

# A life cycle optimization framework for heavy-duty vehicles: Conceptualization and use cases

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## ABSTRACT

The environmental impacts of heavy-duty vehicles (HDVs) are a growing concern due to technical difficulties to reduce emissions. This research proposes a Life Cycle Optimization (LCO) framework for HDVs, integrating mathematical optimization algorithms for environmental impacts into product development to enable more eco-efficient and eco-effective product system designs. The framework builds upon the framework for life cycle engineering (LCE) but integrates an optimization loop based on recent vehicle optimization studies within a five-step process. It hereby systematically links product system design with the life cycle inventory, impact assessment, evaluation of target fulfilment, and optimization algorithm. All elements are based on the preliminary findings of a structured literature review (n= 315) coupled with an expert workshop (n=8) to ensure alignment between HDV development challenges and life cycle optimization requirements. The framework is pre-tested on a theoretical vehicle development (a mid-class 40t long-haul HDV for the European market) to provide a first proof-of-concept. It is capable to guide development choices toward an eco-effective design while maintaining functional performance. Its modular and customizable structure allows for adaptation to different system levels and product configurations (top-down and bottom-up), supporting a dynamic evolvement of the optimization focus corresponding to the actual HDV development process. Due to the iterative

optimization process entailing a multi-level perspective of the product system (the engineering processes as well as the physical manifestation of the product and its background system), the proposed framework enables key insights into how component-level optimizations manifest on the HDV's life cycle performance, emphasizing the role of data-driven decision-making in vehicle development. Future research should aim to refine the matching of HDV development phases onto data requirements for the life cycle optimization via case studies, streamlining the evaluation of target fulfilment, and integrating the spatiotemporal specificity.

## 1. INTRODUCTION

Achieving global sustainability targets remains elusive without substantial transformations in the transport sector (Folke et al., 2021). Among all vehicle types, heavy-duty vehicles (HDVs) contribute disproportionately to greenhouse gas emissions, resource use, and energy consumption (Wolff et al., 2021). Their size, long lifespans, and high utilization rates—especially in freight transport—make them central actors in the sustainability transition.

However, addressing the environmental performance of HDVs requires more than efficiency improvements in powertrains. It necessitates a comprehensive re-evaluation of the entire product system, encompassing road infrastructure, energy and fuel production systems, and the vehicle's physical and digital design (Sacchi et al., 2021). In particular, emerging powertrain technologies (e.g., battery-electric or hydrogen fuel cell electric) promise major reductions in operational emissions, but often shift environmental burdens to other life cycle stages (Argonne, 2025; Sacchi et al., 2025).

The challenge, therefore, is not merely to make HDVs incrementally more environmentally sustainable but to design them—and the systems they depend on—for eco-effectiveness across their life cycles. This involves ensuring that environmental performance aligns with Earth system boundaries (ESBs) while maintaining technical and functional requirements (Kara et al., 2023).

Various frameworks exist to support sustainable product development, ranging from qualitative eco-design checklists to data-intensive, model-based tools like brightway. However, the complexity of HDV development—with its multi-level (part, component, vehicle, system), multi-objective (cost, performance, impact), and data-constrained nature—poses specific challenges for applying these approaches in practice. High-resolution life cycle data is

often not available during early design phases, and design decisions evolve rapidly over time (Diaz et al., 2023).

This proposes a Life Cycle Optimization (LCO) framework specifically tailored for HDVs to optimize their environmental performance. The core idea is to match assessment and optimization depth to the availability and precision of data at each development milestone. Two research questions guide our work:

1. *What types of engineering challenges and data limitations arise along the HDV development process?*
2. *How can the assessment and optimization of eco-efficiency and eco-effectiveness of HDV product systems be operationalized?*

To address these questions, we propose a modular and iterative LCO framework grounded in literature analysis and expert validation. It is demonstrated through a theoretical case study involving a 40-ton HDV for long-haul applications in Europe.

## 2. METHODS

This study employs a mixed-method approach to develop a life cycle optimization (LCO) framework tailored to the design and engineering challenges of heavy-duty vehicle (HDV) development. Two complementary methods were applied: a systematic literature review to establish the conceptual foundation and state-of-the-art, and an expert workshop to ground the framework in real-world engineering practice and data availability across development milestones.

