

Article

Influence of Parameter Uncertainties in Carbon Footprint Assessments on the Magnitude of Product-Related Ecological Measures

Scalli Rommelfanger ^{1,2,*} , Sebastian Kilchert ²  and Stefan Hiermaier ² 

¹ Porsche AG, Porschestraße 911, 71287 Weissach, Germany

² Institute for Sustainable Systems Engineering (INATECH), Albert-Ludwigs-Universität Freiburg, Emmy-Noether-Straße 2, 79110 Freiburg im Breisgau, Germany; sebastian.kilchert@inatech.uni-freiburg.de (S.K.); stefan.hiermaier@inatech.uni-freiburg.de (S.H.)

* Correspondence: scally.rommelfanger@porsche.de

Abstract: This study seeks to provide guidance on how top-down greenhouse gas emission reduction targets (GHG ERTs), deriving, for example, from corporate decarbonization strategies, can be translated into quantifiable targets for component measures. Furthermore, it shows how these targets need to be adjusted during the development process to account for parameter uncertainties resulting from the lack of data availability and validity in the early design stage. The scope of the analysis focuses on ecological measure magnitude (EMM) targets for mass reduction and the content of recycled material. The study is split into two sections: The first section introduces a method on how to calculate EMMs based on a partial carbon footprint assessment (CFPA). The second and main section elaborates on an analysis of how parameter uncertainties in the CFPA influence initially defined EMM targets by using perturbation analysis. In the presented paper, the method is applied exemplarily to an automotive component in an internal combustion engine vehicle. The study shows that a parameter uncertainty in the environmental impact of the mass-induced use phase or the primary material production (and semi-finished product provision) has a significant influence on the required EMMs. In the authors' opinion, this study can increase the awareness of how CFPA parameter uncertainties can affect the credibility of EMM development targets. The used approach can help designers and engineers to minimize the risk of a non-fulfillment of GHG emission-related development targets.

Keywords: carbon footprint assessment; parameter uncertainties; perturbation analysis; greenhouse gas emission reduction; ecological measures; sensitivity analysis; sustainable design; ecological measures; measure magnitudes; parameter uncertainties LCA



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1. Introduction

The anthropogenic climate change caused by greenhouse gas (GHG) emissions, like CO₂, is one of the biggest challenges for mankind. To limit the impact of global warming, the European Union (EU) agreed on the Paris Climate Agreement in 2015 with the main objective to hold “the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” [1]. In addition, through the European Green Deal, the EU is striving to achieve climate neutrality, with a target of net-zero GHG emissions by 2050 [2].

To achieve this goal, the Sustainable and Smart Mobility Strategy of the EU includes the target of net-zero emissions by 2050 for “nearly all cars, vans, buses as well as new heavy-duty vehicles” [3]. Several studies show that in addition to the legal requirements, climate change, energy security concerns, the shortage of resources as well as increasing prices for resources are the main drivers for the automotive industry to reduce its GHG emissions [4–6]. According to an analysis by Poligkeit et al. [7], many original equipment

manufacturers (OEMs) have already implemented decarbonization strategies in their corporate strategy. As GHG emissions from the use phase account for a large percentage of the total emissions of an internal combustion engine vehicle (ICEV), many automotive companies have, so far, focused on the electrification of the powertrain [8]. In an analysis of C-segment vehicles, Hannon et al. [8] highlighted that, due to the steadily increasing market share of electric cars, the share of use phase emissions will decrease, while the relative share of material emissions in total vehicle emissions will increase from about 18% in 2020 to about 60% in 2040. OEMs will, therefore, have to focus their decarbonization strategy not only on the use phase of the vehicle but also on the design and material selection of the individual components [8].

In order to achieve a reduction in GHG emissions, it is important for development teams to have specific component (design) related targets so that they can consider them in conjunction with other product objectives such as safety, quality, or costs. This research seeks to provide guidance for development teams on how top-down GHG emission reduction targets (ERT), derived, for example, from decarbonization strategies, can be translated into quantifiable magnitude targets for component measures. The scope of the analysis focuses on magnitude targets for mass reduction and the content of recycled material. Furthermore, this research pays special attention to the influence of uncertainties on the derived magnitude targets. The approach is based on a partial carbon footprint assessment (CFPA) according to EN ISO 14067:2018 [9]. As data availability and validity may be lacking in the early design phase [10,11], assumptions have to be made for the CFPA required process- and component-specific parameters (e.g., the components scrap rate, the energy demand of the components' manufacturing process, and the powertrain concept in the use phase). These assumptions could be subject to uncertainties, especially in early design phases, that directly affect the validity of the derived development targets for the ecological measure magnitudes (EMM, e.g., mass reduction, recycled content). In order to still meet a set GHG ERT, it may be necessary to adjust the EMMs at later stages of product development; otherwise, the GHG ERT may not be met. Since the degree of freedom for design changes decreases and the associated costs and effort increase during the development process [11], a required adjustment of the EMMs becomes more difficult in later phases of the development process. Since decision-making has a significant influence in the early design phase and component adaptations can be made cost-efficiently [11], the authors propose the necessity of accounting for parameter uncertainties in the early design phase.

In Section 2, the authors provide a literature review and discuss the current research gap. Section 3 covers the calculation basis and gives a brief overview of the visualization methods used. The case study in Section 4 elaborates on an arbitrary aluminum sheet component using a perturbation analysis to examine the influence of parameter uncertainties on GHG ERT-required EMMs. To increase the comprehensibility and better illustrate the applicability, a generic use case is presented in Section 5. Although the analysis is exemplarily conducted for an aluminum sheet component, the method presented is not limited to this scope and could easily be adapted to non-automotive products.

2. Literature Review

This section covers the definition of ecological measures and shows how they can be used to lower the environmental impact of products. It additionally gives a brief but comprehensive overview of how uncertainties are classified and incorporated in life cycle assessments (LCAs).

2.1. Ecological Measures to Reduce a Product's Carbon Footprint

The term *product-related ecological measure* is introduced in this work to refer to measures that reduce the overall carbon footprint (CFP) of a product and have a direct impact on the macroscopic or microscopic properties of the selected product. They do not consider the use of energy from renewable sources to reduce GHG emissions. The considered ecological measures (mass reduction and use of recycled material) are to be understood as examples

to show the applicability of the presented method. The authors point out that the method is not limited to these two measures. The selected product-related ecological measures can be used individually or in combination to contribute to a GHG mitigation strategy. It should be noted that the magnitude of each ecological measure needs to be chosen in line with other component requirements (e.g., quality, safety, stiffness).

Mass reduction: A reduction in GHG emissions through mass reduction can be achieved through various lightweight measures, like a material substitution, a load-adaptive structural design, or an increased knowledge of the load collective [12]. Since a material substitution does not automatically lead to a lower embodied impact, it is excluded as a mass reduction measure in this work.

Recycled material: Recycled material is divided into the categories of pre- and post-consumer waste, depending on whether it comes from industrial processes or recovery from end-of-life products. Before being used in the manufacturing process, the recycled material goes through a collecting, sorting, and recycling process, which is briefly summarized as the recycling process. The complexity of the recycling process may depend on the degree of impurities of the used material. In general, the use of recycled material promotes the responsible use of finite resources by substituting virgin material. It results in a reduction in energy needed for the extraction and production of the primary material and, thus, in a reduction in GHG emissions [13–17].

Several authors have investigated the influence of measures on the environmental impact of a vehicle, with a primary scope on either lightweight design, material selection, or both in combination as primary measures [18–29]. Mayyas et al. [24] proposed, for example, a method for the material selection of lightweight ecological designs for the body-in-white. Gallimore and Cheung [25] investigated the influence of different manufacturing processes and materials on the footprint of an automotive component. All the named studies have in common that an LCA is used to determine how successful certain measures are in reducing the ecological impact of a product. If a new product needs to be developed from scratch, the development process starts with an assessment of targets for the development teams. Vehicle mass targets and, thus, processes for weight management are common practices in automotive development processes [30]. In addition, targets for the magnitude of recycled content, derived, for example, from regulations (see European Commission proposal [31]) or corporate strategies can be implemented in development processes.

The authors propose that LCAs could not only be used to determine the impact of ecological measures on the CFP but also vice versa to determine the required magnitude of product-related ecological measures in GHG ERT-driven development processes. Thus, the assessment could be easily used to derive development targets for EMMs. So far, no studies on this topic have been found in the existing literature.

2.2. The State of the Art of Uncertainties in Life Cycle Assessments and the Necessity for User-Friendly Approaches

LCAs are subject to uncertainties that need to be handled to ensure the reliability of LCA results, especially when the results are used for decision-making [32–35]. One of the first works that considered uncertainties in LCAs and their influence on the results was done by Huijbregts [34], who developed a framework to apply variability and uncertainty analysis. The considered types of LCA uncertainties were through choices, model uncertainties, and parameter uncertainties. Uncertainties due to choices cover, for example, the choice of the allocation method and functional unit. Model uncertainties can occur when the model is not complex enough to consider complex processes like the fate of substances. Whereas parameter uncertainties could result from unrepresentative, missing, or imprecise data [34].

Weyand et al. [36] analyzed the influence of different uncertainty factors derived from comparing the common CFP accounting standards. Ross et al. [37] emphasized that neglecting uncertainties in LCAs can lead to false conclusions and misinterpretations. They also stated the importance of the integration of qualitative uncertainty discussions in the ISO 14040 series of standards. In the work by Björklund [38] methods were summarized to predict the influence of uncertainties. Furthermore, the application of these methods in LCA studies was discussed. According to Igos et al. [35], the reliability of LCA results needs to be increased by raising awareness of uncertainties. If decisions are led by LCA results, the reliability of the results should be clear [33]. This is concluded as well by Guo and Murphy [39] who recommended an explicit interpretation of LCA uncertainties for robust decision-making. Thonemann et al. [40] determined that the highest uncertainties regarding LCA occur in the early phase, where decisions have the most impact on the technology. Heijungs and Kleijn [32] presented techniques to analyze the reliability of LCA results. They subdivided the numerical approaches into different types of algorithms. If the uncertainty magnitudes are known in advance, they suggested an uncertainty analysis based on Monte Carlo simulations for a single product alternative or discernibility analysis if the scope included several product alternatives. Heijungs and Kleijn [32] suggested, for a single product alternative, a perturbation analysis to calculate the gradients based on the input parameters or a contribution analysis to estimate the weighting of different impacts if the uncertainty magnitudes are unknown. If the scope included various product alternatives, they recommended a comparative analysis as the method of choice.

The perturbation analysis, also known as marginal analysis, is based on the propagation of small perturbations applied to the input parameters. The ratio between a percentual input parameter change and the percentual output result change describes the sensitivity and can be helpful in classifying the importance of the parameter. An advantage of a perturbation analysis is that there is no need to know the exact uncertainty ranges of the input parameters [32,35].

