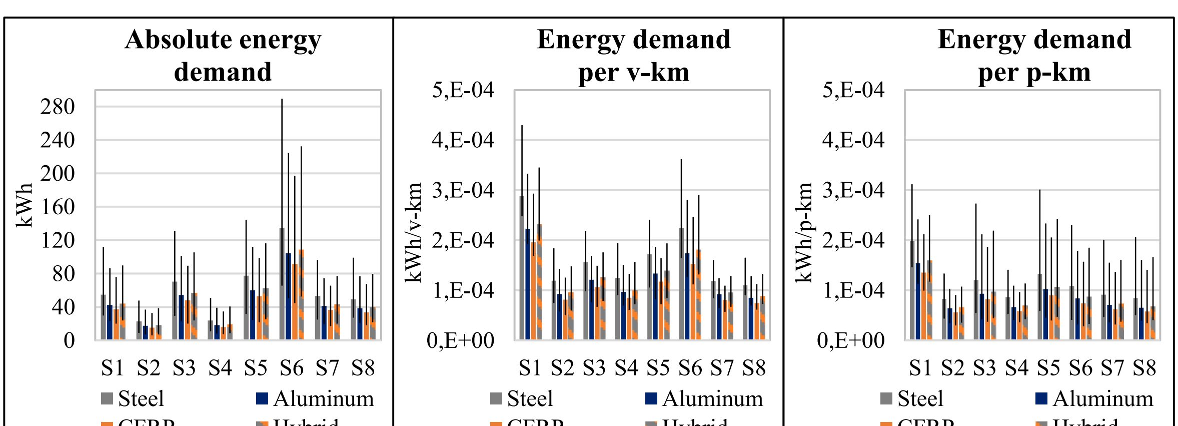


Fig. 4. Mean use stage energy demands of the component material designs for the investigated scenarios, absolute (left), per v-km (center), and per p-km (right). The error bars indicate the minimum and maximum values based on the input data from Tables A.4 and A.5.

defined goal and scope. Value choices regarding the selection and modeling of impact categories and factors are limited to those inherent in the CML-IA method itself and no further subjective assumptions or value-based modifications were introduced.

It is important to note that the results of the impact assessment are relative statements and do not provide any predictions about effects on the impact endpoints, exceeding of boundary values or risks.

4.4. Interpretation including visualization

Fig. 5 shows the EI of the production and EoL stages of the seat crossmember designs normalized to the maximum value in each IC, considering the two EoL processing routes.

Fig. 5 shows that the alternative EoL process routes only result in a change in the ranking of the material designs for the IC FAETP, which can be attributed to the avoidance of the landfilling of the CFRP. The production and EoL of the CFRP variant show the highest values in 9 (case 1) respective 8 (case 2) of 11 ICs. The steel variant shows the lowest values in all ICs for production and, together with the EoL stage, in ten of eleven ICs. As the differences between the two alternative EoL processing routes are therefore minor, the following analyses are limited to case 1 as the more established route in industrial practice.

The aggregation of the EI from production ($EI_{C,P,I}$), use ($EI_{C,U,I}$) and EoL $\left(EI_{C,EoL,I}\right)$ stages results in 352 data points for the lifecycle EI $\left(EI_{C,LC,I}\right)$, which are calculated according to Formula 5.

$$EI_{C,LC,I} = EI_{C,P,I} + EI_{C,U,I} + EI_{C,EoL,I} \text{ with } EI_{C,U,I} = ED_C \cdot I_{A,I} \text{ for BEVs and } EI_{C,U,I} = FC_C \cdot I_{A,I} \text{ for ICEVs} \tag{5}$$

To support decision making in the LCE process for complex LCA results with many data points, heat maps have proven to be a suitable method for visualization (Cerdas et al., 2017). Fig. 6 shows a heat map visualizing the lifecycle EI for all material designs and use stage scenarios of the case study using the mean values for the use stage energy demands from Fig. 4.

With this heat map, the absolute lifecycle EI of the seat crossmember designs in the different use stage scenarios (vertical columns) as well as the ranking of the material designs within a use stage scenario (horizontal) can be analyzed for each IC. In this way, the influence of the mobility system applications on the EI of the seat crossmember designs can be evaluated and the most suitable product design for each scenario can be selected. Since the favorable design alternative in terms of EI depends on the individual weighting of the ICs, only the results in the individual ICs are presented in this study.

When comparing the absolute EI for the different mobility system applications (vertical columns), the density of yellow and red fields shows a tendency for the absolute EI of the seat crossmember in on-demand service vehicles, particularly in scenarios 3, 5 and 6, to be higher than in vehicles for MIT applications (scenarios 1, 2, 4). Depending on the impact indicator per unit of energy in a mobility system application and IC ($I_{A,I}$) and the associated share of the use stage in the lifecycle EI, this can be attributed to the more dynamic (higher $ERV_{V,A}$) and extended usage (higher $d_{V,A}$) of the vehicles in the on-demand mobility scenarios considered. Fig. 8 at the end of this section demonstrates this with the example of scenarios 4 and 5 in the ICs GWP (high influence of the use stage) and FAETP (low influence of the use stage). The effect of the vehicle and its mobility system application in the use stage on the lifecycle EI of a lightweight structure can thus vary depending on the IC under consideration. When comparing the EI of lightweight structures in vehicles for different mobility systems, it should be noted that the choice of the functional unit and the associated reference unit can have a significant influence on the results and their interpretation. If one lifecycle of a component is selected as functional unit, it can be concluded that the EI of structures in on-demand service vehicles (scenarios 3, 5, 6, 7, 8) are higher than in vehicles for MIT (scenarios 1, 2, 4). This can be attributed to the more intensive vehicle use (more dynamic driving profile and higher milage) and is shown by the absolute LCA results in several ICs (Figs. 6 and 7 top and 8). However, if the transport performance of the vehicles, in which the structures are installed, is considered and the provision of one passenger kilometer (p-km) is selected as functional unit, it can be concluded that the EIs of the lightweight structures in on-demand service vehicles are lower than in MIT vehicles (Fig. 7 bottom for GWP and FAETP using the mean values for the use stage energy demands from Fig. 4). This is attributable to the higher transport performance over the use stage of on-demand service vehicles compared to those in MIT. When comparing different mobility applications of lightweight structures, it is therefore recommended to consider and communicate the results for both functional units. A comparison of the seat crossmember applications in BEVs (scenarios 2 and 4) and ICEVs (scenario 1) for MIT shows that the absolute EI of the BEV scenarios are lower in most ICs. This result can be attributed to the higher energy demand in scenario 1 (Fig. 4) and the direct emissions from fuel combustion and is consistent with existing LCA studies of structural components, such as that by (Shanmugam et al., 2019).

Using the mean energy demands from Fig. 4, the analysis of the number of ICs in which a material design has the lowest values within a use stage scenario shows that the steel design features the highest number of ICs in all scenarios except scenario 6 (minibus in RP service). In scenario 6, the hybrid design has the lowest EI in most ICs. However, it should be noted that the deviations in EI between the steel and hybrid design are below 10 % in 5 ICs (Fig. 6), indicating that the steel variant also has comparatively low EI in this scenario. So, while the steel variant has the lowest production EI in all ICs, depending on the use stage scenario and IC, a change in the design with the lowest EI can occur over the use and EoL stages. Thus, if all ICs are weighted equally, there is a tendency for the steel design for scenarios 1, 2, 3, 4, 5, 7 and 8 and for the hybrid design for scenario 6 to be advantageous from an ecological perspective. However, the selection of a material design obviously depends on the relevance and the corresponding weighting of the various

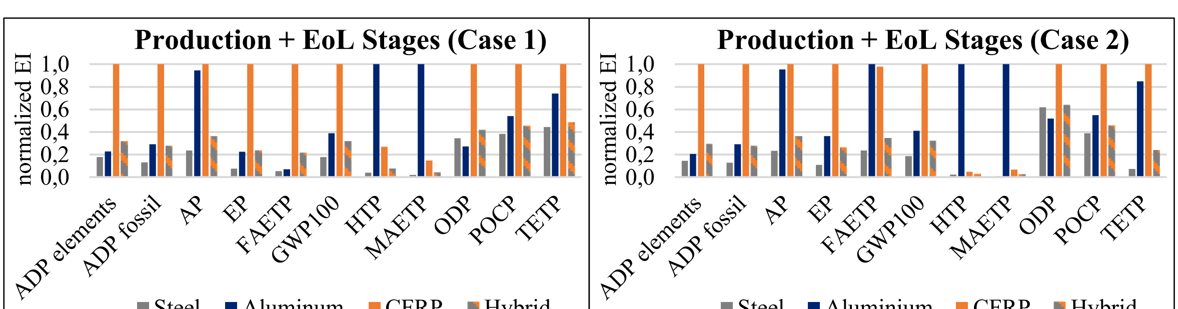


Fig. 5. Normalized environmental impacts for the production and EoL stages of the seat crossmember material variants; EoL case 1 - dismantling and shredding (left); EoL case 2 - dismantling for reuse (right).