### 2.1 SYSTEMATIC LITERATURE REVIEW

The literature review followed the PRISMA guidelines to ensure transparency and reproducibility. The Scopus database was queried using a comprehensive search string targeting peer-reviewed publication from 2015 onward. The search combined terms related to life cycle methods (“Life Cycle Assessment”, “Life Cycle Optimization”, “Life Cycle Engineering”) with HDV-related terminology (“truck”, “freight transport”, “commercial vehicle”). Additionally, either terms related to environmental aspects (“GHG emissions”, “resource use”, “eco-impact”) or system modelling and product development (“model”, “functional unit”, “powertrain technologies”) had to be included.

This search yielded 651 results. During the screening phase, studies were excluded, if they were duplicates (n=3), inaccessible (n=63), not in English (n=7), or not related to HDVs or their product systems (n=259), leaving 319 papers. These were then assessed for eligibility based on the clarity of their system model descriptions, functional unit definitions, and representation of HDV development needs and constraints. After full-text screening, 315 publications were retained and analysed.

The review revealed model structures and design assumptions relevant to HDV optimization. These insights informed the core structure of potential product system designs and functional requirements of the proposed LCO framework.

## **2.2 EXPERT WORKSHOP**

To contextualize the framework from an engineering perspective, a structured expert workshop was conducted with eight senior industry professionals. The workshop aimed to understand the multi-faceted HDV development process, including (1) a mapping of milestones and subsystems, (2) the identification of specific engineering challenges and some potential optimization needs at each development phase, and (3) the data availability and precision along the development process.

## **2.3 DEVELOPMENT OF THE LIFE CYCLE OPTIMIZATION FRAMEWORK FOR HEAVY-DUTY VEHICLES**

Together, the literature review and expert workshop informed the development of a flexible and iterative LCO framework that aligns assessment and optimization efforts with the evolving data realities of HDV development. This ensures relevance, scalability, and applicability of the framework across different product configurations and system levels.

## **2.4 CASE STUDY: A 40T LONG-HAUL HEAVY-DUTY VEHICLE FOR THE EUROPEAN MARKET**

To provide a first validation of the framework from an operationalization perspective, a case study was defined around a 40t mid-range HDV designed for long-haul operation in Europe. The focus was set on the first development phases, as early phases offer the greatest sustainability potential due to high

design flexibility but low data availability (Chebaeva et al., 2021). The later development phases are rather broadly rendered regarding engineering challenges and potential sustainability optimization goals and scopes.

### **3. THE LIFE CYCLE OPTIMIZATION FRAMEWORK FOR HEAVY-DUTY VEHICLES**

#### **3.1 BACKGROUND AND KEY FINDINGS**

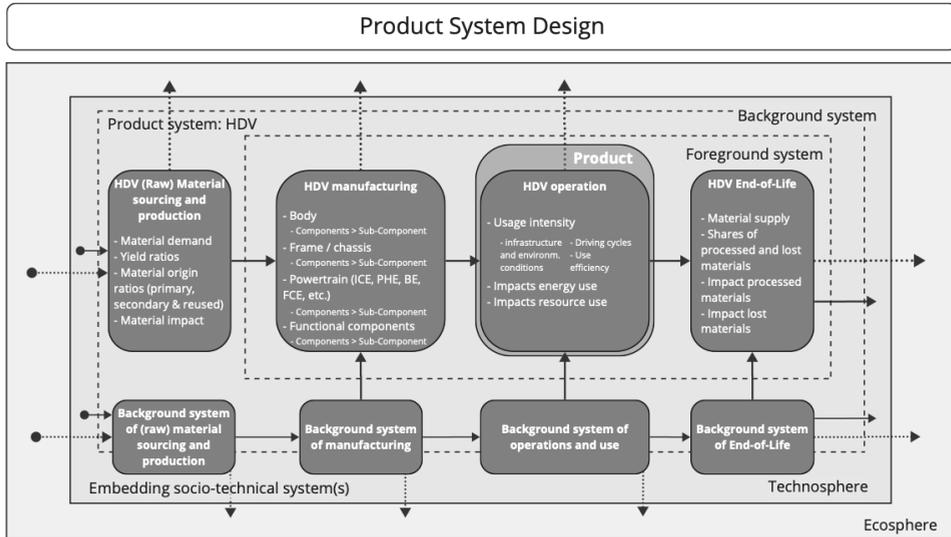
The development of heavy-duty vehicles (HDVs) involves a sequence of distinct engineering phases, each characterized by different challenges, decision-making logics, and levels of data availability and precision. Findings from the structured literature review and the expert workshop conducted as part of this study revealed that HDV development is not a purely linear process, but rather consists of parallel and nested sub-system developments, each with their own iterations and constraints.