In a meta-review with a scope of 2687 journal articles published between 2014 and 2018, Bamber et al. [41] determined that only a minority of the published LCA case studies have considered parameter uncertainties even if multiple techniques to handle LCA uncertainties had become available in the meantime. They determined that even if there might be methods that are more time-efficient, the most common technique is the use of Monte Carlo sampling. It is mentioned by Igos et al. [35] that perturbation analysis can be applied to more simple than complex procedures like Monte Carlo simulations. Furthermore, Bamber et al. [41] concluded that Monte Carlo samplings should not be used as a default method—moreover, the practitioners should choose the most applicable method. Mahmood et al. [42] proposed incorporating uncertainty consideration with a three-level framework based on the experience of the practitioner.

2.3. Influence of Uncertainties on Ecological Measure Magnitude Targets

It is widely known that uncertainties can have a major impact on LCA results. If EMMs are estimated in GHG ERT-driven development processes by an LCA (or a CFPA), the authors proposed an approach to consider the influence of parameter uncertainties. The novel approach is based on a streamlined CFPA in combination with a perturbation analysis. This approach can be used to increase the robustness and validity of development targets that are derived from GHG emission mitigation strategies. To reach a broad audience of users and to increase the usage of the method, the authors strived for a user-friendly approach that could be easily implemented in product development processes. Björklund [38] emphasized that streamlined tools, even if they have drawbacks in accuracy, are important because of their higher acceptance by practitioners. This was explained as being due to user-friendly approaches being applied more often and, therefore, having a higher impact in the long run [38].

3. Materials and Methods

This section gives a step-by-step explanation of the authors' approach (Section 3.1), an overview of the method used and its assumptions (Sections 3.2 and 3.3) and concludes with an explanation of the visualization methods used (Section 3.4). The calculation and visualization were conducted by using Python 3.11 with plotly 5.15 library.

3.1. Influence of CFPA Parameter Uncertainties on the Magnitude of Ecological Measures

The authors' approach to exploring the influence of CFPA parameter uncertainties on the EMMs derived from top-down GHG ERTs can be divided into the following three steps:

Step 1: A fixed GHG ERT derived, for example, top-down from a company's decarbonization strategy, can be set as an objective for the development of a new generation component compared to a reference component. The reference component can be a predecessor component or, if no predecessor component exists, a baseline of the new component without environmental measures (Figure 1—step 1). This means that the user can deal with either a redesign or a design from scratch of a component;

Step 2: The estimation of the EMMs that are required to meet the GHG ERT (Figure 1—step 1) is based on a CFPA. Calculating the EMMs (Figure 1—step 2) early in the development process at timestamp $t = t_0$ requires that initial assumptions have to be made for several product- and process-related parameters $x_1(t_0)$, such as the expected environmental impact of the components manufacturing process E_M or the scrap rate p_S . Due to the limited data availability and validity in the early stage of the development process, the parameter assumptions $x_1(t_0)$ for the next-generation component can be adapted from a potential predecessor component x_0 or be based on empirical values or data from LCA databases. It should be noted that there is not just one EMM combination that is valid for meeting the GHG ERT. In fact, the most appropriate combination of mass reduction measures and recycled content depends mostly on the overall component requirements;

Step 3: As the development process progresses and the component design is finalized, parameter availability and validity increase [10,11]. An uncertainty in the CFPA parameters directly influences the magnitude of mass reduction or recycled material actually required to fulfill the GHG ERT. Therefore, it is necessary to review the initially assumed EMM targets (Figure 1—step 2) with the actual magnitudes that are required to meet the set GHG ERT (Figure 1—step 3).

In general, there are three potential scenarios to distinguish (Figure 1—step 3b): Scenario 1: No adjustment of the EMM is required as there is no difference between the assumed (Figure 1—step 2) and the actual CFPA parameters ($x_1(t_1) = x_1(t_0)$). Scenario 2: In this case, the actual CFPA parameters are lower than the initially assumed ones ($x_1(t_1) < x_1(t_0)$). The GHG ERT would still be met, even if the EMMs were reduced to a certain level, for example, in favor of other component requirements, such as an improvement in the vehicle crashworthiness by increasing the mass. If all component requirements are fulfilled, there is no need to reduce the EMMs. Scenario 3: In this scenario, it is assumed that the actual CFPA parameters are higher than the initially assumed ones ($x_1(t_1) > x_1(t_0)$). This is crucial information for the development, as meeting the GHG ERT now requires an increase in the EMMs ($p_{MR,1}(t_1) > p_{MR,1}(t_0)$ and/or $p_{R,1}(t_1) > p_{R,1}(t_0)$).

It is important to note that the EMMs cannot be changed at any point in the development process. Increasing the recycled content or reducing the mass above a certain threshold could compromise the component's performance requirements (e.g., quality, crashworthiness, stiffness). Furthermore, the costs associated with EMM adaptations increase as the development process progresses. The authors, therefore, suggest preparing for downsides from uncertainties already in the early design phase, where changes to a component can be made cost-effectively [10].

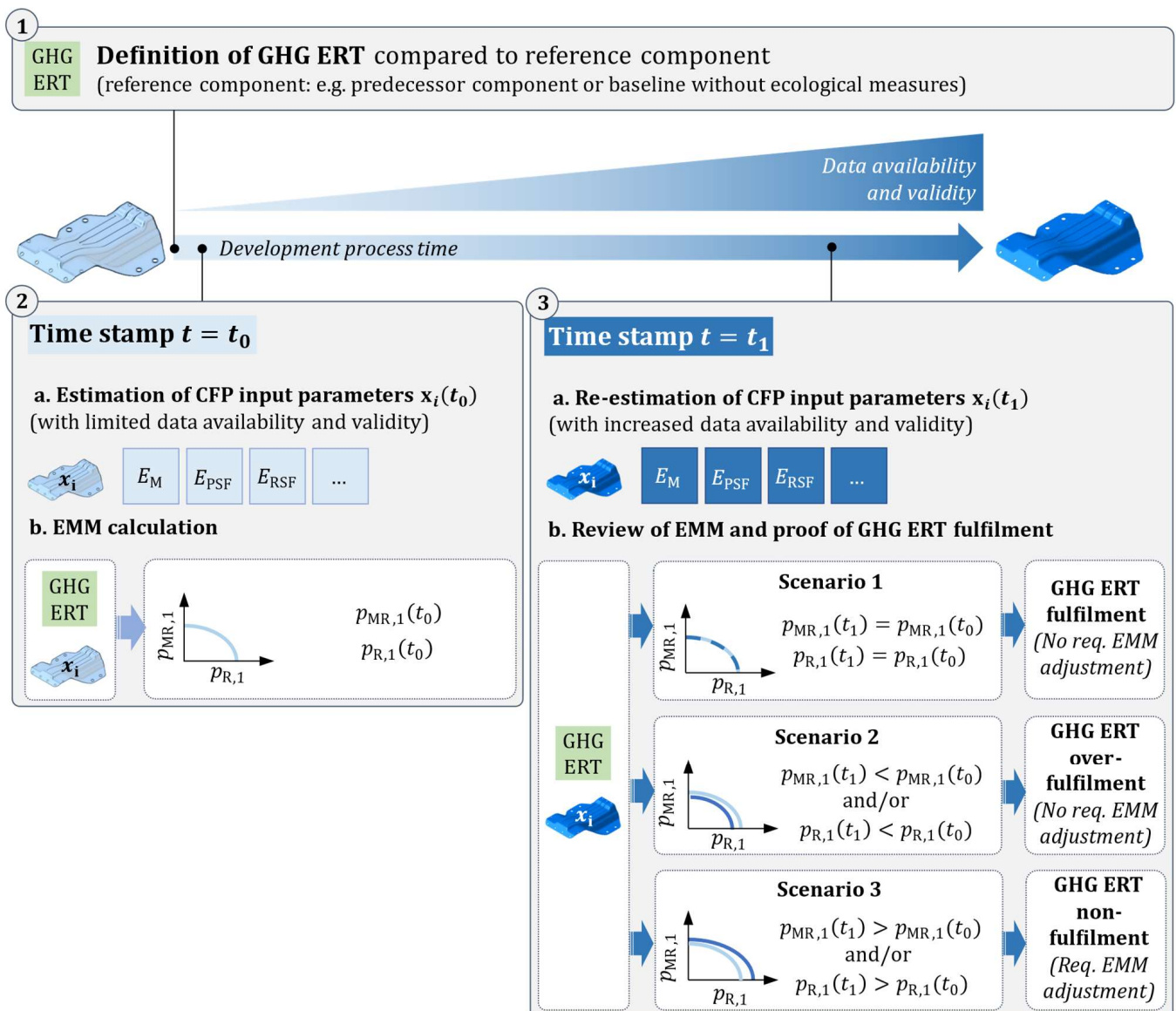


Figure 1. Possible scenarios of carbon footprint assessment (CFPA) parameter uncertainties and their implications on the ecological measure magnitudes (EMM).

3.2. CFPA Calculation Basis

Due to the large amount of prevailing literature on the topic of LCAs and CFPAs, a detailed definition has been omitted in this paper, and the common ISO standards (e.g., DIN EN ISO 14040:2021-02 [43], DIN EN ISO 14044:2021-02 [44] and EN ISO 14067:2018 [9]) are recommended to the interested reader.

The streamlined assessment of the CFP was based on EN ISO 14067:2018 [9] recommendations. The Recycled Content approach was used as an allocation method [45]. According to the Recycled Content Approach, the recycled material itself enters the overall balance without any encumbrance, and the benefit of recycling is fully attributed to the component that uses recyclables [45]. The use of recycled material only has to account for emissions that are generated during the recycling process of the material [45]. The streamlined partial CFPA considers the raw material acquisition, semi-finished product provision, the manufacturing process, and the use phase. The end-of-life and the transport/logistics of the product have been neglected in this case study, which is in line with Kaebemick et al. [46], who stated that the phase of raw material acquisition and the use phase have, for most of the products, the highest relevance when considering their environmental impact. It is

important to consider that the scope of investigation and, thus, the considered stages in the life cycle of the product could be easily extended to analyze further parameter interactions. This also applies to the considered ecological measures. The limitation of the considered life cycle stages and selected EMMs is only intended for simplification. It should be noted that the presented equations are of general value and are not limited to automotive components (despite the calculation in phase 3). To simplify scalability and comparability, the declared unit of the streamlined partial CFPA was a one-kilogram component mass. The scope of the investigation and the reference flow of the partial CFPA are shown in Figure 2.

