Design-to-CO_2 with OPED: AI-powered design optimisation of electric powertrains

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ABSTRACT

Electric vehicles (EVs) do not produce local greenhouse gas (GHG) emissions during operation. However, their indirect emissions categorized as scope 3 according to the GHG protocol still result in a relevant carbon footprint and reporting of those emissions is mandatory. Accordingly, it is important to follow a design-to-CO2 approach when developing new EVs: GHG emissions are already considered in the early-stage design of EVs and engineers aim at minimising the emissions. In the present work, this is achieved by considering scope 3 emissions in a design optimisation software for electric axle drives (e-drives), which is called OPED (Optimisation of Electric Drives). OPED utilises AI-methods to generate best possible e-drive design solutions for engineers and provide them with a solid basis for decision-making. That way, the emissions of newly developed e-drives can be directly minimised alongside the optimisation of other design objectives, e.g., production cost, energy efficiency and package integration. Furthermore, different supply chains are considered and characterised by their specific costs and GHG emissions. The supply chains include standard as well as low-carbon-footprint materials and different supply routes. As a result, a Pareto front of optimal design solutions for specified e-drive requirements is obtained. The method is applied to a case study, which involves the optimisation of an e-drive for a passenger car. The obtained Pareto front and found trade-offs between scope 3 emissions, cost and energy efficiency are discussed, and a promising design solution from the Pareto front is selected to guide subsequent development.

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1. INTRODUCTION

The transition to electric vehicles (EVs) in road mobility represents a critical step in addressing the environmental impact of conventional internal combustion engine vehicles (ICEVs). While EVs do not produce local greenhouse gas (GHG) emissions during operation, they are still responsible for certain indirect emissions when considering the full life cycle. These emissions occur during vehicle production as well as from the generation and distribution of electricity required for operation. Such indirect emissions – occurring both upstream and downstream in the value chain of OEMs and suppliers – are categorized as scope 3 emissions under the Greenhouse Gas Protocol [2] (see Fig. 1). Although these emissions are not directly produced by OEMs and suppliers, they are influenced by the quantity and type of materials in their products as well as utilised supply chains. Driven by growing environmental awareness among consumers, regulatory mandates, and corporate sustainability commitments, reducing the carbon footprint of EVs has become increasingly important. To address this, a comprehensive approach for minimizing GHG emissions must be integrated into the EV development process. This requires engineers to optimise vehicle designs not only for cost and energy efficiency but also for minimal GHG emissions (design-to-CO_2). Such design objectives are typically conflicting, meaning no design fulfils all objectives best and a design solution that balances all objectives in the most favourable manner needs to be found, which represents a highly complex problem in developing new EVs. This complexity is further amplified by the emergence of alternative supply chains, which offer materials and components with lower carbon footprints. While environmentally favourable, these supply chains often come with higher costs, introducing an additional trade-off. Consequently, selecting the most appropriate supply chains becomes a new design variable, enabling engineers to more effectively balance scope 3 emissions and overall product cost.