Scenario	Use case	Material	ADP elements in kg SB eq.	ADP fossil in MJ	AP in kg SO_2 eq.	EP in kg PO_4 eq.	FAETP in kg DCB eq.	GWP100 in kg CO_2 eq.	HTP in kg DCB eq.	MAETP in kg DCB eq.	ODP in kg CFC-11 eq.	POCP in kg Ethene eq.	TETP in kg DCB eq.	ICs with lowest value
Scenario 1	midsize ICEV in MIT	Steel	5.3E-06	308.8	2.6E-02	3.7E-03	0.22	24.3	1.4	9.2E+02	1.1E-09	9.1E-03	5.8E-02	8
		Aluminum	6.3E-06	343.0	6.4E-02	5.8E-03	0.24	27.8	23.9	3.0E+04	8.5E-10	8.5E-03	7.6E-02	1
		CFRP	2.5E-05	702.7	6.6E-02	1.9E-02	2.46	48.0	6.6	4.7E+03	3.1E-09	1.0E-02	9.4E-02	0
		Hybrid	8.5E-06	340.3	3.1E-02	6.0E-03	0.59	25.7	2.2	1.6E+03	1.3E-09	8.1E-03	5.7E-02	2
Scenario 2	small BEV in MIT	Steel	5.9E-06	155.3	2.9E-02	3.1E-03	0.15	13.8	1.3	1.6E+03	1.2E-09	3.3E-03	4.1E-02	10
		Aluminum	6.8E-06	224.1	6.7E-02	5.2E-03	0.18	19.7	23.9	3.1E+04	9.7E-10	4.0E-03	6.3E-02	1
		CFRP	2.5E-05	598.1	6.8E-02	1.8E-02	2.40	40.9	6.6	5.1E+03	3.2E-09	6.6E-03	8.3E-02	0
		Hybrid	9.0E-06	217.0	3.3E-02	5.5E-03	0.53	17.2	2.1	2.1E+03	1.4E-09	3.5E-03	4.3E-02	0
Scenario 3	small BEV in RH	Steel	9.2E-06	333.7	6.1E-02	6.8E-03	0.18	29.2	2.1	3.8E+03	1.6E-09	5.6E-03	5.5E-02	7
		Aluminum	9.3E-06	362.3	9.2E-02	8.1E-03	0.21	31.6	24.5	3.2E+04	1.2E-09	5.8E-03	7.4E-02	1
		CFRP	2.8E-05	719.7	9.0E-02	2.1E-02	2.43	51.4	7.1	6.6E+03	3.4E-09	8.1E-03	9.2E-02	0
		Hybrid	1.2E-05	360.3	5.9E-02	8.5E-03	0.56	29.6	2.7	3.9E+03	1.7E-09	5.3E-03	5.4E-02	3
Scenario 4	midsize BEV in MIT	Steel	6.0E-06	159.0	3.0E-02	3.1E-03	0.15	14.1	1.3	1.7E+03	1.2E-09	3.4E-03	4.2E-02	10
		Aluminum	6.8E-06	227.1	6.7E-02	5.3E-03	0.19	19.9	23.9	3.1E+04	9.7E-10	4.0E-03	6.3E-02	1
		CFRP	2.5E-05	600.7	6.9E-02	1.8E-02	2.41	41.1	6.6	5.2E+03	3.2E-09	6.6E-03	8.3E-02	0
		Hybrid	9.0E-06	220.0	3.4E-02	5.5E-03	0.53	17.5	2.1	2.2E+03	1.4E-09	3.6E-03	4.4E-02	0
Scenario 5	midsize BEV in RH	Steel	9.7E-06	360.7	6.6E-02	7.4E-03	0.19	31.5	2.2	4.1E+03	1.6E-09	6.0E-03	5.7E-02	6
		Aluminum	9.7E-06	383.3	9.6E-02	8.6E-03	0.22	33.4	24.6	3.3E+04	1.3E-09	6.0E-03	7.5E-02	1
		CFRP	2.8E-05	738.1	9.4E-02	2.1E-02	2.43	53.0	7.2	6.8E+03	3.5E-09	8.3E-03	9.4E-02	0
		Hybrid	1.2E-05	382.0	6.3E-02	8.9E-03	0.56	31.5	2.8	4.1E+03	1.7E-09	5.6E-03	5.6E-02	4
Scenario 6	E-minibus in RP	Steel	1.4E-05	575.3	1.1E-01	1.2E-02	0.23	50.1	3.1	6.7E+03	2.0E-09	8.7E-03	7.4E-02	3
		Aluminum	1.3E-05	549.4	1.3E-01	1.2E-02	0.25	47.8	25.3	3.5E+04	1.6E-09	8.2E-03	8.8E-02	3
		CFRP	3.1E-05	884.3	1.2E-01	2.4E-02	2.46	65.6	7.8	8.6E+03	3.7E-09	1.0E-02	1.1E-01	0
		Hybrid	1.5E-05	554.4	9.4E-02	1.3E-02	0.60	46.4	3.5	6.2E+03	2.1E-09	7.8E-03	6.9E-02	5
Scenario 7	LEV in RH	Steel	8.1E-06	270.2	5.0E-02	5.5E-03	0.17	23.7	1.8	3.0E+03	1.4E-09	4.8E-03	5.0E-02	9
		Aluminum	8.4E-06	313.2	8.3E-02	7.1E-03	0.20	27.4	24.3	3.2E+04	1.1E-09	5.1E-03	7.0E-02	1
		CFRP	2.7E-05	676.4	8.3E-02	2.0E-02	2.42	47.6	6.9	6.1E+03	3.4E-09	7.6E-03	8.9E-02	0
		Hybrid	1.1E-05	309.3	5.0E-02	7.4E-03	0.55	25.2	2.5	3.2E+03	1.6E-09	4.7E-03	5.1E-02	1
Scenario 8	LEV-Platoon in RP	Steel	7.8E-06	255.2	4.7E-02	5.2E-03	0.17	22.4	1.7	2.8E+03	1.4E-09	4.6E-03	4.9E-02	9
		Aluminum	8.2E-06	301.5	8.1E-02	6.9E-03	0.20	26.4	24.2	3.2E+04	1.1E-09	5.0E-03	6.9E-02	1
		CFRP	2.7E-05	666.2	8.1E-02	2.0E-02	2.42	46.8	6.9	6.0E+03	3.3E-09	7.4E-03	8.8E-02	0
		Hybrid	1.0E-05	297.2	4.8E-02	7.1E-03	0.54	24.2	2.4	3.1E+03	1.6E-09	4.5E-03	5.0E-02	1

Lowest value in IC within scenario

≤ 10% deviation from lowest value in IC

High

Low

EI in IC

Fig. 6. Heat map visualizing the absolute lifecycle EIs of the seat crossmember material designs for the use stage scenarios.

ICs for a decision-maker.

To support decision-making, more detailed analysis can be used to investigate the development of the EI over the lifecycle stages depending on the influencing parameters and their variation, especially for the ICs of high relevance for the decision-makers. In this context, uncertainty and sensitivity analysis are suitable to estimate the range of results based on the variation of input data, identify critical influencing parameters and thereby obtain more robust results and improve the reliability of decisions. Based on the basic approach for uncertainty analysis from (Igos et al., 2019) and the minimum and maximum values of the influencing parameters according to Formulas 2–5, a best-case and a worst-case scenario are evaluated to analyze the range of results. The parameters and data used for the best- and worst-case scenarios are provided in Table A.6 and were selected to minimize and maximize the EI of the seat crossmembers in the respective use stage scenarios, taking into account realistic combinations of parameter values. The absolute life cycle EI of the seat crossmember designs in the eight use stage scenarios are provided in Figure A.2 for the best-case scenario and Figure A.3 for the worst-case scenario. The comparison of the heat maps of the worst, best and baseline (Fig. 6) scenarios shows that the variation of the influencing parameters leads to significant differences in the EI of the material designs and the material design that is advantageous from

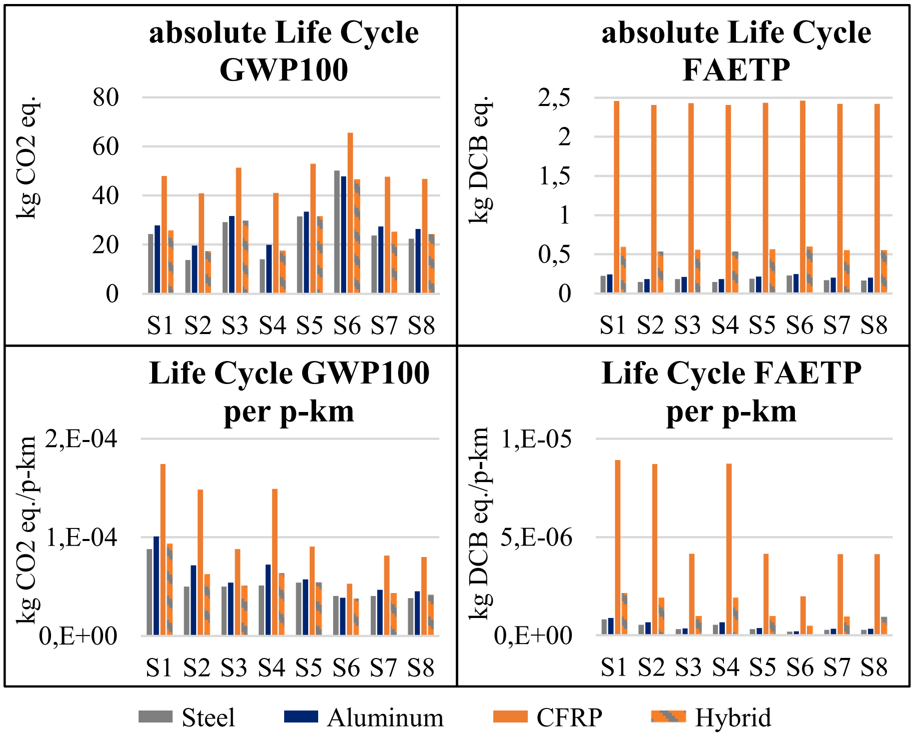


Fig. 7. Lifecycle GWP100 (left) and FAETP (right) of the design variants for the investigated use stage scenarios, absolute (top) and per p-km (bottom).

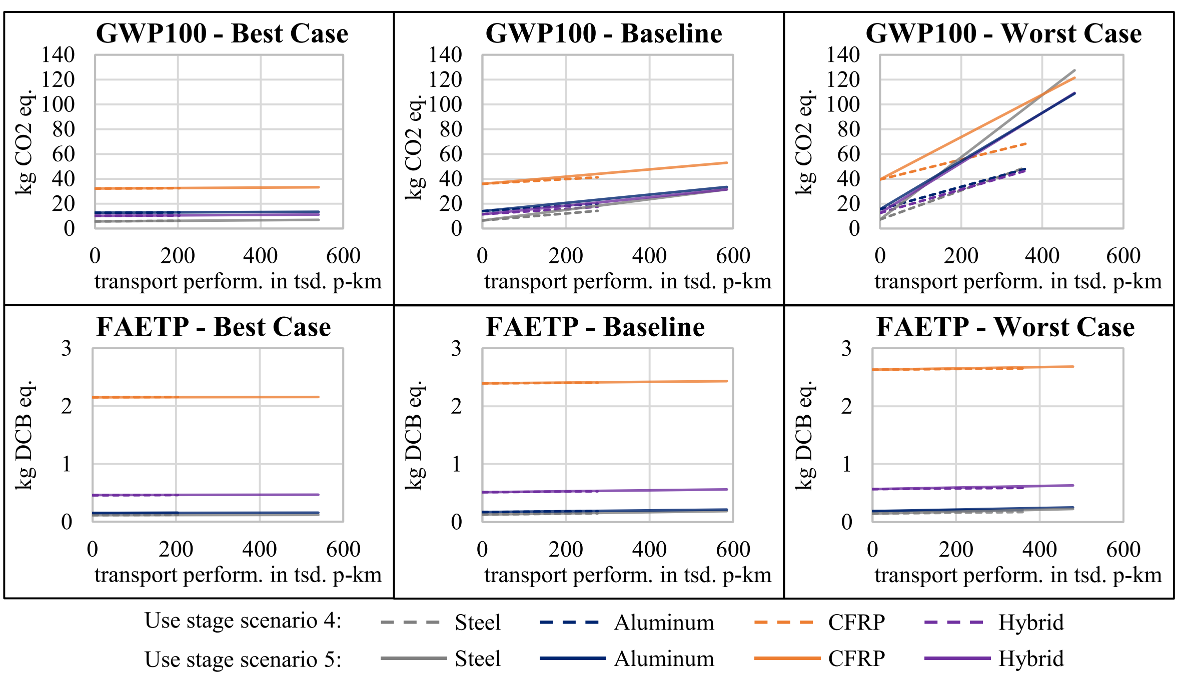


Fig. 8. Lifecycle GWP100 (top) and FAETP (bottom) over the use stage of the component designs for use stage scenarios 4 and scenario 5 and the defined baseline-, best- and worst-case scenarios for uncertainty analysis. EI of the production and EoL stages are plotted at the transport performance of zero.

an ecological perspective. In the best-case scenario, the steel variant clearly has the lowest EI in most ICs for all use stage scenarios (nine ICs in scenario 1, ten ICs in scenarios 2–8). Except for use stage scenario 1 (midsize ICEV in MIT), the material design with the lowest life cycle EI in all ICs corresponds to that of the production and EoL stages (Fig. 5). For the worst-case scenario, the results are much more heterogeneous. In none of the use stage scenarios a material design can be identified that clearly has lowest EI in most ICs. The observed differences in both absolute EI and material ranking shifts across the individual ICs and scenarios can be attributed to substantial variations in the input parameters, as well as to the differing sensitivities of the material variants' EI to these changes. To reduce complexity, these interactions between the input parameters, their variation and the effect on the EI and rankings of the material designs in different ICs are explained by the example of use stage scenarios 4 and 5 (midsize BEV in MIT and RH) and the ICs GWP and FAETP. The EI of the material designs in the two use stage scenarios and ICs are shown in Fig. 8 over the use stage transport performance for the baseline, best-case and worst-case scenarios.