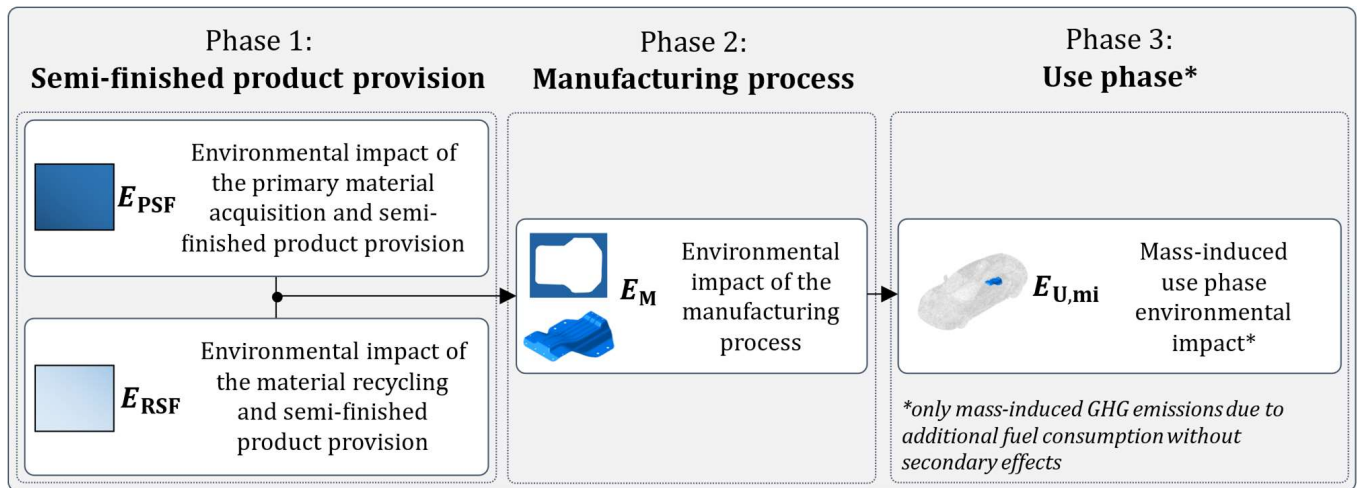


Figure 2. Partial component CFPA scope of investigation: Stages of the product life cycle considered in the system boundary (note: The component shown only serves to illustrate the scope and does not serve as the basis for the following calculations.).

The calculation for the three phases in the scope of investigation is described in the following:

Phase 1 + Phase 2: The first phase of the investigated scope included the GHG emissions of the primary material acquisition and the ecological impact of the semi-finished product provision (e.g., bar, coil, ingot) $e_{PSF,i}$. Moreover, the CFPA of the first phase included (partially) the environmental impact of the material recycling and semi-finished product provision $e_{RSF,i}$. The environmental impact of the manufacturing process $e_{M,i}$ of the component (extrusion, deep drawing, casting, injection molding, etc.) was assigned to the second phase of the investigated scope. The environmental impact (CFP) of the first two phases E_{P1+P2} can be expressed as follows, taking into account the required material input mass $m_{in,i}$:

$$E_{P1+P2} = m_{in,i} * ((1 - p_{R,i}) * e_{PSF,i} + p_{R,i} * e_{RSF,i} + e_{M,i}) \quad (1)$$

with

$$e_{PSF,i} = e_{P,i} + e_{SF,i} \quad (2)$$

$$e_{RSF,i} = e_{R,i} + e_{SF,i} \quad (3)$$

Phase 3: The third phase of the CFPA scope incorporated the use phase emissions due to mass-induced fuel consumption. The calculation of fuel consumption as well as exhaust gas emissions of a component can be found in various studies [47–51]. According to Eberle and Franze [52], the use phase fuel consumption can be subdivided into mass-dynamic factor and mass-static factors. The mass-dynamic factor is dependent on mass and, therefore, reducible by a mass reduction. It describes the mass-induced fuel consumption. Whereas the mass-static factor (mass independent) represents the fuel consumption occurring from friction and secondary energy use [52].

To predict the impact of the component's use phase, an appropriate method can be found in the work of the European Council for Automotive R&D (EUCAR) LCA project, which is based on research done by Ridge [53]. In general, the work distinguished between an incremental and a proportional method. The incremental method only takes the mass-induced resistance into account and is suggested to be used for mass changes smaller than 20% of the total vehicle mass [53]. A methodology to determine the fuel consumption based on the incremental method of a single component can be found in the work of Koffler and Rohde-Brandenburger [47]. According to this work, for a gasoline engine, the fuel that is needed to move one unit of mass one kilometer (based on engine physics and laws of motion without friction losses) is

$$V_{100\text{kg},\text{NEDC},i} = 0.15 \text{ L} / (100 \text{ km} * 100 \text{ kg}) \quad (4)$$

which is in line with the findings by Ridge [53].

The mass-induced environmental impact of the use phase can be calculated by multiplying $V_{100\text{kg},\text{NEDC},i}$ with the component's mass (output mass), the vehicle's mileage, the fuel emission factor, and the fuel's density:

$$E_{P3} = m_{\text{out},i} * d_{\text{m},i} * V_{100\text{kg},\text{NEDC},i} * i_{\text{F},i} * \rho_{\text{F},i} = m_{\text{out},i} * e_{\text{U},\text{mi},i} \quad (5)$$

Koffler and Rohde-Brandenburger [47] pointed out that mass-induced fuel consumption accounts for approximately 31% of the total use phase emissions for an exemplary Golf VI. Assuming that the mass change for a specific component is less than 20% of the total vehicle mass, this work only considered the mass-induced fuel consumption derived from the mass-dynamic factor and, furthermore, did not incorporate secondary effects. Secondary effects mean, for example, a change in the gear ratios or engine parameters derived as a result of a mass reduction to lower emissions by still fulfilling the same vehicle performance indicators. The authors suggested this simplification in line with the research by Ridge [53]. Due to the approach of Ridge [53] and Koffler and Rohde-Brandenburger [47], the CFP of phase 3 (without secondary effects and a component mass change <20% vehicle mass) can be incorporated into the CFPA according to Equation (5).

CFPA of the component: The total component CFP E_i is the sum of the considered environmental impacts of the three phases (P_i) included in the scope of investigation.

$$E_i = E_{P1} + E_{P2} + E_{P3} \quad (6)$$

Considering possible product-related ecological measures, such as the use of recycled material $p_{\text{R},i}$ or mass reduction $p_{\text{MR},i}$, the specific component CFP e_i (per unit output mass) for the investigated scope is expressed as follows:

$$e_i = (1 - p_{\text{MR},i}) * (1 / (1 - p_{\text{S},i}) * ((1 - p_{\text{R},i}) * e_{\text{PSF},i} + p_{\text{R},i} * e_{\text{RSF},i} + e_{\text{M},i}) + e_{\text{U},\text{mi},i}) \quad (7)$$

with

$$e_i = E_i / m_{\text{out},i} \quad (8)$$

The scrap rate $p_{\text{S},i}$, which includes manufacturing waste like cuttings, in Equation (7) describes the relationship between the required input mass $m_{\text{in},i}$ and output mass $m_{\text{out},i}$ of the component.

$$p_{\text{S},i} = (m_{\text{in},i} - m_{\text{out},i}) / m_{\text{in},i} \quad (9)$$

If the CFP of an ecologically optimized next-generation component e_1 and a reference component e_0 is compared, the achievable percentual reductions φ of the CFP can be expressed by Equation (10).

$$\varphi(e_0, e_1) = \frac{\Delta e}{e_0} = (e_0 - e_1)/e_0 \quad (10)$$

3.3. Estimation of the GHG ERT Required EMMs and the Uncertainty Derived EMM Adjustments

For the estimation of the required EMMs for the next-generation component (Figure 1—step 2b), Equation (10) needs to be rearranged for the mass reduction $p_{MR,1}$ or the recycled material percentage $p_{R,1}$ or can be solved numerically. The notation of the output parameters and necessary input parameters at the two timestamps, to solve the equations for p_{MR} and p_R , can be found in Table 1.

Table 1. Necessary input parameters for the calculation of the next-generation component EMM targets.

Timestamp Development Process of Next-Generation Component	Output Parameters	Input Parameters	
		Reference Component (x_0)	Next-Generation Component (x_1)
t_0	$p_{MR,1}(t_0), p_{R,1}(t_0)$	$e_{PSF,0}, e_{RSF,0}, e_{M,0}, e_{U,mi,0}, p_{R,0}$	$e_{PSF,1}(t_0), e_{RSF,1}(t_0), e_{M,1}(t_0), e_{U,mi,1}(t_0)$
t_1	$p_{MR,1}(t_1), p_{R,1}(t_1)$	$e_{PSF,0}, e_{RSF,0}, e_{M,0}, e_{U,mi,0}, p_{R,0}$	$e_{PSF,1}(t_1), e_{RSF,1}(t_1), e_{M,1}(t_1), e_{U,mi,1}(t_1)$

If the input parameters x_1 of the next-generation component are subject to uncertainties and, thus, change between two different timestamps in the development process $x_1(t_1) \neq x_1(t_0)$, the required EMMs ($p_{MR,1}(t_1), p_{R,1}(t_1)$) do so as well. The (required) absolute EMM adjustment ($\Delta p_{MR,1}$ and/or $\Delta p_{R,1}$), to still achieve the GHG ERT φ_{RC} , can be calculated with Equations (11) and (12).

$$\Delta p_{MR,1} = p_{MR,1}(x_0, x_1(t_1)) - p_{MR,1}(x_0, x_1(t_0)) \quad (11)$$

$$\Delta p_{R,1} = p_{R,1}(x_0, x_1(t_1)) - p_{R,1}(x_0, x_1(t_0)) \quad (12)$$

To improve readability, a time-dependent representation of the variables (e.g., $p_{S,i} = p_{S,i}(t_i)$) was omitted in all Equations (1)–(10).

3.4. Visualization Methods

To increase the comprehensibility, the two visualization methods used in Sections 4 and 5 will be explained in advance.

Figure 3a shows the possible EMM combinations (absolute values)—mass reduction $p_{MR,1}$ and recycled material share $p_{R,1}$ —that are required to reach a top-down GHG ERT φ_{RC} . This visualization was based on a rearrangement of Equation (10) for $p_{MR,1}$. The graphs (Figure 3a) can be interpreted as follows: Bold line—no CFPA parameter uncertainties (scenario 1: $x_1(t_1) = x_1(t_0)$, Figure 1), Dashed line—CFPA parameter uncertainty that requires an increase in the EMMs to meet the GHG ERT (scenario 3: $x_1(t_1) \neq x_1(t_0)$, Figure 1), Dotted line—CFPA parameter uncertainty, which results in a possible decrease in the EMMs to meet the GHG ERT (scenario 2: $x_1(t_1) \neq x_1(t_0)$, Figure 1).