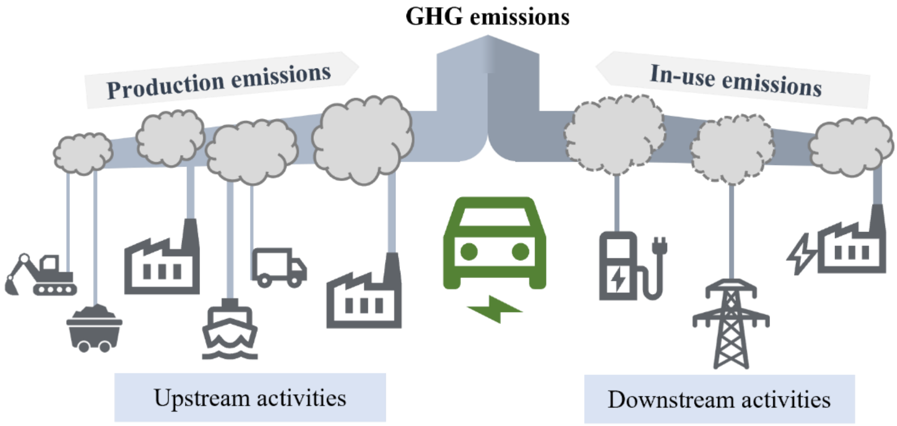

Figure 1: Schematic illustration of production and in-use emissions of an EV

In order to address the problem complexity, a computer-based design optimisation method such as OPED (Optimisation of Electric Drives) [6] can be applied. OPED is capable of synthesizing designs from given system level requirements by addressing multiple conflicting design objectives simultaneously and thus find best possible system solutions. OPED has recently been extended to be capable of minimizing the carbon footprint of electric drives (e-drives). However, it does not consider different supply chain variants in the design optimisation – meaning this degree of freedom in e-drive designing is not utilised by OPED. The present work suggests an extension to OPED, which considers a number of supply chain variants for certain materials of an e-drive and introduces additional optimisation parameters. That way, the design optimisation algorithm of OPED is capable of identifying the best possible supply chains for given e-drive requirements and optimally balance scope 3 emissions with other design objectives such as cost, energy efficiency and package integration.

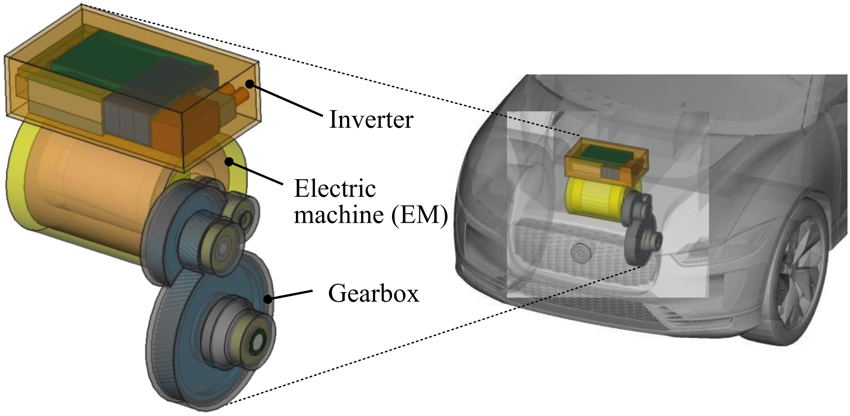

Figure 2: Visualisation of e-drive architecture; vehicle model from [5]

2. METHODOLOGY

The design optimisation software OPED focuses on the design process of e-drives, which consist of three major components (see Fig. 2):

1) inverter
2) electric machine (EM) and
3) gearbox.

For that purpose, OPED utilises an optimisation algorithm and parametric virtual models of an e-drive. In the scope of the optimisation, around 50 design parameters of all three components are varied to synthesize optimal e-drive designs from given requirements. A schematic illustration of the design optimisation process is shown in Fig. 3: Based on specified e-drive requirements, the optimisation algorithm simultaneously varies all design parameters to generate different e-drive designs. While doing so, the optimisation algorithm employs self-learning artificial neural networks to boost optimisation performance. The designs are then evaluated with the virtual models to confirm compliance with the requirements and calculate certain optimisation objectives (e.g., production cost, energy efficiency). The algorithm then rates the designs based on the calculated objectives and decides about new values for all design parameters based on the best found designs so far. This closed loop of design synthesis by the optimisation algorithm and e-drive analysis continues until no more improvements are observable and thus converging behaviour is present. The output of OPED is then a set of different e-drive designs, which contains optima regarding all defined optimisation objectives and also best possible trade-offs in between. This optimal set corresponds to the Pareto front in the context of multi-objective optimisation [7]. More information on OPED can be found in [6].