GWP and FAETP are selected as the GWP is currently the most relevant in the automotive industry, and FAETP, as the results partly deviate significantly from those of the GWP and allow further conclusions. The procedure is, however, transferable to the other ICs. The results of a local sensitivity analysis in the two scenarios in the two ICs are shown in Figure A.4, using one-at-a-time variation of the influencing parameters within their defined value ranges according to Table A.6. It shows that the variation in the absolute lifecycle EI in the IC GWP (endpoints of the curves in Fig. 8 top) can primarily be attributed to the variations in the electricity mix (quantified by the impact indicator per unit of energy $I_{A,I}$), the ERVs, the mileage and the component masses. The vehicle characteristics, driving profiles and mileages in the various mobility applications therefore have a major influence on the GWP of the seat crossmember designs. Based on the linear correlation between the use stage EI and the input parameters ERV, mileage, charging efficiency and impact indicator per unit of energy (Formulas 2−5), they exhibit the same sensitivity measures for the material designs. The different effects of their variation on the EI therefore result from their different variation ranges. In the IC FAETP, the relative changes in the EI due to the input parameter variations are lower. The reason for this is the lower proportion of the use stage in the life cycle EI and the associated lower sensitivity measures of the use stage input parameters (ERV, mileage, impact indicator of energy). The main influencing parameter is the EI of the EoL stage (highest sensitivity measures in S4 and S5), which has a share of between 44 % (aluminum design in S5) and 96 % (CFRP design in S5) of the life cycle EI in the baseline scenarios, but whose variation in the best and worst-case scenarios is comparatively low at 10 %.

Regarding the ranking of the life cycle EI of the material designs across the two use stage scenarios and the two ICs in Fig. 8, deviations in the seat crossmember design with the lowest EI emerge. In the IC FAETP, the ranking of the material designs for both use stage scenarios corresponds to that of the EI from the production and EoL stages (Fig. 5), both for the baseline scenario and considering the input parameter variations in the best- and worst-case scenarios. Limiting the material selection to the EI in the IC FAETP, the decision for the steel seat crossmember design in a midsize BEV thus appears robust for both mobility system applications, MIT and RH. In the IC GWP, the material ranking for use stage scenario 4 corresponds to that of the production and EoL stages in the baseline and best-case cases. In the worst-case scenario, there is a break-even point (BEP) of the aluminum and hybrid designs with the steel design over the use stage, so that the hybrid design has the lowest life cycle EI. However, since the deviation between the hybrid and steel design is comparatively low at 6 %, a decision for the steel design seems reasonable, considering the variation of the input parameters. For the application of the same vehicle in an RH service (scenario 5), the steel design only has the lowest life cycle EI for the best-case scenario. In the baseline scenario, there is a BEP with the hybrid and in the worst-case scenario with all three lightweight material variants. The hybrid and aluminum designs thus have the lowest EI in the IC GWP for the baseline and worst-case scenarios of use stage scenario 5. Thereby, the GWPs of the steel, hybrid and aluminum designs in the baseline scenario and of the aluminum and hybrid designs in the worst-case scenario differ by less than 10 % (Fig. 6 and A.3). The decision for a material design in this use stage scenario is therefore associated with higher uncertainty. If the baseline or a more pessimistic scenario is considered likely by the decision-makers, the hybrid and aluminum designs prove to be suitable. If they consider a more optimistic case closer to the best-case scenario to be likely, a decision for the steel design seems appropriate.

Whether a BEP between a reference and a lightweight design variant occurs within a use stage scenario can be derived by calculating the break-even mileage in v-km ($d_{V,A}$) or transport performance in p-km ($P_{V,A}$) after which a lightweight design variant has the same or a lower lifecycle EI in an IC ($EI_{L,LC,I}$) compared to a reference ($EI_{R,LC,I}$). If this mileage or transport performance is within the values defined in the respective use stage scenario, the lightweight design variant achieves lower lifecycle EI in the IC under consideration than the reference. Based on Formula 5, the break-even mileage and transport performance are calculated according to Formulas 6 and 7 for BEVs and enable the following conclusions for the LCE of lightweight structures in vehicles for different mobility system applications, assuming a constant charging efficiency (η_{charge_V}) and occupancy rate of a vehicle in its mobility system application ($r_{V,A}$) as well as a lightweight design variant with a lower mass ($m_L < m_R$) but higher EI in IC I from the production and EoL stages than the reference $\left(\left(EI_{L,P,I} + EI_{L,EoL,I}\right) > \left(EI_{R,P,I} + EI_{R,EoL,I}\right)\right)$: The lower the ERV ($ERV_{V,A}$) and impact indicator per unit of energy ($I_{A,I}$), the lower the additional EI from the production and EoL stages of a lightweight design variant can be per kilogram of saved mass compared to a reference, to achieve a specified break-even mileage or transport performance (and vice versa).

$$d_{V,A} \geq \frac{\left[\left(EI_{L,P,I} + EI_{L,EoL,I}\right) - \left(EI_{R,P,I} + EI_{R,EoL,I}\right)\right] \cdot \eta_{charge_V}}{(m_R - m_L) \cdot ERV_{V,A} \cdot I_{A,I}} \tag{6}$$

$$P_{V,A} \geq d_{V,A} \cdot r_{V,A} \tag{7}$$

For the baseline scenarios of use stage applications 4 and 5 in the IC FAETP shown in Fig. 8, the differences in the production and EoL EIs of the lightweight design variants compared to the steel reference are high enough that no BEPs occur within the defined vehicle mileages and transport performances for the underlying mass differences, ERVs, impact indicator of energy and charging efficiency. Due to the low magnitude and differences in sensitivity of the material variants' EI to the variation of component masses, ERV, mileage, impact indicator of energy and charging efficiency (Figure A.4) and the limited variation of the EoL EI, there are still no BEPs in the best- and worst-case scenarios. In the IC GWP, the baseline scenario for the seat crossmember application in a midsize BEV in MIT (use stage scenario 4) shows that the estimated mileage and transport performance are not sufficient to result in a BEP within these for the underlying values of the input parameters from Formula 6 (mass differences of the components, ERV, charging efficiency, impact indicator of energy). Due to the higher magnitude and differences in sensitivity of the material variants' EI to the variation of the ERV (as only changed input parameter from Formula 6 between baseline use stage scenarios 4 and 5) and the higher underlying vehicle mileage, a BEP occurs in the baseline use stage scenario 5 in contrast to scenario 4. The magnitude and differences in sensitivity of the EI of the material variants in the IC GWP to variations in ERV, mileage and energy impact indicator compared to the IC FAETP also lead to the ranking shifts of the material variants' EI across the baseline, best-case and worst-case scenarios of use stage applications 4 and 5.

In summary, the occurrence of a ranking shift in the EI of the material variants within a use stage scenario and an IC (e.g. use scenario 4 in IC GWP) over the components life cycle stages depends on the specification of the input parameters in Formula 6. The robustness of the rankings and thus the robustness of decisions in the material selection process against variations and uncertainties in the input parameters from Formula 6 depends on the magnitude of the parameter variations as well as on the magnitude and the differences in the sensitivities of the material variants' EI to these parameter variations. Accordingly, the occurrence of a ranking shift in the EI of the material variants in an IC across different use stage scenarios depends on the magnitude and the differences in the sensitivities of the EI of the material variants to the variation of the parameters from Formula 6, which change between the considered use stage scenarios (in the baseline scenarios of use stage applications 4 and 5 in Fig. 8 the ERV due to varying driving profiles and vehicle loading) as well as the extend of these parameter variations.

Based on the interactions described between the vehicle characteristics, their usage profiles and energy supply in different mobility system applications as well as EIs from the production and EoL processing of structural components of different masses, conclusions for their LCE under consideration of future developments (e.g. technological evolutions) can be drawn. For example, assuming future decreasing ERVs (e.g. through more efficient vehicles or less dynamic driving behavior) and decreasing EIs of energy supply (e.g. through increasing use of renewable energies), to achieve a specified mass saving for a vehicle structure by using lightweight materials without increasing its lifecycle EI for a given driving distance or transport performance, either the EI of production and EoL stages must be reduced compared to the reference or the mass saving must be increased. The visualizations and Formulas 5-7 thus allow the identification of the material design with the least EI in an IC for different vehicle and mobility system applications as a function of the influencing parameters on different system levels. In addition, the effects of parameter variation, such as changes in the EI of the energy supply due to the usage of vehicles in another region, can be analyzed.

4.5. Knowledge generation and direct application

The results of the case study emphasize that the application profile of the vehicle in which a component is installed can have a significant influence on its lifecycle EI and on the design with the least EI. The EI of the component and vehicle are thus influenced by decisions in LCE activities. So, component and vehicle manufacturers should conduct such studies at an early stage to be able to take suitable development and strategic decisions. To be able to precisely estimate the EI of the components continuously, the calculation models and data sets created need to be made available and accessible throughout the LCE procedure (Herrmann et al., 2018). By continuously updating the models and data, the EI can be estimated more precisely, and better decisions can be made in LCE activities. The findings obtained are to be reviewed in future studies and integrated into development and strategic decisions. Based on section 4.4, the following list includes the key implications of the case study for future LCA based LCE, product and strategy development activities in the context of lightweight structures in (on-demand) mobility system applications, divided by general implications regarding the evaluation of EI by LCA and implications regarding the material selection within different vehicle applications:

4.5.1. EI of lightweight structures in different mobility system applications, including on-demand services

- For holistically evaluating EIs of lightweight structures in vehicles for different mobility system applications by LCA, parameter changes at relevant system levels (from the component to the mobility system level), several ICs and the transport performance provided by the vehicle should be considered. So, when comparing the EI of lightweight structures in vehicles for different mobility systems, the choice of the functional unit and the associated reference unit can have a significant influence on the results, and it is recommended to consider and communicate absolute lifecycle EI as well as EI per p-km.
- The application of lightweight structures in vehicles for on-demand mobility services can lead to an increase in their absolute EI and a decrease in their EI per p-km provided compared to applications in vehicles for MIT, which should be considered by manufacturers when (strategically) aligning the product portfolio against the background of their sustainability strategy.
- The uncertainty and sensitivity analyses reveal a strong influence of vehicle characteristics, mileage, usage profiles, and energy supply on the EI of lightweight structures. Reducing the high data uncertainty of these parameters, particularly in on-demand mobility systems, is essential to improve the robustness of LCA results and support more informed decision-making in LCE activities.