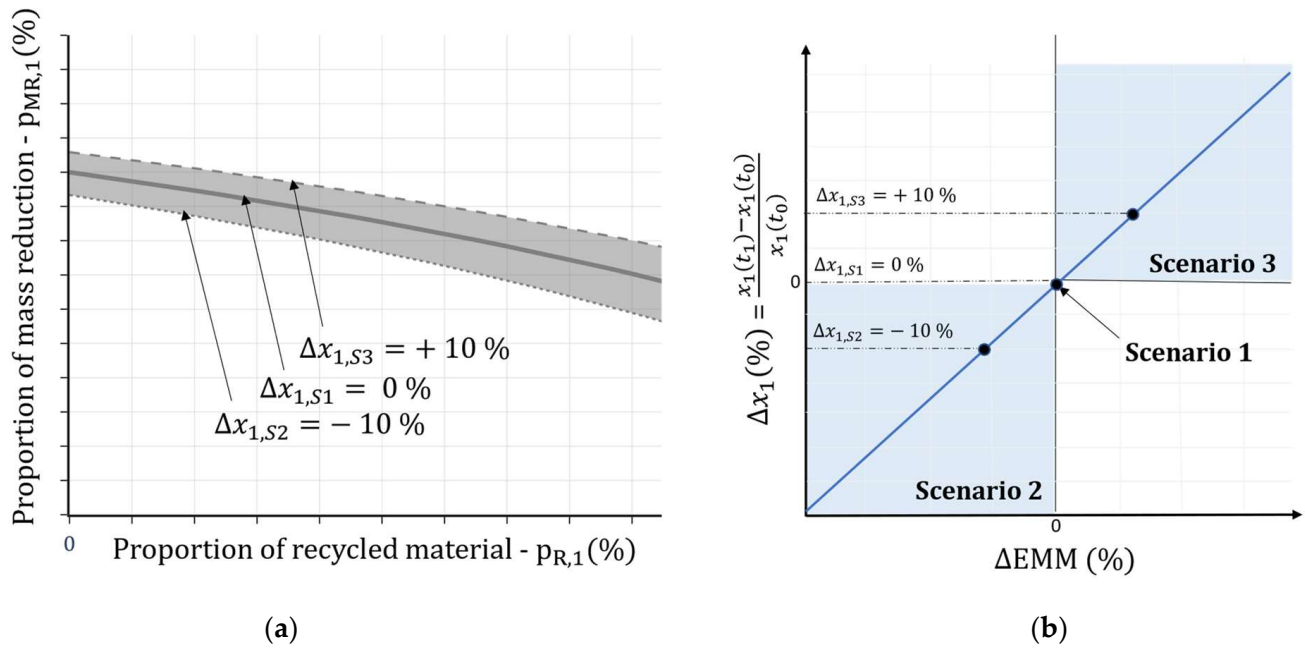


Figure 3. Qualitative example of the visualization methods for a relative parameter uncertainty of $\pm 10\%$ —(a) Required recycled content and mass reduction share for a deviating CFPA parameter x_1 , (b) Resulting required and possible absolute EMM adjustment.

In Figure 3b, the sensitivity of the EMMs (ΔEMM) regarding a CFPA parameter uncertainty (Δx_i) is illustrated. It can be interpreted as the height (EMM: mass reduction) or width (EMM: recycled content) of the colored area in Figure 3a. Figure 3b is based on Equations (11) and (12) and can be interpreted as follows: Origin of the coordinate system—no CFPA parameter uncertainty (scenario 1: $x_1(t_1) = x_1(t_0)$, Figure 1) occurred, so no EMM adjustment is necessary, 3rd quadrant of the coordinate system—CFPA parameter uncertainty, which would make a decrease in the EMMs possible while still fulfilling the GHG ERT (scenario 2: $x_1(t_1) \neq x_1(t_0)$, Figure 1) (note: The GHG ERT is already fulfilled (means reached or exceeded) in this scenario. The additional savings could be used in favor of other components requirements.), 1st quadrant of the coordinate system—CFPA parameter uncertainty that requires an increase in the EMMs to meet the GHG ERT (scenario 3: $x_1(t_1) \neq x_1(t_0)$, Figure 1).

To exclude results where an uncertainty leads to an unrealistic parameter range of the EMMs, two criteria were set to limit the range of validity, Equations (13) and (14).

$$0 \leq p_{MR,i} < 100 \quad (13)$$

$$0 \leq p_{R,i} \leq 100 \quad (14)$$

4. Results—Perturbation Analysis

The investigation of the influence of parameter uncertainties on the magnitude of mass reduction and recycled material was carried out under the assumption that a fixed GHG ERT must be met or exceeded. The GHG ERT has to be met even if there are unexpected changes in the CFPA parameters during the development process. An aluminum sheet component in an ICEV was used as an example for the demonstration. It was assumed that the CFPA parameters of the next-generation component matched the parameters of the reference component in the early design stage ($x_1(t_0) = x_0$). Table 2 shows the CFPA parameter values for $x_1(t_0)$ for the study based on an aluminum sheet component in an ICEV.

Table 2. Default input values for the demonstration of the investigations based on an aluminum (Al) sheet component in an internal combustion engine vehicle (ICEV).

Equation Symbol	Explanation	Value and Unit	Reference
e_P	Environmental impact of the primary material acquisition	Al primary material: 12 kgCO ₂ -eq/kg	[54]
e_{SF}	Environmental impact of the semi-finished product provision	Al sheet production: 0.4 kgCO ₂ -eq/kg	[55]
e_{PSF}	Environmental impact of the primary material and semi-finished product provision	12.4 kgCO ₂ -eq/kg	Calculated with Equation (2)
e_R	Environmental impact of the material recycling process	Al recycling process: 2.1 kgCO ₂ -eq/kg	[54]
e_{RSF}	Environmental impact of the material recycling process and semi-finished product provision	2.5 kgCO ₂ -eq/kg	Calculated with Equation (3)
e_M	Environmental impact of the manufacturing process	Al deformation processing: 0.21 kgCO ₂ -eq/kg	[54]
$V_{100\text{kg,NEDC}}$	Mass-induced fuel consumption ICEV (note: under the assumption of no secondary effects)	0.15 L/(100 km * 100 kg)	[47,53]
d_m	Vehicle lifetime mileage	200,000 km	[53,56]
i_F	Emission factor Super Plus gasoline	3.141 tCO ₂ -eq/t	[57]
ρ_F	Density gasoline	0.75 kg/L	[47]
$e_{U,mi}$	Mass-induced environmental impact in the use phase	≈ 7.07 kgCO ₂ -eq/kg	Calculated with Equation (5)
p_S	Scrap rate	30%	arbitrary
$p_{R,0}$	Recycled material share of the reference component	Al: 43%	[54]

4.1. Influence of a CFPA Parameter Uncertainty on the Required EMM

For the analysis, three arbitrary GHG ERTs (20%, 40%, and 60%) were in the scope of investigation. For each of the relevant CFPA parameters ($e_{U,mi,1}$, $p_{S,1}$, $e_{M,1}$, $e_{PSF,1}$, and $e_{RSF,1}$) perturbation analysis (one-at-a-time variation) was conducted to illustrate parameter uncertainties between −40% and +40%. The uncertainty range was plotted in +/−10% increments and did not necessarily represent real uncertainty values but merely served to visualize the influence of various parameter uncertainty magnitudes. Each diagram represents the influence of a different parameter uncertainty in the CFPA on the three arbitrary GHG ERTs, with the observed parameter highlighted in the top right corner of each diagram (e.g., Figure 4—top left diagram—uncertainty in the mass-induced environmental impact of the use phase $\Delta e_{U,mi}$).

The colored area indicates the sensitivity and, therefore, the (necessary) adjustment to the EMM combinations, resulting from a parameter uncertainty for different GHG ERTs. In general, there is no universal answer to the question of which EMM combination is best, as this depends primarily on the component and its requirements. The width and height of the colored area (sensitivity) depended on both the targeted GHG reduction and the observed CFPA parameter and are further analyzed in Section 4.2.

4.2. Uncertainty-Related Adjustment of Mass Reduction or Recycled Content to Fulfill a GHG ERT

In this section, the (required) EMM adjustment of either the recycled content (width of the colored area, Figure 4) or the mass reduction (height of the colored area, Figure 4) is investigated for the five chosen CFPA parameters. The GHG ERT was set to 40% and the uncertainty range for each CFPA parameter to −40% to +40% in this analysis.