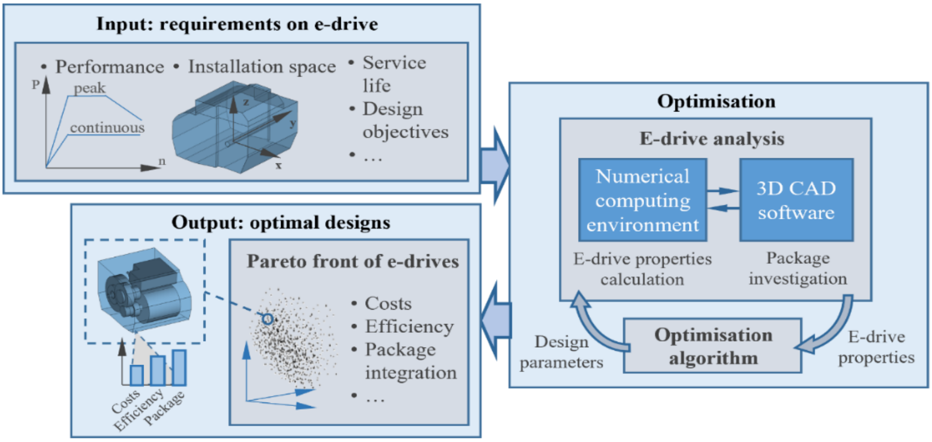

Figure 3: Simplified visualisation of e-drive optimisation process with OPED [8]

In order to minimise the scope 3 emissions of an e-drive, the carbon footprint composed of production and in-use emissions

$$m_{\text{CO2 tot}} = m_{\text{CO2 prod}} + m_{\text{CO2 in-use}}. \quad (1)$$

can be selected as objective in OPED [4]. However, the supply chains to determine the production emissions and cost are predefined and not varied in the scope of the optimisation. In order to enable the consideration of supply chain options, OPED is extended by a number of supply chain options that are provided as input to OPED. Each supply chain is characterised by its cost and carbon footprint. An example is shown in Fig. 4, which depicts two supply chain options for aluminium used in the housing of inverter, EM and gearbox. The conventional supply chain utilises electricity from coal power plants to produce primary aluminium and features rather long transport routes. This results in a relatively high carbon footprint of the material sourced via this supply chain. However, the cost per kg is low. An alternative supply chain is denoted as “green Al” in Fig. 4. This supply chain utilises electricity from renewable resources and local sourcing. Accordingly, the carbon footprint can be reduced by around 68% compared to the conventional supply chain, while the cost per kg increases by around 10% [1].

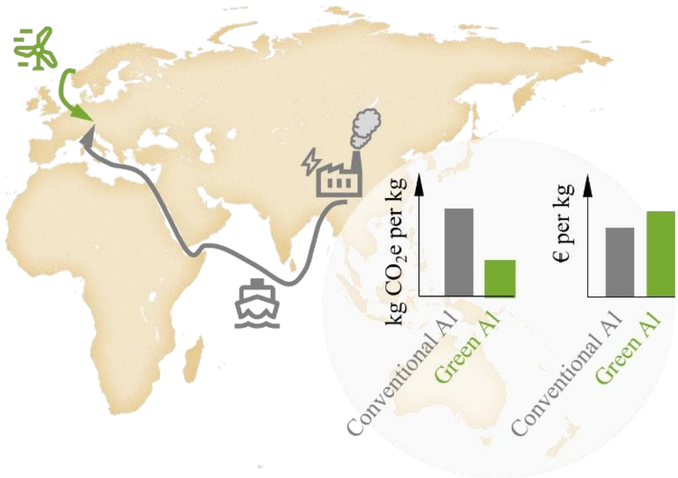

Figure 4: Example of supply chain options for aluminium with associated carbon footprint and cost

In order to select one of the provided supply chain options, the optimisation algorithm is given additional optimisation parameters. The values of the optimisation parameters determine which supply chain option is used for the respective material (e.g., for aluminium, steel, copper, magnets). For example, a first supply chain parameter x_{SC1} is added to the list of optimisation parameters, which covers the aluminium supply chain options. In analogy to the example shown in Fig. 4, a value of $x_{SC1} = 0$ represents the conventional supply chain, while a value of $x_{SC1} = 1$ represents the green supply chain. This logic continues until a supply chain parameter for every relevant material is defined. Concatenation of the existing optimisation parameters $\vec{x}_{eDrive}$ in OPED (which define the full e-drive design) with the new supply chain parameters $\vec{x}_{SC}$ yields the new total set of optimisation parameters

$$\vec{x} = (x_{SC1}, x_{SC2}, \dots, x_{eDrive1}, x_{eDrive2}, \dots). \qquad (2)$$

Every value of $\vec{x}$ is simultaneously varied by the optimisation algorithm in order to solve the design optimisation problem. The calculation of the scope 3 emissions according to [4] as well as the production cost of an e-drive is now based on the values of the supply chain parameters and thus on the selected supply chain options by the optimisation algorithm. This extension allows to consider different supply chain options directly in the optimisation process and thus enables a holistic minimisation of scope 3 emissions alongside the optimisation of production cost, energy efficiency and package integration, as well as potentially also other objectives.