4.5.2. Material selection for lightweight structures in different mobility system applications

- As the steel variant has the lowest EI in the production and together with the EoL stage, the choice of this variant is ecologically advantageous if these lifecycle stages are in the focus of the decision-maker (e.g. for decisions based on cradle-to-gate analyses).
- Depending on the IC, the use stage and the effect of mass saving by lightweight design can be of varying relevance for the lifecycle EI and should be included accordingly in development decisions. Therefore, the design alternatives should be evaluated specifically for use stage scenarios and ICs which are relevant to the decision makers. Based on Formulas 5 and 6 as well as uncertainty and sensitivity analyses, interactions and variations of influencing parameters should be considered to robustly assess whether a lightweight variant can have lower lifecycle EI than a reference within the intended use stage application across multiple ICs.
- The baseline scenarios of the case study show that the assumed more dynamic and extended use stages of vehicles in on-demand mobility systems can lead to lightweight design variants having lower lifecycle EI in most ICs compared to a steel reference (baseline of use stage scenario 6). In the further use stage scenarios, the steel design has the lowest EI in most ICs. Given the strong influence of vehicle characteristics, usage profiles, mileage, and energy supply on the EI of different material designs for lightweight structures, changes in boundary conditions (e.g., operation in a different region) can significantly affect both the EI and the ranking of the material variants across different use stage scenarios.
- Compared to conventional vehicle applications in MIT, certain boundary conditions of vehicle applications on-demand mobility systems (e.g. more dynamic driving profiles, enhanced vehicle mileages) can favor the environmental performance of lightweight design variants (Formula 6). Other boundary conditions (e.g. increasing electrification and energy efficiency of drivetrains, which reduce ERVs) can reduce the environmental benefits of lightweight material variants with higher production and EoL EIs compared to a reference. Considering potential future developments such as decarbonization of electricity grids, improvements in drivetrain efficiency, and less dynamic driving enabled by autonomous vehicles, the potential for lightweight material solutions to outperform steel designs in terms of lifecycle EI may decline. The holistic reduction of lightweight material solutions' EI across all life cycle stages and ICs is therefore of particular importance for their future competitiveness.
- In addition to the ecological product characteristics of the component design alternatives investigated in this study, technical and economic requirements of the components, but also of the overall vehicle, must be considered in product development and strategic decisions.

5. Discussion and conclusions

The paper presents a method for LCA based LCE of lightweight structures in vehicles for different mobility system applications, including on-demand mobility services. Previous approaches for LCE of lightweight structures in mobility applications (Herrmann et al., 2018; Kaluza et al., 2017; Reimer et al., 2020, 2021)), LCA of mobility services (Gawron et al., 2019; Neef, 2020), and calculation models to estimate mass-induced energy savings (e.g. (Del Pero et al., 2020a; Geyer and Malen, 2020a, 2020b; Hofer, 2014; Kim and Wallington, 2013, 2016; Kim et al., 2015; Koffler, 2014; Koffler and Rohde-Brandenburger, 2010)) are combined and extended for this purpose. This is necessary because the number of vehicles for on-demand mobility services is expected to increase and can differ from conventional vehicles for MIT in terms of their specifications but also in terms of the driving and usage profile in a mobility system. The method provides a systematic approach and considers influencing parameters on component, subsystem, vehicle and mobility system levels as well as several environmental ICs. It includes a vehicle simulation model that, based on the vehicle specification and an arbitrary driving profile, calculates the ERV for BEVs as a relevant input parameter for LCA of lightweight structures. The developed method enables LCA practitioners to evaluate and compare the EI of lightweight structure design alternatives in ongoing development procedures and to select the design alternative with the least EI for vehicles in different mobility system applications. In this way, conclusions for the strategic and sustainable alignment of the product portfolio can be drawn and decision-making in product and strategy development can be improved. LCA-based LCE activities such as those in this study, considering parameter interactions at all relevant system levels and several ICs, should therefore be integrated into the development procedure of future on-demand mobility solutions and their vehicles to further reduce their EI and provide a sustainable alternative to MIT.

By applying the method to a case study of a seat crossmember in four material designs for eight use stage scenarios, its practicability is demonstrated. It is shown that the lifecycle EI of the components can differ significantly depending on the vehicle and its mobility system application. The application of lightweight structures in vehicles for on-demand mobility services can lead to an increase in their absolute EI and a decrease in their EI per p-km provided compared to applications in vehicles for MIT. Consequently, when comparing the EI of lightweight structures in vehicles for different mobility system applications, the choice of the functional unit has a significant influence on the results and their interpretation. Regarding the material selection for the seat crossmember in different mobility system applications, the scenarios of the case study show that more dynamic and extended use stages of vehicles in on-demand mobility systems can lead to lightweight design variants having lower lifecycle EI compared to a steel reference in several ICs. In four out of five of the investigated on-demand mobility scenarios, the steel reference has the lowest EI in most of the ICs, as in all scenarios considered with vehicles in MIT. However, the best- and worst-case scenarios considered in the uncertainty analysis reveal that depending on the IC, the substantial variation in key input parameters (e.g. EI from energy supply, vehicle characteristics, driving profiles, mileages) can lead to significant changes in the EI of the seat crossmember material variants and the ranking of their EI in different use stage scenarios. So, general recommendation to focus on a specific material for structures in vehicles for on-demand mobility applications cannot be derived. Design alternatives should be evaluated specifically for use stage scenarios and ICs which are relevant to the decision makers considering interactions and variations of the influencing parameters.

Though the case study is limited to one component of the vehicle structure in different material designs, the procedure of the developed method is transferable to other vehicle lightweight components, but specific aspects need to be considered. The described vehicle simulation model for calculating ERVs is limited to electric vehicles. To take other powertrain types into account, the model would have to be adapted. In addition, if the investigated component affects mass-independent consumption parameters (e.g. drag coefficient), the approach for allocating the vehicle energy demand to the component should be modified so that not only mass-induced energy demand is considered. Furthermore, this study assumes constant masses of the component design variants for all vehicle applications, although these can change depending on vehicle geometry and requirements.

A limitation of the study concerns the high uncertainty of the data used in the product and vehicle models, especially related to on-demand mobility services. The data used for vehicles parameters, driving profiles, mileages and occupancy rates need to be validated and specified in future research, e.g. through operating data, field tests or simulations to reduce and more precisely describe the uncertainty of these data in LCE activities and thus enable more robust decision-making. For example, the ERVs of vehicles for on-demand mobility services are calculated based on representative driving cycles and deviations from real-world operation are estimated using literature data. Real operating data or measurements could be used to analyze the real driving profiles of the vehicles in the individual mobility applications and to evaluate differences in energy demands, FRVs and ERVs between the real-world driving and the driving cycles assumed in this study. For reasons of transparency and comparability and in line with (Koffler and Rohde-Brandenburger, 2010), it should be noted that the consideration of individual driving profiles should not counteract the usage of standardized driving cycles for aspects like external communication of vehicle energy demands. The vehicle simulation model could also be extended to increase its accuracy by including further system components, or by modeling subsystems more detailed. Model parameter tests show that more detailed modeling of powertrain components such as the battery system or the drive motor based on characteristics of the real systems to be installed in the vehicles offers potential for improving model accuracy.

Regarding the developed method, the integration of prospective LCA analyses to consider future perspectives of LCA influencing parameters, for example through technological evolution of vehicles such as autonomous driving, the recycling of CFRP, or the decarbonization of the energy system, could improve the quality of strategic decisions. Based on the study by (Gawron et al., 2019), including autonomous driving could result in a reduced mass-dependent energy demand of vehicles through effects such as more energy efficient driving patterns. However, this needs to be investigated in future studies, considering LCA parameter changes and interactions at all relevant system levels. Regarding the EoL treatment of structural components, the ongoing activities to revise the End-of-Life Vehicles Act in the EU suggest that the process routes investigated will also be deployed in the future. However, in addition to the two process routes investigated, further scenarios could be addressed in future research, for example considering increased secondary material shares and alternative modeling approaches for the EoL stage. The integration of structured methods to identify and characterize future technological developments could support the prospective extension of the proposed method. For example, the SIMPL approach by (Langkau et al., 2023) provides a stepwise method to embed future scenario development within inventory modeling, ensuring consistency and transparency. In this context, the approach presented by (Spreafico et al., 2025), which utilizes patent data as a basis for anticipating technological evolution, offers a promising opportunity. Patent analysis may provide valuable insights into emerging innovations and development directions, particularly for vehicle technologies and key upstream processes. Such methods could support the identification of relevant future changes to LCA parameters and the generation of consistent prospective scenarios. While a systematic integration of this approach was beyond the scope of the present study, it is considered a valuable direction for future research.

In addition, subsequent studies could include economic and social aspects to enable a holistic sustainability assessment of lightweight design alternatives. As the database for this is limited, there is a need for research to collect and provide the necessary information. To analyze further rebound effects associated with the introduction of on-demand mobility services (e.g. induced demand) on the EI of lightweight structures, future research could address extending the scope to an entire product portfolio of components for a vehicle fleet. Based on the findings from this study, the influence on the relative EIs between lightweight and reference designs and thus material selection can be estimated as low. But a potential increase in overall mobility demand, more intensive usage of vehicles in on-demand mobility services and an associated increase in the total number of vehicles could conceivably lead to higher absolute lifecycle EIs of structural component product portfolios. Furthermore, beyond the four material designs considered for the case study of a seat crossmember, there are other materials and components relevant for vehicle structures. Consequently, the quantitative results of the case study cannot be generalized for all components and materials in vehicle structures.

With the presented method, the paper contributes to the method development for LCE of lightweight structures in mobility applications and provides quantitative results by its application to a case study.

CRediT authorship contribution statement

Moritz Ostermann: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Eric Dierkes:** Software, Methodology. **Thorsten Marten:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Thomas Tröster:** Writing – review & editing, Supervision, Funding acquisition.

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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.