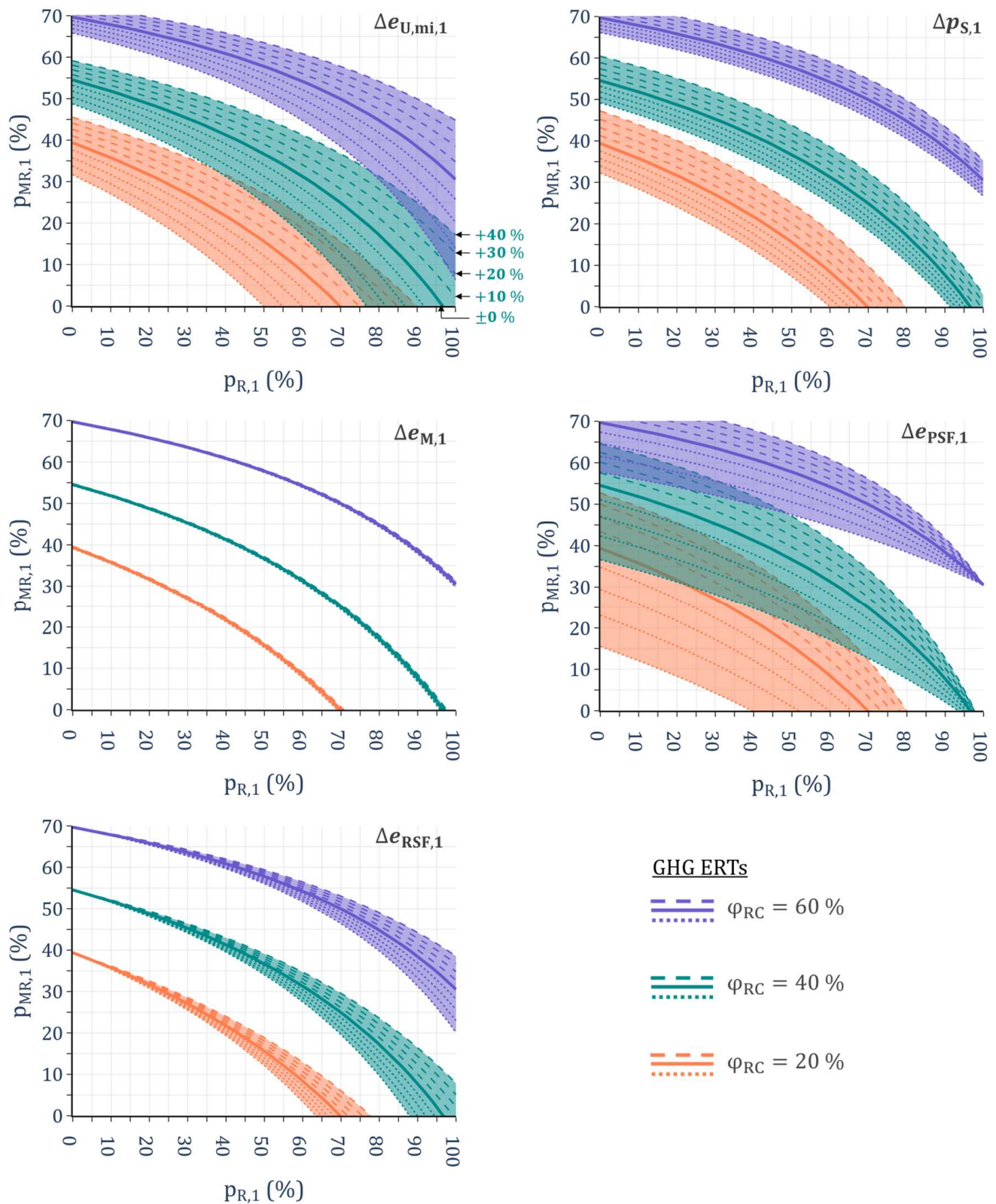


Figure 4. GHG ERT required combinations of EMM for the specific CFPA parameter uncertainties (example: aluminum sheet component in an ICEV).

4.2.1. Uncertainties in the Mass-Induced Use Phase Environmental Impact $\Delta e_{U,mi,1}$

There was a linear relation between an uncertainty in the mass-induced use phase environmental impact and the necessary magnitude adjustment of the recycled material content (Figure 5a). For the chosen parameter set (Table 2), the gradient of the graphs was $\frac{\Delta e_{U,mi}}{\Delta p_R} \approx 0.5$. The length of each graph depended on the set validity range (Equation (14)), in which results were excluded where the recycled content was above 100% or below 0%.

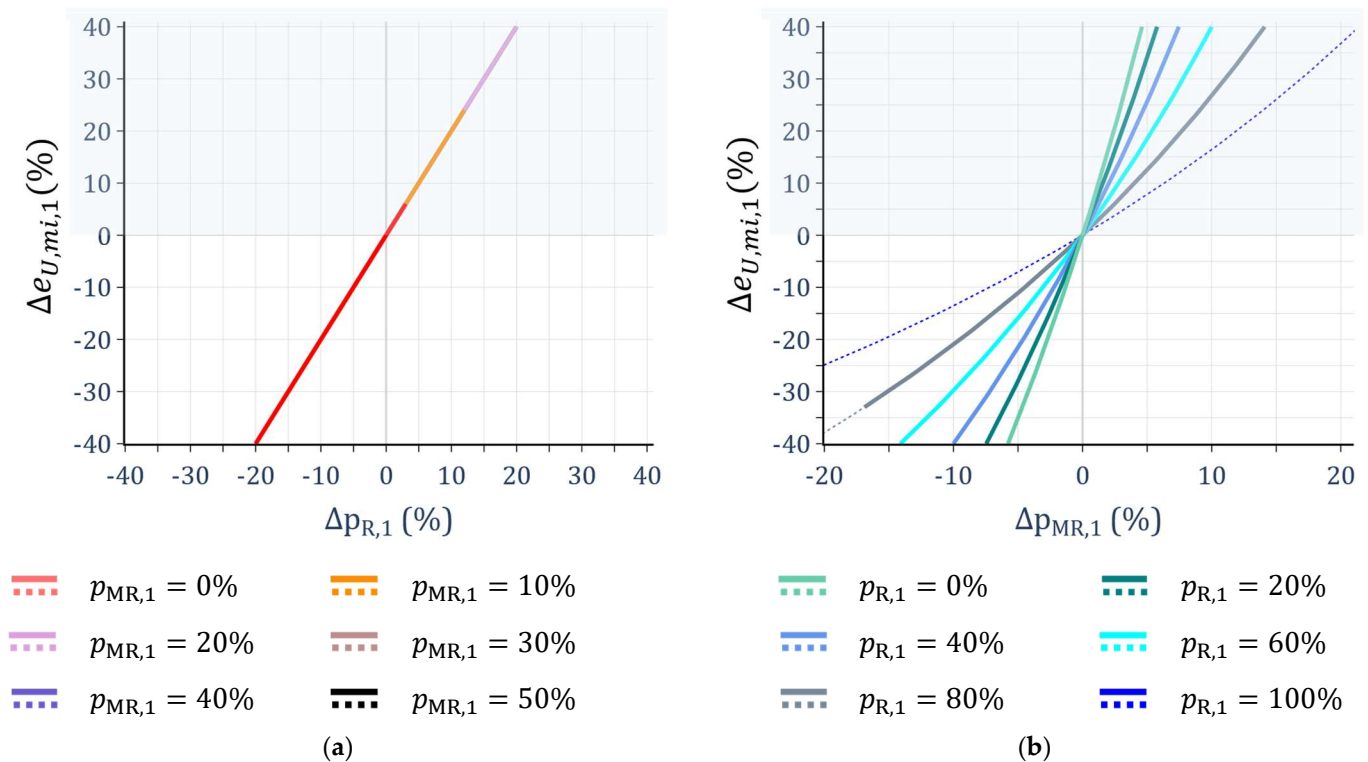


Figure 5. Parameter uncertainty in the mass-induced ecological impact of the use phase $\Delta e_{U,mi,1}$ (GHG ERT: 40%) (a) Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$, (b) Required and possible absolute adjustment of mass reduction magnitude $\Delta p_{MR,1}$.

The mass reduction magnitude adjustment followed a non-linear trend (Figure 5b). The required adjustment increased as the prevailing recycled content increased. This behavior can be explained by taking into account the selected scope of investigation of the CFPA (three phases, Figure 2) and the fixed GHG ERT. The environmental impact of the first two phases decreased as the share of recycled material increased. As the environmental impact of the first two phases decreased, the relative share of the third phase in the total environmental impact of the component increased. This means the more recycled material used, the larger the impact of a CFPA parameter uncertainty in the third phase ($\Delta e_{U,mi}$) on the mass reduction adjustment.

4.2.2. Uncertainties in the Primary Material Acquisition Environmental Impact $\Delta e_{PSF,1}$

Figure 6 shows the EMM adjustments regarding an uncertainty in the ecological impact of the primary material acquisition and semi-finished product provision $\Delta e_{PSF,1}$. There was a nonlinear relation between the $e_{PSF,1}$ uncertainty and the necessary or required magnitude adjustment of the recycled material share (Figure 6a). The adjustment of the recycled material content increased with increasing prevailing mass reduction of the component.

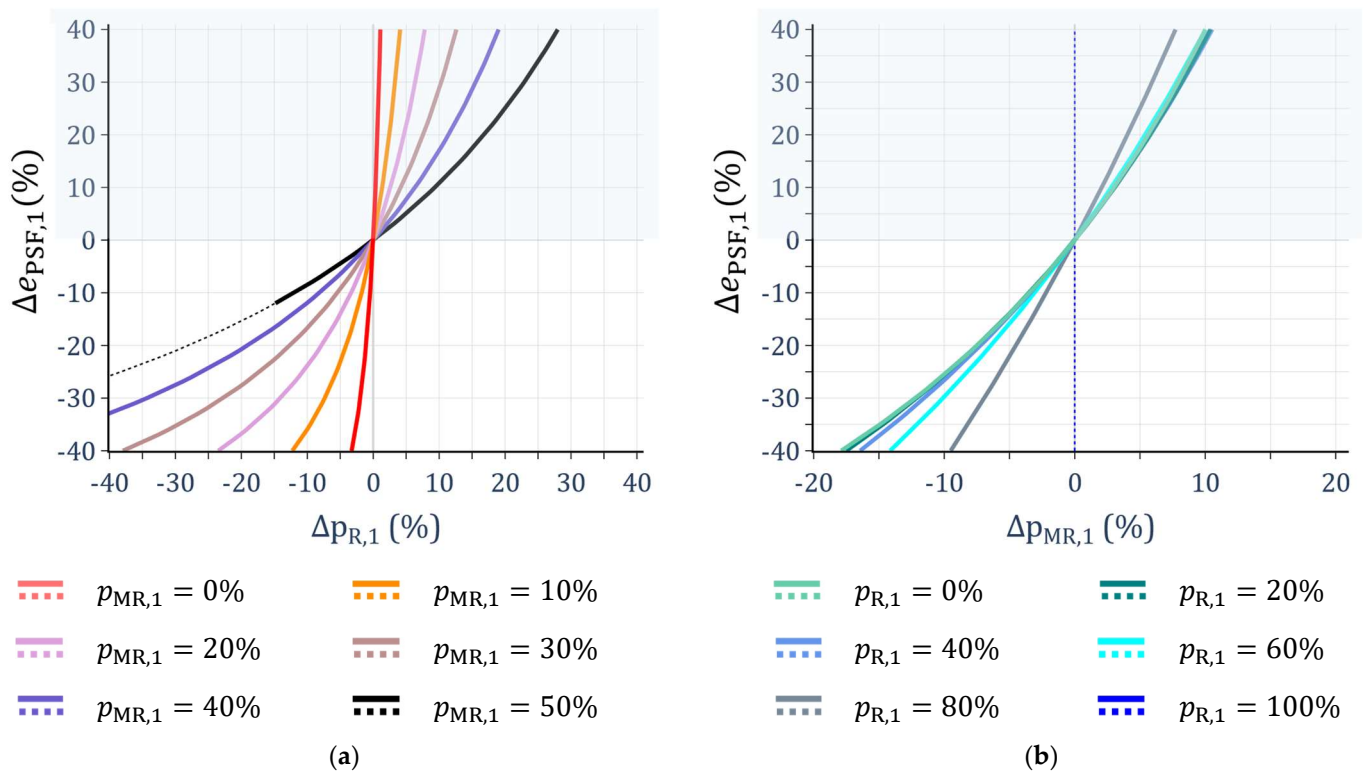


Figure 6. Parameter uncertainty in the environmental impact of the primary material acquisition and semi-finished product provision $\Delta e_{PSF,1}$ (GHG ERT: 40%): (a) Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$, (b) Required and possible absolute adjustment of mass reduction magnitude $\Delta p_{MR,1}$.