3. RESULTS & DISCUSSION

The proposed extension of the OPED method is applied to a case study involving the design optimisation of an e-drive for a passenger car. The main requirements on the e-drive are listed in Table 1 and the available installation space is shown in Fig. 5. The optimisation algorithm investigates a total of 48 design parameters, which affect inverter, EM and gearbox as well as the packaging of the e-drive in the available installation space. Four optimisation objectives are minimised by the algorithm:

1) production cost,
2) e-drive energy losses (based on WLTC class 3b driving cycle [9]),
3) package metric (see Fig. 5b) and
4) total CO_2-equivalent GHG emissions $m_{\mathrm{CO2\,tot}}$ according to [4].

The production cost considers the main cost drivers of inverter, electric machine and gearbox. For that purpose, a mass-based model is applied for this case study, meaning the mass of each subcomponent of the e-drive (e.g., gear wheel) is multiplied with a cost factor (with unit €/kg) depending on the material of the subcomponent and selected supply chain.

The package metric represents the protruding volume of the installation space by the e-drive in its most favourable position, meaning it takes a value of zero in case the e-drive completely fits inside the given installation space (see Fig. 5).

Table 1: Main requirements on e-drive

Peak power (30 s) in kW	150
Continuous power in kW	75
Peak axle torque (30 s) in Nm	3850
Continuous axle torque in Nm	1925
Maximal axle speed in rpm	1400
Required service life in h	9000

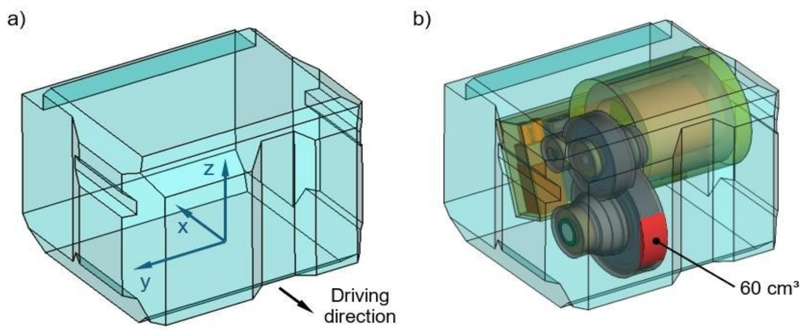

Figure 5: CAD visualisations of e-drive installation space: a) available space, b) package metric definition

Regarding the supply chain options, the optimisation is configured to select a supply chain for aluminium used in the housing of the e-drive and for steel used for shafts and gear wheels. For each material, two supply chain options are specified:

1) a conventional supply chain with higher carbon footprint and lower cost and
2) a green supply chain with lower carbon footprint and higher cost.

In particular, the following differences are applied for the green supply chains compared to the conventional ones:

1) 68% lower carbon footprint and 10% higher cost for aluminium [1],

2) 21.3% lower carbon footprint and 25% higher cost for steel [3].

The optimisation result is shown in Fig. 6, which depicts projections of the obtained four-dimensional Pareto front. The upper chart shows the projection in dimensions “production cost” and “total CO_2-equivalent GHG emissions $m_{CO2\ tot}$”. The lower chart shows the projection in dimensions “production cost” and “e-drive energy losses”. Moreover, only solutions that fit inside the installation space are shown. Two distinct trade-off regions are highlighted in Fig. 6: a cost trade-off region, where smaller production cost can only be achieved by significantly worsening both $m_{CO2\ tot}$ and the WLTC energy losses, and an energy losses trade-off region, where smaller energy losses can only be achieved by significantly increasing cost. However, in the latter region, the total GHG emissions $m_{CO2\ tot}$ behave almost indifferently, meaning lower energy losses do not considerably impact the carbon footprint. This can be explained by the higher production emissions of energy efficient designs, which compensate the lower in-use emissions. Accordingly, the only remaining decision within the energy losses trade-off region is how much cost is acceptable for lowering energy losses and thus increasing driving range.