Nomenclature

Symbols		
A_V	Vehicle frontal area	m^2
c_d	Air drag coefficient	dimensionless
$d_{V,A}$	Mileage of vehicle *V* in mobility system application *A*	km
$EI_{C,EoL,I}$	Environmental impact of component *C* (e.g. reference *R* or lightweight design *L*) from the end-of-life stage in impact category *I*	Depending on impact category
$EI_{C,LC,I}$	Lifecycle environmental impact of component *C* (e.g. reference *R* or lightweight design *L*) in impact category *I*	
$EI_{C,P,I}$	Environmental impact of component *C* (e.g. reference *R* or lightweight design *L*) from the production stage in impact category *I*	Depending on impact category
$EI_{C,U,I}$	Environmental impact of component *C* (e.g. reference *R* or lightweight design *L*) from the use stage in impact category *I*	Depending on impact category
ED_C	Allocated energy demand of component *C*	kWh
ERV_i	Energy reduction value of individual trips	kWh/(100 kg*100 km)
ERV_p	Energy reduction value of platoon trips	kWh/(100 kg*100 km)
$ERV_{V,A}$	Energy reduction value of vehicle *V* (e.g. *LEV*) in mobility system application *A* (e.g. *RP* service)	kWh/(100 kg*100 km)
FC_C	Allocated fuel consumption of component *C*	l
$FRV_{V,A}$	Fuel reduction value of vehicle *V* in mobility system application *A*	
f_R	Rolling resistance coefficient	dimensionless
F_T	Force at vehicle tire	N
g	Acceleration of gravity	m/s^2
$I_{A,I}$	Impact indicator per unit of energy in impact category *I* including EI from energy supply to the vehicle (well-to-tank) and EI from energy conversion for driving (tank-to-wheel).	Depending on impact category, e.g. kg CO_2e./kWh for GWP100
m	Vehicle mass	kg
m_C	Mass of component *C* (e.g. reference *R* or lightweight design *L*)	kg
$P_{V,A}$	Transport performance of vehicle *V* in mobility system application *A*	p-km
$r_{V,A}$	Occupancy rate of vehicle *V* in mobility system application *A*	Passengers
s_i	Distance travelled individually	km
s_p	Distance travelled in platoon	km
s_{total}	Total distance travelled	km
v_r	Relative velocity of vehicle to ambient air	m/s
$\ddot{x}$	Vehicle acceleration	m/s^2
α	Slope angle	°
λ	Torque mass supplement factor	dimensionless
ρ_A	Air density	kg/m^3
η_{charge_V}	Vehicle charging efficiency	dimensionless

Abbreviations

ADP	Abiotic depletion potential
AM	Arithmetic mean
AP	Acidification potential
BEP	Break-even-point
BEV	Battery electric vehicle
CADC	Common Artemis Driving Cycles
CDP	Cathodic dip painting
CFRP	Carbon fiber-reinforced plastic
EI	Environmental impact
EoL	End-of-Life
EP	Eutrophication potential
ERV	Energy reduction value
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FAETP	Freshwater aquatic ecotoxicity potential
FRV	Fuel reduction value
GHGE	Greenhouse gas emissions
GWP	Global warming potential
HTP	Human toxicity potential
IC	Impact category
ICEV	Internal combustion engine vehicle
LCA	Life cycle assessment
LCE	Life cycle engineering
LEV	Light electric vehicle
MaaS	Mobility as a service
MAETP	Marine aquatic ecotoxicity potential
MIT	Motorized individual transport
MLC	Managed LCA content (database by Sphera)
OEM	Original equipment manufacturer
ODP	Ozone layer depletion potential
PAN	Polyacrylonitrile
POCP	Photochemical ozone creation potential
p-km	Passenger kilometer
RH	Ride-Hailing
RP	Ride-Pooling
SOC	Battery state-of-charge
TETP	Terrestrial ecotoxicity potential
v-km	Vehicle kilometer
WHVC	World Harmonized Vehicle Cycle
WLTC	Worldwide Harmonized Light Vehicles Test Cycles

Appendix

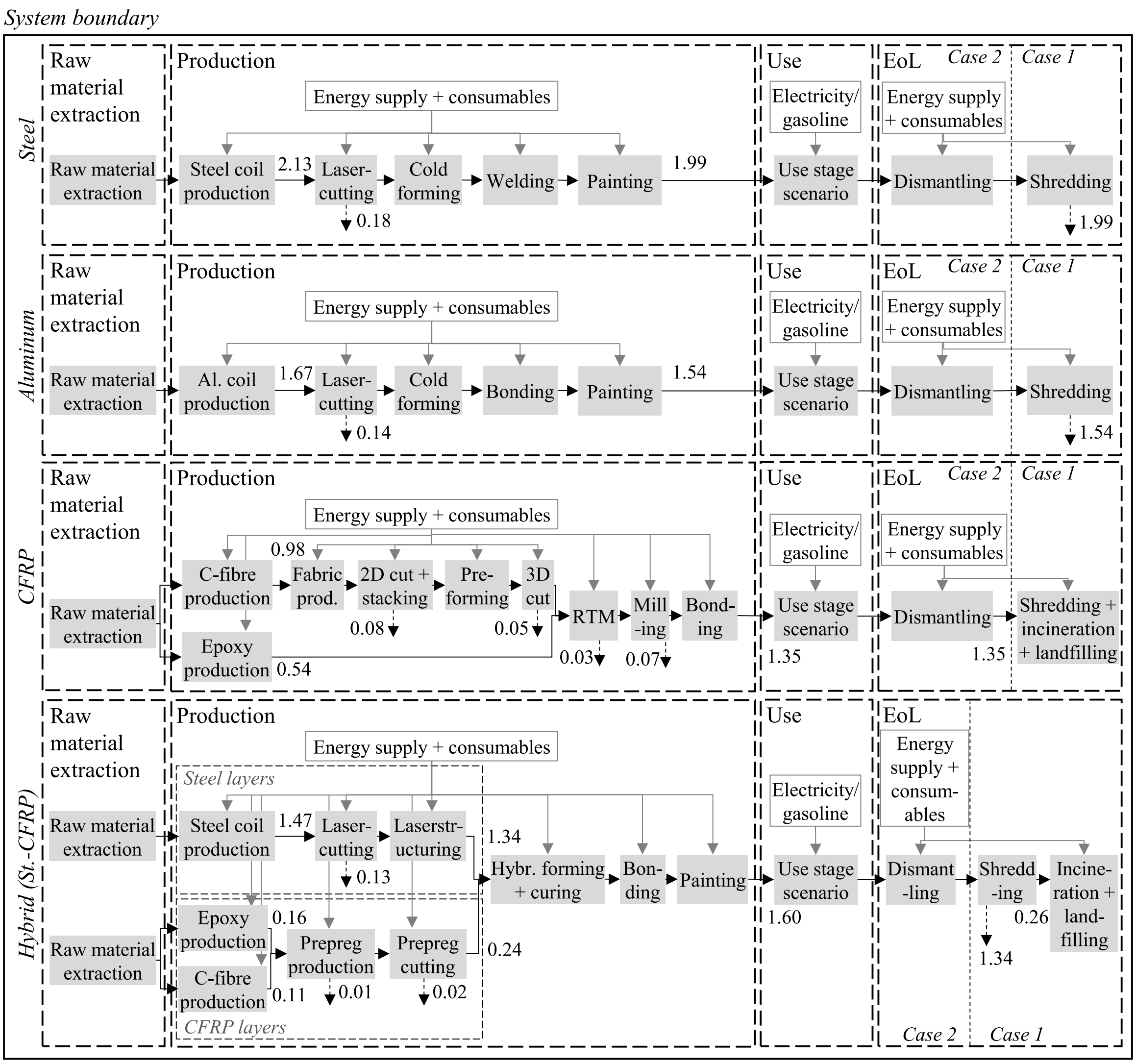

Fig. A.1. Scope and system boundary of the LCA for the seat crossmember design variants.

Table A.1
Main assumptions for the case study

Life cycle stage	Main assumptions
Raw material extraction and production	• Application of common production technologies and process routes in the automotive industry for manufacturing the design variants (see Figure A.1) • Production processes take place in Europe (so European average data sets are used where available, see Table A.2) • Material and energy flows according to Figure A.1 based on data sets described in Table A.2
Use	• Application of the seat crossmember designs in eight mobility system scenarios with specific vehicles, driving profiles, mileages and occupancy rates (see Table 1, Table A.3-A.4) • Use stage takes place in Europe (so European average data sets are used for electricity and gasoline supply, see Table A.2) • Limitation to energy-related EI resulting from the supply of the required driving energy and direct emissions from fuel combustion (no consideration of EI due to maintenance, infrastructure construction, emissions from tire, brake and road abrasion as their influence on the results can be estimated as low based on studies like that of (Hawkins et al., 2013)) • Allocation of the vehicle energy demand to the seat crossmember by mass using the incremental allocation approach according to (Eberle and Franze, 1998) (see Formulas 2-4)
End-of-Life	• EoL processing takes place in Europe • Consideration of two alternative cases for the EoL processing route (Figure A.1): • Case 1: Current standard processing route for EoL vehicles in Europe according to (Directive 2000/53/EC, 2000) with dismantling and shredding of the seat crossmember • Case 2: Processing route for improved circularity with dismantling of the seat crossmember for reuse or complete recycling • Allocation of the EI from vehicle dismantling and shredding to the seat crossmember by mass • EIs from primary material production and recycling processes are allocated to the product where the respective material is used

(continued on next page)

Table A.1 (*continued*)

Life cycle stage	Main assumptions
	• No credits are accounted for avoiding primary material production by using secondary material • EIs from waste treatment are allocated to the product generating the waste

Table A.2
LCI data basis used for the case study

Life cycle stage	Activity	LCI data basis and data collection methods	Conformity with data quality requirements
Raw material extraction and production	Steel coil production (including raw material extraction)	• Global average data for blast furnace and electric arc furnace routes and their shares from (World Steel Association, 2020)	• No (Data not representative for Europe)
	Aluminum coil production (including raw material extraction)	• European average data for primary and secondary aluminum ingot production from Managed LCA Content (MLC) database by Sphera (Sphera, 2022) • Assumption of a secondary material share of 11.1 % based on (European Aluminium, 2018; Wallace, 2011) • European average data for aluminum sheet rolling from the MLC database by Sphera	• Yes • Yes • Yes
	Carbon fibre production (including raw material extraction, production route based on PAN fibres)	• European average data for PAN fibre production from the MLC database by Sphera • Data for processing of PAN fiber to carbon fiber from (Hohmann, 2019)	• Yes • Yes
	Epoxy production (including raw material extraction)	• European average data from PlasticsEurope (Bachmann et al., 2017)	• Yes
	Laser cutting	• Global average data from the MLC database by Sphera	• Yes (Data is not representative for Europe, but modeling enables the process to be supplied with European energy data)
	Cold forming (steel)	• German average data from the MLC database by Sphera	• Yes (Data is not representative for Europe, but modeling enables the process to be supplied with European energy data)
Raw material extraction and production	Cold forming (aluminum)	• German average data from the MLC database by Sphera	• Yes (Data is not representative for Europe, but modeling enables the process to be supplied with European energy data)
	Welding	• Global average data from the MLC database by Sphera	• Yes (Data is not representative for Europe, but modeling enables the process to be supplied with European energy data)
	Bonding	• European average data from the MLC database and PlasticsEurope	• Yes
	Painting (cathodic dip painting)	• Global average data from the MLC database by Sphera	• Yes (Data is not representative for Europe, but modeling enables the process to be supplied with European energy data)
	CFRP processing including fibre fabric production, 2D cutting and stacking, preforming, 3D cutting, RTM, milling	• European average data based on (Hohmann, 2019)	• Yes
	CFRP prepreg production and cutting	• European average data based on (Suzuki and Takahashi, 2005)	• Yes
	Electricity supply	• European average data for the electricity grid from the MLC database by Sphera	• Yes
	Laserstructuring and hybrid forming and curing	• Laboratory measurements with process configuration based on (Heggemann et al., 2020)	• Yes
	Supply of thermal energy from natural gas	• European average data from the MLC database by Sphera	• Yes
Use	Electricity supply	• European average data for the electricity grid from the MLC database by Sphera	• Yes
	Fuel supply including production	• European average data for the production and supply of gasoline from the MLC database by Sphera	• Yes
	Direct emissions from burning fuel in an ICEV	• Test data of a midsize ICEV from (Allgemeiner Deutscher Automobil-Club e.V., 2018)	• Yes
	Component use stage energy demand	• Component energy demand calculated based on formulas 2-4 and the vehicle data from Tables A.3 and A.4	• Yes
End-of-Life	Manual dismantling and shredding	• Global average data from the ecoinvent database version 3.9.1	• No (Data not representative for Europe)
	Incineration and landfilling	• Global average data from the ecoinvent database version 3.9.1	• No (Data not representative for Europe)