There was a nonlinear relation between the $e_{PSF,1}$ uncertainty and the required magnitude adjustment of the mass reduction share as well (Figure 6b). The dotted line represents that the GHG ERT was already over-fulfilled if just recycled material ($p_R = 100\%$) was used. In this case, even an $e_{PSF,1}$ uncertainty of +40% would not threaten the fulfillment of the set GHG ERT (Figure 6b).

4.2.3. Uncertainties in the Scrap Rate $\Delta p_{S,1}$

Considering an uncertainty in the scrap rate, the recycled material adjustment behavior was linear for the given parameter set (Figure 7a). An uncertainty in the scrap rate up to 40% required an absolute adjustment of the recycled material share up to 20% (Figure 7a) in dependency on the prevailing mass reduction.

For the mass reduction measure, an uncertainty of up to 40% required an adjustment below 7% (Figure 7b). For both ecological measures, the required or possible adjustment of one measure increased with an increasing magnitude of the other measure. This effect was stronger for a recycled content adjustment.

4.2.4. Uncertainties in the Recycling Material Environmental Impact $\Delta e_{RSF,1}$

The possible and required adjustments to the EMMs regarding an uncertainty in the ecological impact on the recycling process environmental impact $e_{RSF,1}$ is shown in Figure A1. The adjustment of the recycled content increased with decreasing level of mass reduction of the component (Figure A1a). If no recycled material was used, the influence of an $e_{RSF,1}$ uncertainty became obsolete (Figure A1b). The higher the prevailing recycled content, the higher the required or possible mass reduction adjustment.

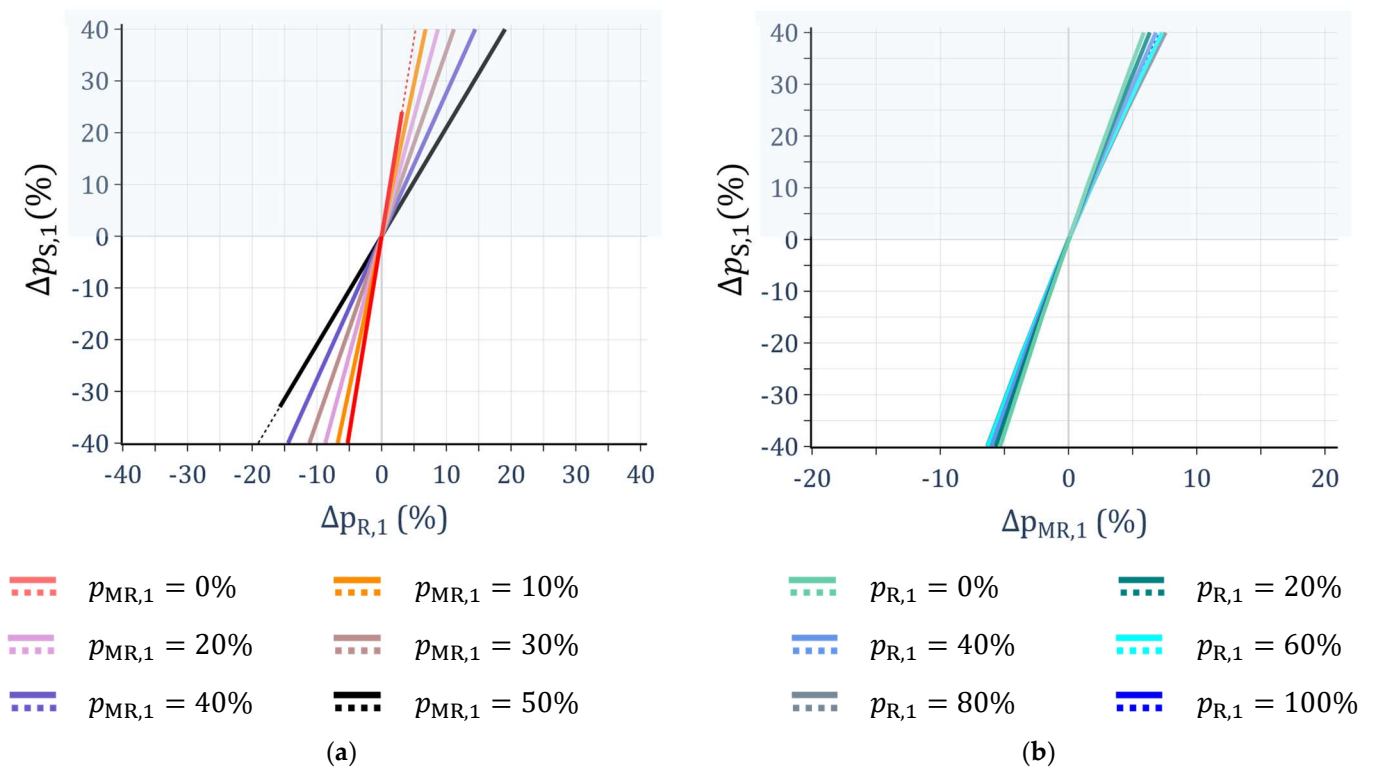


Figure 7. Parameter uncertainty in the scrap rate $\Delta p_{S,1}$ (GHG ERT: 40%): (a) Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$, (b) Required and possible absolute adjustment of mass reduction magnitude $\Delta p_{MR,1}$.

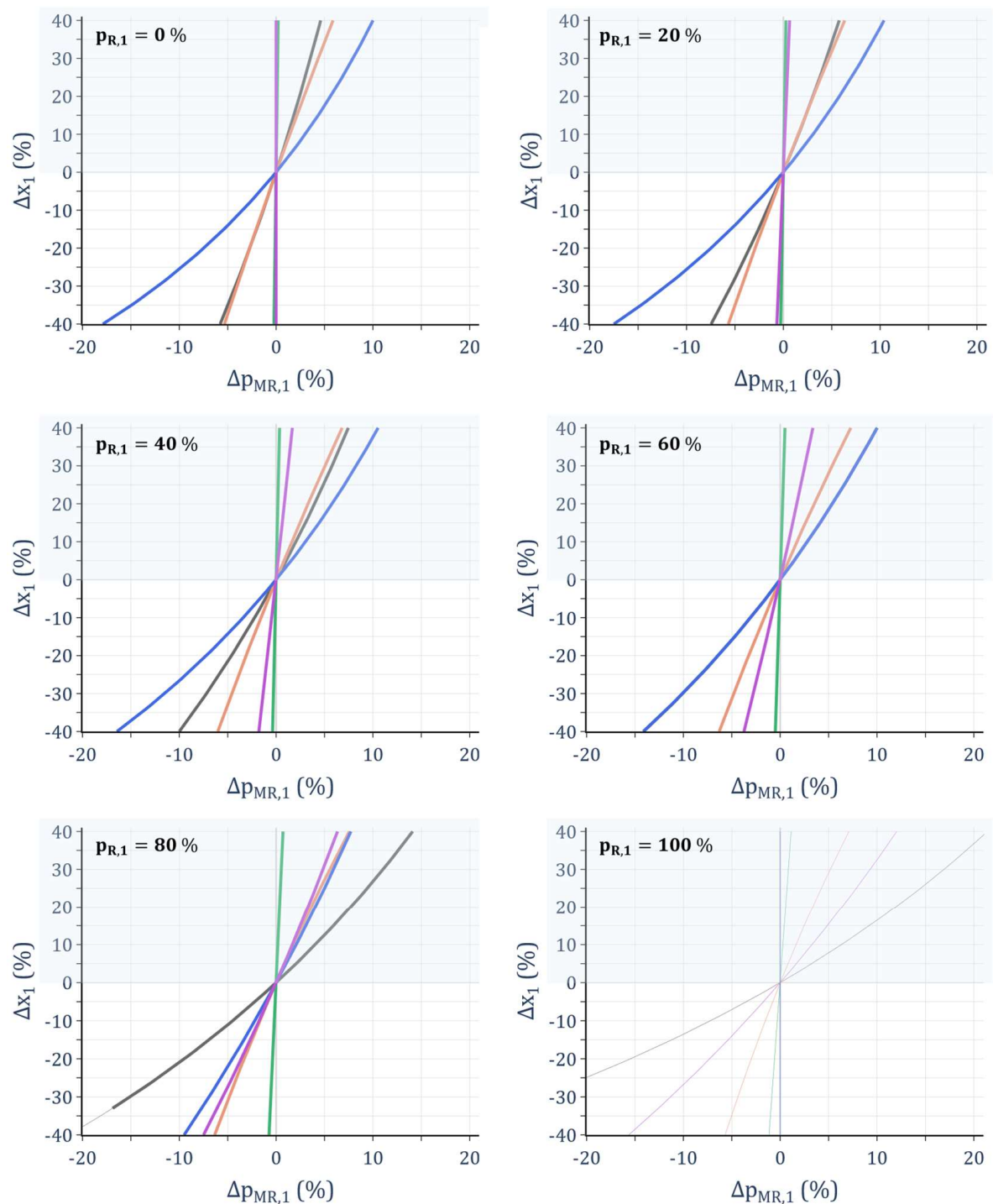
4.2.5. Uncertainties in the Manufacturing Process Environmental Impact $\Delta e_{M,1}$

The impact of a manufacturing process parameter uncertainty on the adjustment of the EMMs was much lower than for the other CFPA parameters (Figure A2). Even a 40% change from the initially targeted EMM values did not enforce a change of more than 2% in the EMMs. It is important to consider that this behavior depended on the chosen CFPA parameter set (Table 2). Since the total ecological impact of the considered aluminum sheet was mostly contributed by phase 1 and not phase 2 of the investigated scope (Figure 2), the impact of an uncertainty in the manufacturing process was almost neglectable.

4.3. Side-by-Side Comparisons of Necessary Measure Adjustments Due to Single Parameter Uncertainties

Since it is particularly relevant to identify the CFPA parameters that have the greatest influence on the EMMs, a side-by-side comparison of the required EMM adjustments for all CFPA parameter uncertainties is presented. Figure 8 shows the required mass reduction magnitude adjustment for different prevailing levels of recycled content (height of the colored area in Figure 4). In this study, the uncertainty in $e_{PSF,1}$ (the ecological impact of the primary material acquisition and semi-finished product provision) had the greatest impact on the mass reduction magnitude adjustment when the recycled material content was below 60%. For a recycled material content of 60%, the necessary mass reduction magnitude adjustment due to an uncertainty in $e_{PSF,1}$ was as high as the adjustment regarding an uncertainty in the mass-induced ecological impact of the use phase $e_{U,mi,1}$. The impact of an e_{PSF} uncertainty became less important when the recycled material content increased and had no impact when just recycled material was used. Above 60% recycled content, an uncertainty in the mass-induced environmental impact in the use phase $e_{U,mi,1}$ overtook the impact of $e_{PSF,1}$ and became the most influential parameter for a necessary mass reduction adjustment. The impact of an uncertainty in the manufacturing phase ecological impact $e_{M,1}$ had the least influence on the adjustment of the mass reduction through all levels of

recycled material share (despite $p_{R,1} = 0\%$). An uncertainty in the environmental footprint of the recycling phase $e_{RSF,1}$ had a greater impact the more recycled material used.