A promising design solution can be found at the boundary of both regions and this solution is denoted as “Selected design solution” in Fig. 6. For this solution, the total GHG emissions are among the best achievable values and at the same time the production cost is reasonably low. The energy losses in the WLTC driving cycle could be slightly improved but only by accepting significantly higher production cost. Accordingly, the selected solution represents a promising optimum to guide the subsequent e-drive development phases.

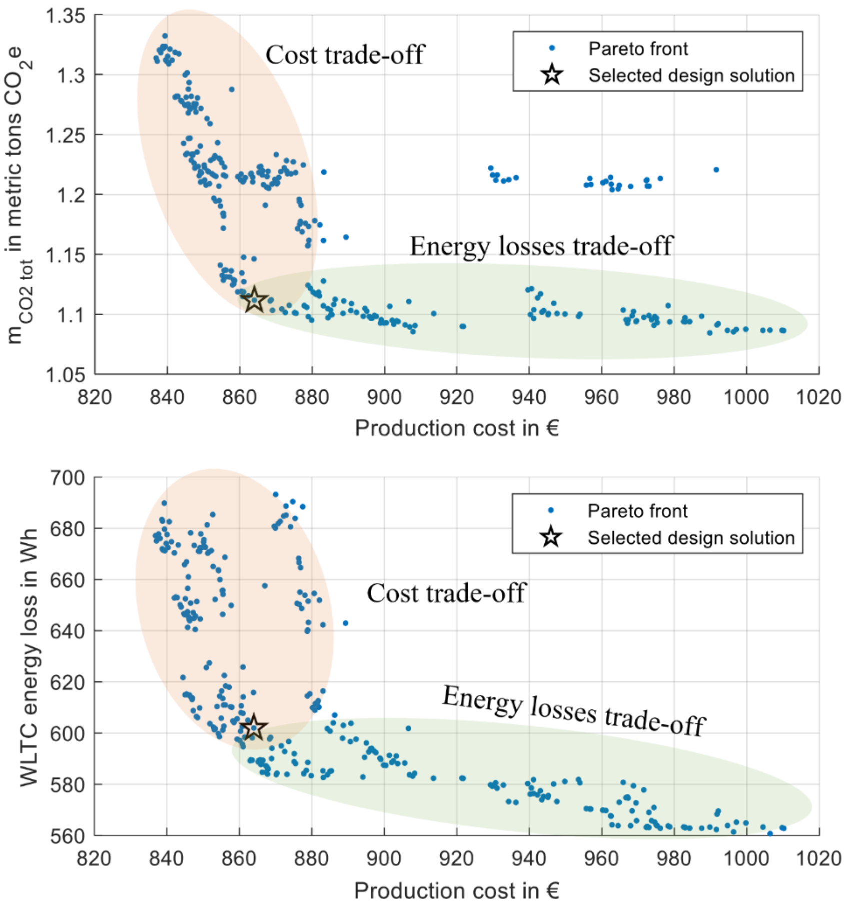

Figure 6: Projections of the obtained Pareto front approximation; only solutions that fit inside the installation space are shown

A CAD visualisation of the selected solution is shown in Fig. 7 and its objective values are listed in Table 2.

Table 2: Objective values of selected design solution

Production cost in €	864
WLTC energy losses in Wh	602
Package metric in cm³	0

$m_{CO2\ tot}$ in metric tons CO2e	1.112

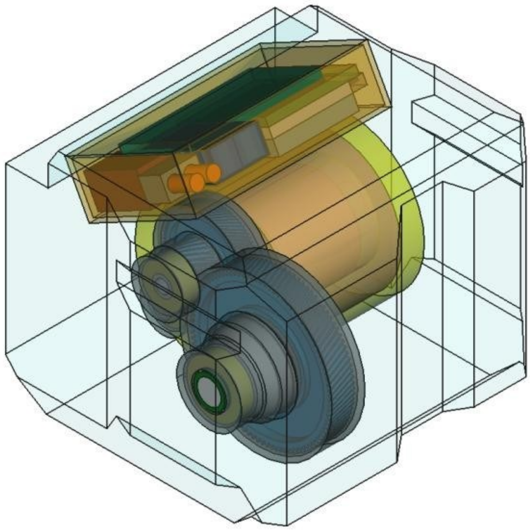

Figure 7: CAD visualisation of selected design solution inside the available installation space