Table A.3
Investigated vehicles and relevant parameters for the ERV calculation.

Vehicle and powertrain type		Curb weight [kg]	Drag coeff. [ ]	Rolling resistance coeff. [ ]	Front surface [m²]	Max. motor power [kW]	Max. motor torque [Nm]	Auxiliary power [W]
Midsize ICEV	*							
LEV	Max.	550.00	0.35	0,011	2.38	15.00	70.00	600
	AM	496.25	0.33	0.010	2.32	13.00	48.30	450
	Min.	408.00	0.31	0,009	2.26	12.00	17.90	300
	Data basis***	L7e vehicles INYO Cab (INYO Mobility GmbH, 2025), Renault Twizy, Microlino, Toyota COMS (Ewert et al., 2021)	L7e vehicle INYO Cab (INYO Mobility GmbH, 2025) and smart fortwo EQ as M1 vehicle with geometric dimensions similar to an L7e vehicle (Lidl, 2018)	Mean value from (Schütz, 2013); max. and min. equal ± 10 % of mean value**	See data basis for drag coeff.	L7e vehicles INYO Cab (INYO Mobility GmbH, 2025), Renault Twizy, Microlino (Ewert et al., 2021) and legal maximum (Regulation EU, 2013)	L7e vehicles INYO Cab (INYO Mobility GmbH, 2025), Renault Twizy, Microlino (Ewert et al., 2021)	Measurements from real-world driving of various BEVs from (Helms et al., 2013, 2022)
Small BEV	Max.	1544.00	0.33	0,011	2.33	110.00	260.00	800
	AM	1422.67	0.31	0.010	2.22	90.00	221.67	600
	Min.	1200.00	0.29	0,009	2.13	60.00	160.00	400
	Data basis	M1 vehicles (Segment A) with ≥4 seats: smart forfour (Pfeffer, 2020), Opel Corsa Electric (Ruhdorfer, 2024), Renault R5 Electric (Werner, 2025)	see LEV	equivalent to curb weight and drag coeff. data basis				see LEV
Midsize BEV	Max.	2095.00	0.32	0,011	2.54	185.00	420.00	1200
	AM	1883.00	0.29	0.010	2.42	161.67	375.00	900
	Min.	1760.00	0.27	0,009	2.36	150.00	310.00	600
	Data basis	M1 vehicles (Segment C) Volkswagen ID3 (Ruhdorfer, 2020), Hyundai Kona (Ruhdorfer, 2018), Volvo EC40 (Werner, 2024)		see LEV	equivalent to curb weight and coeff. data basis			see LEV
Minibus BEV	Max.	2700.00	0.40	0,016	5.47	210.00	560.00	1500
	AM	2609.50	0.35	0.015	4.55	153.33	425.00	1150
	Min.	2502.00	0.29	0,014	3.28	100.00	290.00	800
	Data basis***	EV minibuses for ride-pooling services: Navya Shuttle Evo (Navya SA, 2021), HOLON Mover (Langusch, 2023), VW E-Crafter (MOIA GmbH, 2023), VW ID. Buzz (Ruhdorfer, 2025)	EV Minibuses VW E-Crafter (MOIA GmbH, 2023), VW ID.Buzz (Ruhdorfer, 2025) and omnibus with similar geometry VDL Citea (VDL Bus & Coach bv, 2022)	see LEV	equivalent to curb weight data basis	EV minibuses for ride-pooling services: HOLON Mover (Langusch, 2023), VW E-Crafter (MOIA GmbH, 2023), VW ID.Buzz (Ruhdorfer, 2025)	EV minibuses for ride-pooling services: VW E-Crafter (MOIA GmbH, 2023), VW ID.Buzz (Ruhdorfer, 2025)	see LEV
Towing Vehicle of RP Platoon (BEV)	Max.	2750	0.34	0,016	2.64	176	495	750
	AM	2500	0.31	0.015	2.40	160	450	600
	Min.	2250	0.28	0,014	2.16	144	405	450
	Data basis	Mean values from towing vehicle of NeMo.bil concept (update from values provided by (Ostermann et al., 2023a)); max. and min. equal ± 10 % of mean value. This assumption is made as no information is available on the range of values from real vehicles		see LEV	equivalent to curb weight and drag coeff. data basis			First model calculations from NeMo.bil concept

* The FRV values for the mid-size ICEV in Table 2 are the maximum, minimum and arithmetic mean of eleven mid-size gasoline turbocharged ICEVs whose FRVs without secondary mass effects were determined by (Del Pero et al., 2017). The considered mass range of the vehicles from (Del Pero et al., 2017) was corrected upwards according to the additional mass from the vehicle occupation (Table A.4).

** This assumption is made as no information is available on the range of values from real vehicles.

*** The data basis for the vehicle parameters can vary depending on the data availability of the different real vehicles.

Table A.4
Parameters for different mobility systems

Mobility system	Driving Cycle	Mileage [km]	Occupancy Rate
		Min. AM Max.	Min. Mean value Max.
MIT	WLTC	120,000 190,000 260,000 Data basis: Min. and max. values from studies by (Weymar and Finkbeiner, 2016; Eltohamy et al., 2024; Dun et al., 2015) in which value ranges are given based on empirical data analysis of operating vehicles in MIT in Europe.	1.38 1.45 1.7 Data basis: Mean and min. values based on empirical data for average private vehicle usage in Europe (European Environment Agency, 2008). Max. value based on survey data for European average private vehicle usage provided by (Fiorello et al., 2016)
RH	Hyzem urban	300,000 450,000 600,000 Data basis: Min. and max. values based on estimations of mileages for on-demand mobility services (including RH and RP) (Deloitte Ltd., 2019; Morfeldt and Johansson, 2022; Reimer et al., 2020) and analysis of operating vehicles in on-demand mobility services in Europe (International Association of Public Transport, 2019; Le Petit et al., 2020).	0.8 1.3 1.8 Data basis: Min. and max. values from empirical RH operation data in Denver (Henao and Marshall, 2019) and San Francisco (Rayle et al., 2014). Mean value is the arithmetic mean of min. and max. values. European data could not be found. The indicated values do not include the driver.
RP	Braun-schweig Cycle	300,000 550,000 800,000 Data basis: Equivalent data basis as for RH, but the maximum value is changed to 800,000 as minibuses can have mileages in this range and above according to (Eltohamy et al., 2024).	1.57 2.07 4 Data basis: Mean value is arithmetic mean of model-based estimations for RP services in European cities, i.e. 2.3 by (International Transport Forum, 2017) and 1.83 by (Kagerbauer et al., 2022). Min. value based on only empirical data from RP operation in California (California Air Resources Board, 2019), max. value based on modeling results for a US city by (Santi et al., 2014). The indicated values do not include the driver.
RP with platooning	Hyzem urban (first and last mile) Hyzem road (platooning)	300,000 450,000 600,000 Data basis: Equivalent data basis as for RH, since the vehicles and their usage profile are expected to be similar to a ride-hailing service (Ostermann et al., 2023a).	0.8 1.3 1.8 Data basis: Equivalent data basis as for RH, since the vehicles and their usage profile are expected to be similar to a ride-hailing service (Ostermann et al., 2023a).

Table A.5
Parameters combination for FRV and ERV determination.

Use stage scenario	FRV/ ERV value	Driving cycle	Vehicle type	Vehicle parameter set from Table A.3	Additional vehicle loading based on occupancy rate* [kg]	Adaption factor to represent real-world driving **
1	Min	WLTC	Midsize ICEV	FRVs for midsize ICEVs from (Del Pero et al., 2017) are used so that no vehicle parameters are required. The considered mass range of vehicles was corrected upwards according to the additional loading from the vehicle occupation.	28.50	1
	Mean				37.75	1
	Max				52.50	1.28
2	Min	WLTC	Small BEV	Min	28.50	1
	Mean			AM	33.75	1
	Max			Max	52.50	1.28
3	Min	Hyzem urban	Small BEV	Min	60.00	1
	Mean			AM	97.50	1
	Max			Max	135.00	1.10
4	Min	WLTC	Midsize BEV	Min	28.50	1
	Mean			AM	33.75	1
	Max			Max	52.50	1.28
5	Min	Hyzem urban	Midsize BEV	Min	60.00	1
	Mean			AM	97.50	1
	Max			Max	135.00	1.10
6	Min	Braun-schweig	Minibus BEV	Min	117.75	1
	Mean			AM	155.25	1
	Max			Max	300.00	1.10
7	Min	Hyzem urban	LEV	Min	60.00	1
	Mean			AM	97.50	1
	Max			Max	135.00	1.10
8	Min	Hyzem urban and Hyzem road	LEV platoon	Min	60.00	1
	Mean			AM	97.50	1
	Max			Max	135.00	1.10

* The curb weights of the vehicles already include 75 kg for one passenger including luggage. The values given in this column correspond to the additional masses based on the occupancy rates from Table A.4, assuming 75 kg per passenger in accordance with European legislation (Regulation (EU), 2019). Since the occupancy

rates of the vehicles for on-demand mobility services do not include the driver, the mass of the driver must be additionally considered in scenarios 3, 5, 6, 7 and 8.