CFPA parameter uncertainties Δx_i :

▬ $\Delta e_{PSF,1}$
▬ $\Delta e_{U,mi,1}$
▬ $\Delta p_{S,1}$
▬ $\Delta e_{M,1}$
▬ $\Delta e_{RSF,1}$

Figure 8. Required and possible absolute adjustment of the mass reduction magnitude $\Delta p_{MR,1}$ due to parameter uncertainties for different levels of recycled material share.

In Figure 9, the necessary adjustment to the recycled material content is illustrated for different prevailing levels of mass reduction (width of the colored area in Figure 4). If measure

combinations were not feasible according to the limitations shown in Equations (13) and (14), the graphs were drawn as dotted lines. The influence of an uncertainty in the mass-induced use phase environmental impact $e_{U,mi,1}$, the manufacturing phase $e_{M,1}$, and the scrap rate $p_{S,1}$ was linear to the recycled material content adjustment. If the mass reduction magnitude was below 40%, the recycled material share adjustment was most sensitive to an uncertainty in the mass-induced use-phase environmental impact $e_{U,mi,1}$. For higher amounts of mass reduction, an uncertainty in the primary material acquisition and semi-finished product provision environmental impact $e_{PSF,1}$ led to the highest required adjustments of the recycled material content.

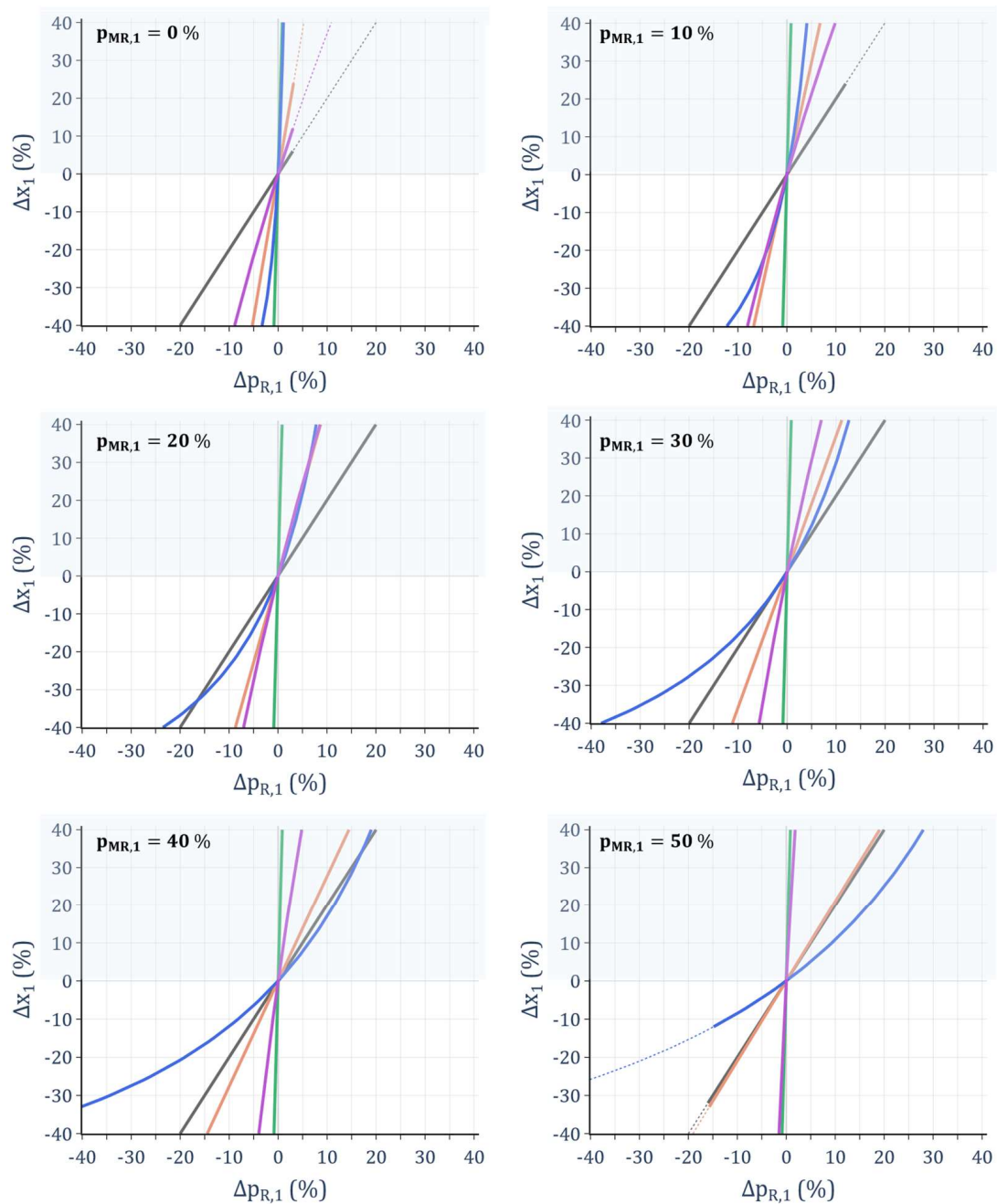


Figure 9. Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$ due to parameter uncertainties for different levels of mass reduction.

5. Discussion—Generic Use Case

In this section, the use case of an increased scrap rate due to an adjustment in the components' design during the development process is used to illustrate the impact of a CFPA parameter uncertainty: In this scenario, the developer initially assumed in the early design phase that the scrap rate of the next-generation component equaled the scrap rate of its predecessor component ($s_1(t_0) = s_0 = 30\%$). Possible EMM combinations to reach the GHG ERT are shown in Figure 10a (green bold line). To prevent a GHG ERT non-fulfillment in the later stages of the development process, a maximum relative scrap rate increase of 30% was expected over the course of the development of the component ($p_{S,1}(t_1) = 1.3 * p_{S,1}(t_0) = 39\%$) (Figure 10a (green dashed line)). The predicted uncertainty could, for example, be based on experiences from previous projects.

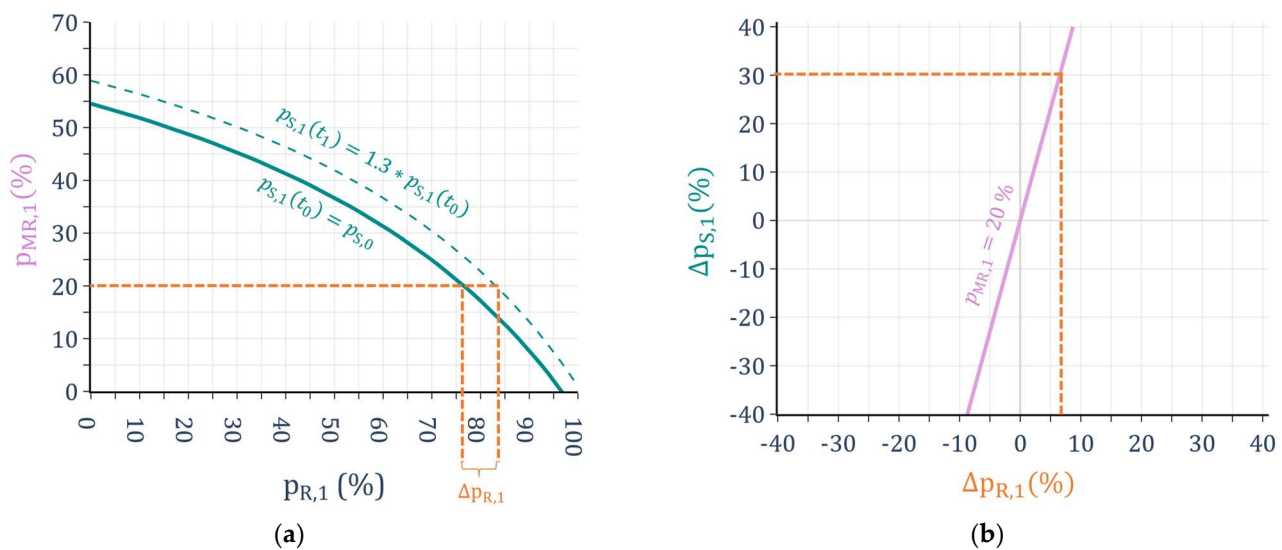


Figure 10. Use case (GHG ERT: 40%): (a) Possible combinations of EMMs to fulfill the GHG ERT, (b) Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$ due to a relative increase in the scrap rate $p_{S,1}$.

Assuming that a recycled content of 76% ($p_{R,1}(t_0) = 76\%$) and mass reduction of 20% ($p_{MR,1}(t_0) = 20\%$) were evaluated as feasible EMM targets at the beginning of the development process (Figure 10a, orange dashed line), a potential adjustment of the recycled content of at least 7% ($\Delta p_{R,1} = 7\%$) needed to be expected to prepare for uncertainty downsides (Figure 10b). This meant that a recycled content of $p_{R,1,U}(t_0) = 83\%$ was necessary to account for the uncertainty in the scrap rate under a constant level of 20% mass reduction ($p_{MR,1}(t_0) = 20\%$).

An additional use case that considered the influence of an uncertainty in the recycling process environmental impact ($e_{RSF,1}(t_0) \neq e_{RSF,1}(t_1)$), is discussed in Appendix A.3.

6. Conclusions and Outlook

In a GHG ERT-driven development process, EMM targets can be derived for development teams by a CFPA. Since, in the early design phase, data availability is lacking, the CFPA parameters are subject to uncertainties. Due to the correlation between the EMM and the CFPA parameter uncertainties, the development targets should, therefore, incorporate an additional margin. Since the EMMs are limited by the component's requirement profile and cannot be increased arbitrarily, the presented study elaborated an opportunity to determine an EMM target that incorporates uncertainties. In particular, it is important to identify and assess the potential need for adjustments of product-related ecological measures at the beginning of the development process when component design or material adjustments can be made in a cost-effective manner. This study can also increase the awareness of how CFPA parameter uncertainties can affect the credibility of EMM development targets.

Thus, the used approach helps designers and engineers minimize the risk of a GHG ERT non-fulfillment.