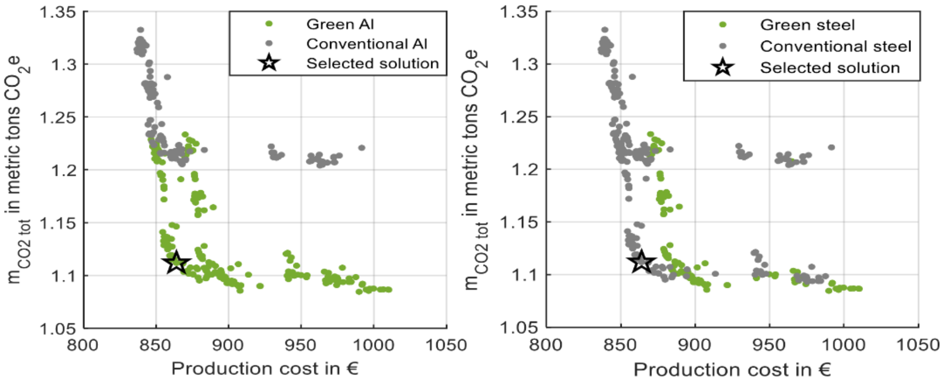

Figure 8: Visualisation of optimal supply chain selection

The supply chain selection for aluminium and steel is visualised in Fig. 8. As can be seen, the selected solution uses green aluminium and conventional steel, which appears as interesting tradeoff: With green aluminium, the carbon footprint can be reduced by around 120 kg CO_2e (9%) while the production cost increases by around 10 € (1.2%) compared to conventional aluminium. The situation is different when comparing green steel with conventional steel. Although the lowest carbon footprint can be achieved by application of green steel, the difference to conventional steel is only around 15 kg CO_2e (1.4%) while the production cost increases by around 20 € (2.4%). Accordingly, the application of green steel for shafts and gear wheels is less effective in reducing the carbon footprint and additionally shows a worse cost trade-off compared to the application of green aluminium for the e-drive housing. Consequently, the most attractive solutions (including the selected one), which show a well-balanced trade-off considering all design objectives, use green aluminium and conventional steel.

4. SUMMARY & CONCLUSION

An extension to an established multi-objective design optimisation method for e-drives is proposed, which enables to minimise scope 3 emissions of e-drives. This is achieved by calculating CO_2equivalent production and in-use GHG emissions, which occur up- and downstream in the value chains of OEMs and suppliers. The production emissions consider different supply chain options for various materials and e-drive components from which the optimisation algorithm can choose from. As a result, a Pareto front of optimal e-drive designs for given requirements is obtained, which directly contains the best possible supply chain selections.

The method is applied to a case study involving an e-drive design optimisation for a passenger car. For the housing of the e-drive as well as for shafts and gear wheels, two supply chain options are specified: Green and conventional aluminium as well as green and conventional steel, respectively. An attractive solution from the resulting Pareto front is selected for the subsequent development, which features very low GHG emissions, low production cost and a reasonably high energy efficiency. This solution utilises green aluminium for the housing and conventional steel for shafts and gear wheels, which generally appears as an attractive supply chain selection for the presented case study. In contrast, selecting conventional aluminium and green steel appears as mostly suboptimal.

With the proposed extension to the OPED method, the additional degree of freedom in selecting supply chains for e-drives is considered and optimised alongside numerous other design parameters. That way, a holistic minimisation of scope 3 emissions can be performed together with the optimisation of production cost, energy efficiency and package integration. Accordingly, the proposed method supports engineers in decision making by reducing the complexity of design problems and suggesting optimal solutions for given requirements.

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