** The FRV/ERV based on the other influencing parameters is multiplied by this factor to estimate the FRV/ERV for real-world driving. The Common Artemis Driving Cycles (CADCs) have shown the smallest deviations in energy demands compared to real driving, so that they are considered representative for real-world driving (Sandrini et al., 2024). The FRV and ERV for the CADCs are approximately estimated using these factors, which are based on a study by (Sandrini et al., 2024). In the study by (Sandrini et al., 2024), ERVs for two BEVs based on the CADCs are compared with those based on the WLTC. It is important to note that this is a rough estimate and that the ERV values for the CADCs of the vehicles studied here may differ from those of (Sandrini et al., 2024). Despite the high uncertainty, this estimate is made to analyze the influence of the underlying driving cycles on the results. Based on (Sandrini et al., 2024) and a weighting of urban (40 %), rural (25 %) and highway (35 %) driving, which are representative of European driving patterns (Kager, 2013; Komnos et al., 2025), a percentage deviation of ERVs based on the CADCs compared to the WLTC of 28 % can be estimated. Since the energy demand differences between driving cycle and real-world driving are significantly lower with the Hyzem cycles for vehicles in urban respective rural traffic and with the Braunschweig cycle for city buses compared to the WLTC for MIT (Johannaber et al., 2007; Nylund et al., 2019), a reduced deviation (10 %) of the maximum ERVs is assumed for the RH and RP applications.

Table A.6
Data basis of scenarios for the uncertainty analysis

Parameter	Symbol	Baseline	Best Case	Worst Case
EI of component from production stage in impact category *I*	$EI_{C,P,I}$	Mean value based on system boundary from Figure A.1 and data basis from Table A.2	−10 % from baseline value (simplified assumption, as the focus of the study is on the use stage)	+10 % from baseline value (simplified assumption, as the focus of the study is on the use stage)
EI of component from EoL stage in impact category *I*	$EI_{C,EoL,I}$	Mean value based on system boundary for case 1 from Figure A.1 and data basis from Table A.2	−10 % from baseline value (simplified assumption, as the focus of the study is on the use stage)	+10 % from baseline value (simplified assumption, as the focus of the study is on the use stage)
Mass of component	m_C	Mean values for material designs from Fig. 3.	−10 % from baseline value, e.g. by design optimization (assumption that has been evaluated as valid by development experts for vehicle components). In addition, it is assumed that mass change leads to changes in the EI of the production and EoL stages by the same value (changed material and energy demand of processes).	+10 % from baseline value, e.g. due to changed requirements (assumption that has been evaluated as valid by development experts for vehicle components). In addition, it is assumed that mass change leads to changes in the EI of the production and EoL stages by the same value (changed material and energy demand of processes).
Fuel reduction value for scenario 1; energy reduction values for scenarios 2-8	$FRV_{V,A}$; $ERV_{V,A}$	Mean values for each use stage scenario from Table 2	Min values for each use stage scenario from Table 2	Max values for each use stage scenario from Table 2
Mileage of vehicle	$d_{V,A}$	Mean value for the mobility system application of each use stage scenario from Table A.4	Min value for the mobility system application of each use stage scenario from Table A.4	Max value for the mobility system application of each use stage scenario from Table A.4
Vehicle charging efficiency	η_{charge_V}	0.95 based on (Reimer et al., 2020)	0.955 (assumption to reduce charging losses by 10 %)	0.945 (assumption to increase charging losses by 10 %)
Occupancy rate of vehicle in mobility system application	$r_{V,A}$	Mean value for the mobility system application of each use stage scenario from Table A.4	Max value for the mobility system application of each use stage scenario from Table A.4	Min value for the mobility system application of each use stage scenario from Table A.4
Impact indicator per unit of energy in impact category *I* for gasoline supply (only relevant for use stage scenario 1)	$I_{A,I}$	European average data for the production and supply of gasoline from the MLC database by Sphera	German average data for the production and supply of gasoline from the MLC database by Sphera (representative of comparatively efficient refineries, short transport distances and high shares of renewable energy carriers in the electricity grid mix)	Indian average data for the production and supply of gasoline from the MLC database by Sphera (representative of comparatively inefficient refineries, long transport distances and low shares of renewable energy carriers in the electricity grid mix)
Impact indicator per unit of energy in impact category *I* for electricity supply	$I_{A,I}$	European average data for the electricity grid from the MLC database by Sphera	Norwegian average data for the electricity grid from the MLC database (representative of a high share of renewable energy carriers in the electricity grid mix)	Polish average data for the electricity grid from the MLC database (representative of a high share of fossil energy carriers in the electricity grid mix)

Scenario		Material	ADP elements in kg SB eq.	ADP fossil in MJ	AP in kg SO_2 eq.	EP in kg PO_4 eq.	FAETP in kg DCB eq.	GWP100 in kg CO_2 eq.	HTP in kg DCB eq.	MAETP in kg DCB eq.	ODP in kg CFC-11 eq.	POCP in kg Ethene eq.	TETP in kg DCB eq.	ICs with lowest value
Scenario 1	ICEV in MIT	Steel	5.2E-06	185.4	1.8E-02	3.3E-03	0.17	15.2	1.0	7.1E+02	9.6E-10	5.5E-03	4.1E-02	9
		Aluminum	6.0E-06	237.1	5.4E-02	5.1E-03	0.20	19.9	21.4	2.7E+04	7.6E-10	5.5E-03	6.0E-02	1
		CFRP	2.3E-05	569.4	5.6E-02	1.7E-02	2.19	38.7	5.9	4.1E+03	2.8E-09	7.6E-03	7.7E-02	0
		Hybrid	8.0E-06	232.0	2.4E-02	5.4E-03	0.51	17.8	1.8	1.3E+03	1.2E-09	5.2E-03	4.2E-02	1
Scenario 2	small BEV in MIT	Steel	4.2E-06	65.9	1.3E-02	1.2E-03	0.12	6.1	0.9	6.0E+02	9.6E-10	2.0E-03	3.2E-02	10
		Aluminum	5.2E-06	144.5	5.0E-02	3.5E-03	0.15	12.8	21.3	2.7E+04	7.6E-10	2.9E-03	5.3E-02	1
		CFRP	2.2E-05	488.0	5.2E-02	1.5E-02	2.15	32.5	5.8	4.0E+03	2.8E-09	5.2E-03	7.1E-02	0
		Hybrid	7.1E-06	135.9	1.9E-02	3.7E-03	0.46	10.5	1.7	1.2E+03	1.2E-09	2.4E-03	3.5E-02	0
Scenario 3	small BEV in RH	Steel	4.7E-06	72.1	1.3E-02	1.3E-03	0.12	6.9	1.1	7.2E+02	9.7E-10	2.1E-03	3.2E-02	10
		Aluminum	5.6E-06	149.3	5.0E-02	3.6E-03	0.16	13.4	21.4	2.7E+04	7.7E-10	2.9E-03	5.3E-02	1
		CFRP	2.2E-05	492.2	5.3E-02	1.5E-02	2.16	33.0	5.9	4.1E+03	2.8E-09	5.3E-03	7.1E-02	0
		Hybrid	7.6E-06	140.9	2.0E-02	3.8E-03	0.47	11.1	1.8	1.3E+03	1.2E-09	2.4E-03	3.5E-02	0
Scenario 4	midsize BEV in MIT	Steel	4.2E-06	66.4	1.3E-02	1.2E-03	0.12	6.2	0.9	6.1E+02	9.6E-10	2.0E-03	3.2E-02	10
		Aluminum	5.2E-06	145.0	5.0E-02	3.5E-03	0.15	12.9	21.3	2.7E+04	7.6E-10	2.9E-03	5.3E-02	1
		CFRP	2.2E-05	488.4	5.2E-02	1.5E-02	2.15	32.5	5.8	4.0E+03	2.8E-09	5.3E-03	7.1E-02	0
		Hybrid	7.2E-06	136.4	1.9E-02	3.7E-03	0.46	10.5	1.7	1.2E+03	1.2E-09	2.4E-03	3.5E-02	0
Scenario 5	midsize BEV in RH	Steel	4.8E-06	72.7	1.3E-02	1.3E-03	0.12	7.0	1.1	7.3E+02	9.7E-10	2.1E-03	3.2E-02	10
		Aluminum	5.7E-06	149.8	5.0E-02	3.6E-03	0.16	13.5	21.4	2.7E+04	7.7E-10	2.9E-03	5.3E-02	1
		CFRP	2.2E-05	492.7	5.3E-02	1.5E-02	2.16	33.1	5.9	4.1E+03	2.8E-09	5.3E-03	7.2E-02	0
		Hybrid	7.6E-06	141.5	2.0E-02	3.8E-03	0.47	11.2	1.8	1.3E+03	1.2E-09	2.5E-03	3.5E-02	0
Scenario 6	E-minibus in RP	Steel	5.7E-06	83.0	1.5E-02	1.5E-03	0.12	8.3	1.3	9.3E+02	9.8E-10	2.2E-03	3.4E-02	10
		Aluminum	6.4E-06	157.8	5.1E-02	3.8E-03	0.16	14.5	21.6	2.7E+04	7.7E-10	3.0E-03	5.4E-02	1
		CFRP	2.3E-05	499.6	5.4E-02	1.6E-02	2.16	34.0	6.1	4.3E+03	2.8E-09	5.4E-03	7.2E-02	0
		Hybrid	8.4E-06	149.7	2.1E-02	3.9E-03	0.47	12.2	2.0	1.5E+03	1.2E-09	2.5E-03	3.6E-02	0
Scenario 7	LEV in RH	Steel	4.6E-06	70.8	1.3E-02	1.3E-03	0.12	6.7	1.0	6.9E+02	9.7E-10	2.1E-03	3.2E-02	10
		Aluminum	5.5E-06	148.3	5.0E-02	3.6E-03	0.16	13.3	21.4	2.7E+04	7.6E-10	2.9E-03	5.3E-02	1
		CFRP	2.2E-05	491.3	5.3E-02	1.5E-02	2.16	32.9	5.8	4.1E+03	2.8E-09	5.3E-03	7.1E-02	0
		Hybrid	7.5E-06	139.9	2.0E-02	3.7E-03	0.47	11.0	1.8	1.3E+03	1.2E-09	2.4E-03	3.5E-02	0
Scenario 8	LEV-Platoon in RP	Steel	4.6E-06	71.3	1.3E-02	1.3E-03	0.12	6.8	1.1	7.0E+02	9.7E-10	2.1E-03	3.2E-02	10
		Aluminum	5.6E-06	148.8	5.0E-02	3.6E-03	0.16	13.4	21.4	2.7E+04	7.7E-10	2.9E-03	5.3E-02	1
		CFRP	2.2E-05	491.7	5.3E-02	1.5E-02	2.16	33.0	5.9	4.1E+03	2.8E-09	5.3E-03	7.1E-02	0
		Hybrid	7.5E-06	140.3	2.0E-02	3.7E-03	0.47	11.0	1.8	1.3E+03	1.2E-09	2.4E-03	3.5E-02	0

Lowest value in IC within scenario

≤ 10% deviation from lowest value in IC

High – Low: EI in IC

Fig. A.2. Heat map visualizing the minimum absolute life cycle EI of the seat cross member material designs in the best-case scenario.