For a presented example of an aluminum sheet component, the most important parameters that had an influence on an (required) adjustment to the EMMs were the mass-induced environmental impact in the use phase and the primary material and semi-finished product provision. This means that it is particularly important to incorporate downsides for these parameters to prevent a non-fulfillment of GHG ERTs. The lowest influence through all EMMs had an environmental impact on the manufacturing process. It should be noted that all these trends are only valid for the aluminum sheet component example used. Therefore, a side-by-side comparison concluding all CFPA parameters and their influence on the EMM adjustment could help development teams investigate the most crucial parameter when defining EMM targets (Figures 8 and 9). The developed systematic approach can be used to define robust EMM targets and can help obtain an overview of the EMM sensitivity in relation to CFPA parameter uncertainties. Thus, the approach can be used to plan for possible uncertainties in advance when defining EMM targets.

The analysis can be extended by further product-related ecological measures, like a material substitution or a scrap rate reduction. A Monte Carlo sampling of the input parameters of the CFPA could be made to account for multiple uncertainties at once. In addition, the consideration can be expanded by a cost analysis to examine the economic risks and opportunities of a measure adjustment. The scope of investigation can be expanded to include additional life cycle stages (e.g., end-of-life), and the modeling of life cycle stages can be adapted. Even if the approach is exemplary for an automotive component, the proposed method could also be used for use cases in other industrial sectors.

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Abbreviations and Symbols

Abbreviations

CFP	Carbon Footprint
CFPA	Carbon Footprint Assessment
EMM	Ecological Measure Magnitude
eq	Equivalent
ERT	Emissions Reduction Target
EU	European Union
GHG	Greenhouse Gas
ICEV	Internal Combustion Engine Vehicle
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment

Symbols

$E_{M,i}$	kgCO ₂ -eq	Environmental impact of the manufacturing process
$E_{PSF,i}$	kgCO ₂ -eq	Environmental impact of the primary material acquisition and semi-finished product provision
$E_{RSF,i}$	kgCO ₂ -eq	Environmental impact of the recycling process and semi-finished product provision
E_{P1}	kgCO ₂ -eq	Environmental impact of phase 1 of the scope of investigation
E_{P2}	kgCO ₂ -eq	Environmental impact of phase 2 of the scope of investigation
E_{P3}	kgCO ₂ -eq	Environmental impact of phase 3 of the scope of investigation
$E_{U,mi,i}$	kgCO ₂ -eq	Mass-induced environmental impact of the use phase
$V_{100kg,n}$	L/(km * kg)	Mass-induced fuel consumption ICEV
d_m	km	Vehicle's mileage
$e_{M,i}$	kgCO ₂ -eq/kg	Environmental impact of the manufacturing process per unit mass
$e_{PSF,i}$	kgCO ₂ -eq/kg	Environmental impact of the primary material acquisition and semi-finished product provision per unit mass
$e_{RSF,i}$	kgCO ₂ -eq/kg	Environmental impact of the recycling process and semi-finished product provision per unit mass
e_{P1}	kgCO ₂ -eq/kg	Environmental impact per unit mass of phase 1 of the scope of investigation
e_{P2}	kgCO ₂ -eq/kg	Environmental impact per unit mass of phase 2 of the scope of investigation
e_{P3}	kgCO ₂ -eq/kg	Environmental impact per unit mass of phase 3 of the scope of investigation
$e_{U,mi,i}$	kgCO ₂ -eq/kg	Mass-induced environmental impact of the use phase per unit mass
i_F	kgCO ₂ -eq/kg	Fuel emission factor
$m_{in,i}$	kg	Mass of the needed input material (input mass)
$m_{out,i}$	kg	Mass of the component (output mass)
$p_{MR,i}$	%	Mass reduction percentage
$p_{R,i}$	%	Recycled material share
$p_{S,i}$	%	Scrap rate
ρ_F	kg/L	Density fuel
t		Development process timestamp
φ	%	Percentual carbon footprint reduction

Appendix A

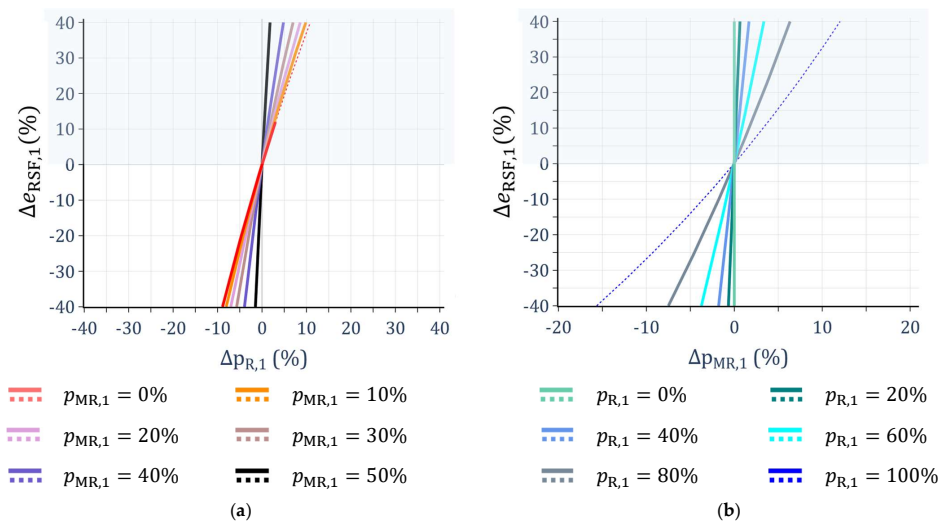
Appendix A.1. Diagrams—Uncertainties in the Recycling Process Environmental Impact $\Delta e_{RSF,1}$ 

Figure A1. Parameter uncertainty in the environmental impact of the recycling process and semi-finished product provision $\Delta e_{RSF,1}$ (GHG ERT: 40%): (a) Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$, (b) Required and possible absolute adjustment of mass reduction magnitude $\Delta p_{MR,1}$.

Appendix A.2. Diagrams—Uncertainties in the Manufacturing Process Environmental Impact $\Delta e_{M,1}$

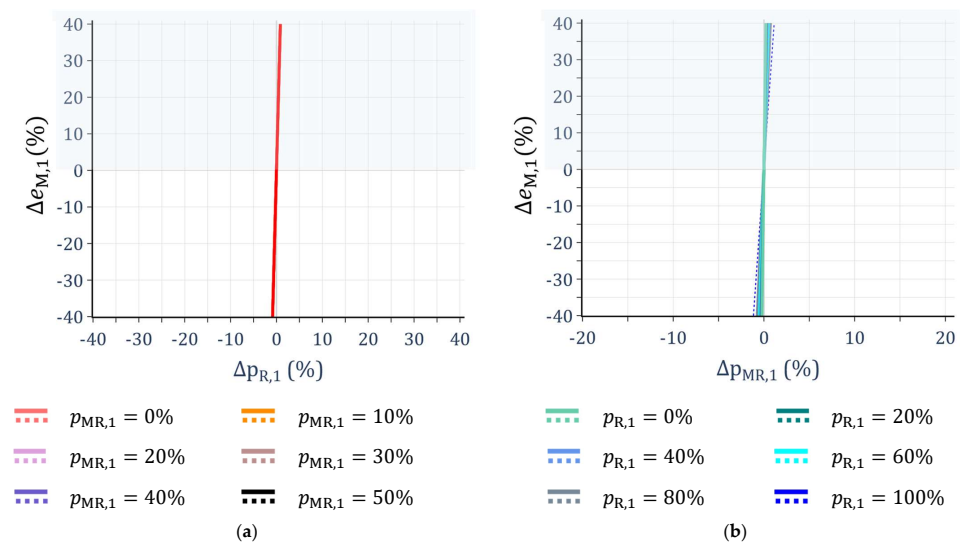


Figure A2. Parameter uncertainty in the manufacturing process environmental impact $\Delta e_{M,1}$ (GHG ERT: 40%): (a) Required and possible absolute adjustment of the recycled material share $\Delta p_{R,1}$, (b) Required and possible absolute adjustment of the mass reduction magnitude $\Delta p_{MR,1}$.

Appendix A.3. Use Case 2: Increased Energy Demand of the Recycling Process

In this example, the maximum possible recycled material share $p_{R,1}$ of the next-generation component was 80% (orange dashed line—Figure A3a). The necessary mass reduction share $p_{MR,1}(t_0)$ was then about 17% (GHG ERT of 40%). Already in the early design phase, it was known that the CFP parameter $e_{RSF,1}$ was subject to a relative uncertainty of 30% (for example, because it had not yet been decided which recycled material from which supplier would be used) (green dashed line—Figure A3a). To prepare for this uncertainty, additional lightweight measures of approximately $\Delta p_{MR,1} = 5\%$ must be considered to still meet the GHG ERT of 40% (orange dashed line—Figure A3b). To account for the uncertainty in the recycling CFP parameter, the development target for $p_{MR,1}$ should be set to 22% and not to 17%.

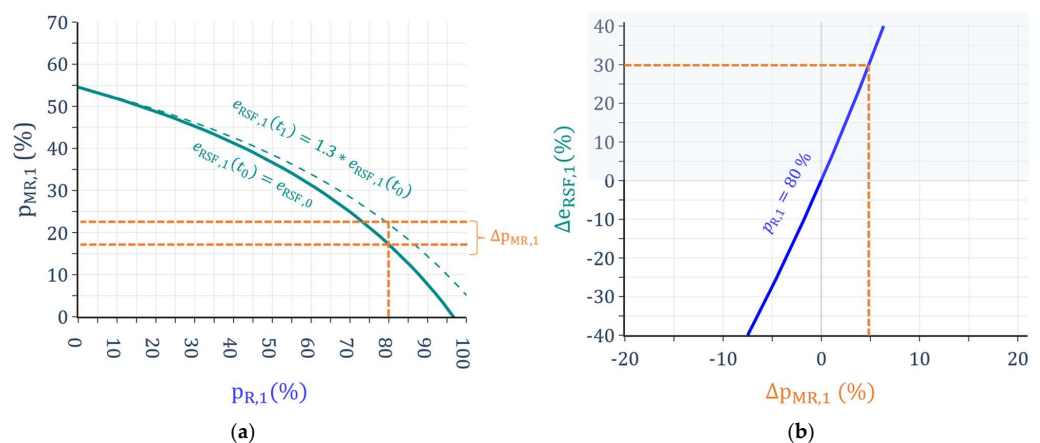


Figure A3. Use case: (a) Possible combinations of EMMs to fulfill the GHG ERT, (b) Required absolute adjustment of the mass reduction $\Delta p_{MR,1}$ due to an increase in the recycling process energy demand $e_{RSF,1}$.

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