Scenario	Vehicle	Material	ADP elements in kg SB eq.	ADP fossil in MJ	AP in kg SO_2 eq.	EP in kg PO_4 eq.	FAETP in kg DCB eq.	GWP100 in kg CO_2 eq.	HTP in kg DCB eq.	MAETP in kg DCB eq.	ODP in kg CFC-11 eq.	POCP in kg Ethene eq.	TETP in kg DCB eq.	ICs with lowest value
Scenario 1	ICEV in MIT	Steel	5.1E-06	545.7	6.8E-02	9.1E-03	0.25	43.2	2.2	1.6E+03	1.2E-09	1.9E-02	5.4E-02	6
		Aluminum	6.3E-06	536.9	1.0E-01	1.0E-02	0.27	43.4	26.9	3.4E+04	9.3E-10	1.6E-02	7.6E-02	2
		CFRP	2.7E-05	913.3	1.0E-01	2.4E-02	2.71	64.1	7.8	5.6E+03	3.4E-09	1.7E-02	9.7E-02	0
		Hybrid	8.7E-06	539.8	6.5E-02	1.1E-02	0.66	41.5	2.9	2.2E+03	1.4E-09	1.6E-02	5.4E-02	3
Scenario 2	small BEV in MIT	Steel	6.3E-06	477.2	9.8E-02	9.7E-03	0.17	46.9	2.5	5.1E+03	1.3E-09	9.2E-03	6.8E-02	5
		Aluminum	7.3E-06	483.8	1.2E-01	1.1E-02	0.21	46.3	27.1	3.6E+04	9.9E-10	8.7E-03	8.7E-02	1
		CFRP	2.8E-05	866.7	1.2E-01	2.4E-02	2.65	66.6	8.0	7.9E+03	3.5E-09	1.1E-02	1.1E-01	0
		Hybrid	9.7E-06	484.8	9.0E-02	1.1E-02	0.59	44.5	3.1	5.0E+03	1.5E-09	8.3E-03	6.6E-02	5
Scenario 3	small BEV in RH	Steel	9.1E-06	1172.1	2.4E-01	2.4E-02	0.22	116.3	5.0	1.3E+04	1.4E-09	2.1E-02	1.2E-01	3
		Aluminum	9.4E-06	1022.0	2.4E-01	2.2E-02	0.25	100.0	29.0	4.2E+04	1.1E-09	1.8E-02	1.3E-01	4
		CFRP	3.0E-05	1340.2	2.2E-01	3.4E-02	2.68	113.9	9.7	1.3E+04	3.6E-09	1.9E-02	1.4E-01	0
		Hybrid	1.2E-05	1043.0	2.1E-01	2.3E-02	0.63	100.2	5.1	1.1E+04	1.6E-09	1.8E-02	1.1E-01	4
Scenario 4	midsize BEV in MIT	Steel	6.4E-06	500.1	1.0E-01	1.0E-02	0.17	49.2	2.6	5.3E+03	1.3E-09	9.6E-03	6.9E-02	5
		Aluminum	7.4E-06	501.6	1.3E-01	1.1E-02	0.21	48.1	27.1	3.6E+04	9.9E-10	9.0E-03	8.8E-02	1
		CFRP	2.8E-05	882.3	1.2E-01	2.5E-02	2.65	68.2	8.0	8.1E+03	3.5E-09	1.1E-02	1.1E-01	0
		Hybrid	9.8E-06	503.2	9.4E-02	1.1E-02	0.59	46.3	3.2	5.2E+03	1.5E-09	8.6E-03	6.7E-02	5
Scenario 5	midsize BEV in RH	Steel	9.5E-06	1285.8	2.7E-01	2.7E-02	0.23	127.6	5.4	1.4E+04	1.4E-09	2.3E-02	1.3E-01	3
		Aluminum	9.8E-06	1110.1	2.6E-01	2.4E-02	0.25	108.8	29.3	4.3E+04	1.1E-09	1.9E-02	1.3E-01	5
		CFRP	3.0E-05	1417.6	2.4E-01	3.6E-02	2.69	121.6	9.9	1.4E+04	3.6E-09	2.0E-02	1.5E-01	0
		Hybrid	1.2E-05	1134.4	2.3E-01	2.5E-02	0.63	109.3	5.5	1.2E+04	1.6E-09	1.9E-02	1.1E-01	3
Scenario 6	E-minibus in RP	Steel	1.4E-05	2495.7	5.2E-01	5.2E-02	0.31	248.3	9.7	2.7E+04	1.7E-09	4.3E-02	2.2E-01	1
		Aluminum	1.3E-05	2047.1	4.5E-01	4.3E-02	0.32	202.2	32.7	5.4E+04	1.3E-09	3.5E-02	2.0E-01	5
		CFRP	3.3E-05	2242.0	4.1E-01	5.3E-02	2.74	203.8	12.9	2.3E+04	3.8E-09	3.4E-02	2.1E-01	2
		Hybrid	1.6E-05	2106.2	4.3E-01	4.5E-02	0.70	206.3	9.0	2.3E+04	1.8E-09	3.6E-02	1.8E-01	3
Scenario 7	LEV in RH	Steel	7.9E-06	881.2	1.8E-01	1.8E-02	0.20	87.3	3.9	9.6E+03	1.3E-09	1.6E-02	9.7E-02	3
		Aluminum	8.6E-06	796.7	1.9E-01	1.7E-02	0.23	77.5	28.2	4.0E+04	1.1E-09	1.4E-02	1.1E-01	3
		CFRP	2.9E-05	1141.9	1.8E-01	3.0E-02	2.67	94.1	9.0	1.1E+04	3.5E-09	1.6E-02	1.3E-01	0
		Hybrid	1.1E-05	809.3	1.6E-01	1.8E-02	0.61	76.9	4.3	8.6E+03	1.6E-09	1.4E-02	8.9E-02	5
Scenario 8	LEV-Platoon in RP	Steel	8.0E-06	906.3	1.9E-01	1.9E-02	0.20	89.8	4.0	9.8E+03	1.3E-09	1.6E-02	9.9E-02	3
		Aluminum	8.6E-06	816.1	1.9E-01	1.8E-02	0.23	79.4	28.3	4.0E+04	1.1E-09	1.4E-02	1.1E-01	3
		CFRP	2.9E-05	1159.0	1.8E-01	3.0E-02	2.67	95.8	9.0	1.1E+04	3.5E-09	1.6E-02	1.3E-01	0
		Hybrid	1.1E-05	829.5	1.6E-01	1.8E-02	0.61	78.9	4.4	8.8E+03	1.6E-09	1.4E-02	9.1E-02	5

Lowest value in IC within scenario

≤ 10% deviation from lowest value in IC

High

Low

EI in IC

Fig. A.3. Heat map visualizing the maximum absolute life cycle EI of the seat cross member material designs in the worst-case scenario.

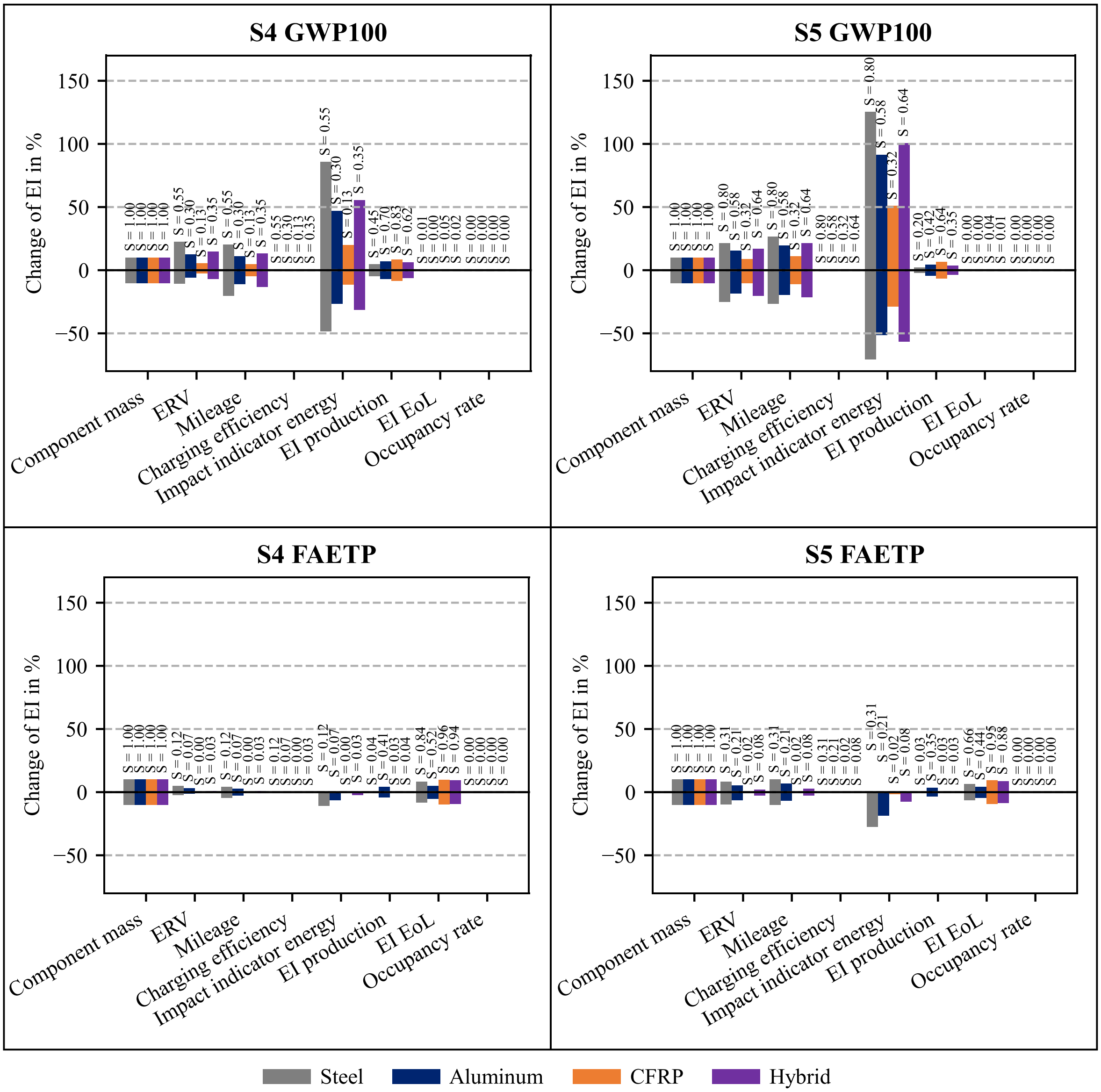

Fig. A.4. Sensitivity of absolute EI in ICs GWP and FAETP for use stage scenarios 4 (S4) and 5 (S5). The bars illustrate the relative change in EI based on the variation of the input parameters around the mean value according to Table A.6. The indicated sensitivity measures S result from the ratio of the relative change in EI and the relative variation of the input parameter.

Data availability

Data will be made available on request.

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