A key challenge in HDV development is the eco-design paradox (Chebaeva et al., 2021): Most design decisions are taken well before all relevant environmental data are available at sufficient granularity. Nevertheless, these early decisions often determine the majority of the vehicle's life cycle impacts, particularly in terms of energy consumption and use-phase emissions. Therefore, any life cycle-based optimization framework must match its methods and models to the engineering realities of each development stage.

Three dominant vehicle system models were identified in the literature: GREET (Argonne, 2025), Carculator (Sacchi et al., 2025), and Ricardo-AEA (Ricardo-AEA Ltd., (2020)). Other studies focused on specific HDV components and parts, or on related background systems. They either aimed to provide a holistic assessment entailing a multi-level system model approach, e.g. (Bouchouireb et al., 2019; Hung et al., 2022), incorporating similar structures as the stated three LCA system models, or they solely focused on a very specific element of the HDV product system, e.g., (Chen et al., 2024; Feng et al., 2024; Raugei et al., 2019). Overall, the studies analysed aligned very well regarding the system model structure. Despite eventual different wording,

they defined very similar definitions of system model elements, each with a hierarchical structure, as presented in Figure 1:

Figure 1: Modular hierarchical structure for the product system model derived from the structured literature review. Abbreviations for powertrain technologies: ICE: in-



ternal combustion engine; PHE: plug-in hybrid electric; BE: battery electric; and FCE: fuel cell electric.

This hierarchical structure also corresponds to the engineering and design approaches, as the expert workshop revealed. In practice, mid-range HDVs are rarely designed from scratch but rather assembled by adapting and integrating existing or modularized components to match specific use-case scenarios. As such, the optimization must remain flexible, targeted, and responsive to changing technical and sustainability constraints. The expert workshop provided the following information about the four primary development phases and the corresponding data maturity and optimization scope:

1. **Task Clarification:** HDV development takes place at the vehicle system level and is typically scenario-based. Data availability is low, but the design space is relatively broad. One primary goal is to identify the most suitable powertrain technology (e.g., battery electric, fuel cell electric, hybrid, or internal combustion engine) for the targeted use-case.

2. **Concept & Technology Development:** The HDV development hereafter shifts to the component and sub-component level, supported by simulation results. This phase sees the emergence of multi-level optimization problems linking component- to vehicle-level performance (and in some cases to the fleet or transport system level). The design space is thus more focused on technical implementation on the components level and engineering and environmental models become more specific.
3. **Embodiment Design:** At this stage, other real-world constraints are introduced including the longevity and safety of prototypes, and supplier specifications. The development focus shifts toward supply chain challenges and the background system in general (e.g., manufacturability and reliability, cost-improvements, capacities and purchase agreements).
4. **Detailed Design:** The last development stage narrows in on validation, compliance, and system fine-tuning. The product system is largely defined, and improvements now target specific features and anything that is related to the market introduction. High-resolution data enable more detailed modelling and environmental impact differentiation.

Based on these findings, a life cycle optimization framework for the HDV development may be established, as presented in the following sections.

### **3.2 THE CONCEPTUAL FOUNDATION FOR THE LIFE CYCLE OPTIMIZATION FRAMEWORK OF HEAVY-DUTY VEHICLES**

The overall structure of the LCO framework for HDVs proposed in this study builds upon vehicle optimization studies analysed for the structured literature review (Bouchouireb et al., 2019; Hung et al., 2022; Wolff et al., 2021), and the life cycle engineering (LCE) framework proposed by (Kara et al., 2023). While the LCE framework provides a structural foundation for integrating the assessment of (eco-efficiency and) eco-effectiveness into product development in general, some key adaptations based on the optimization studies are made to integrate and operationalize mathematical optimization algorithms for the HDV development process. E.g., Bouchouireb et al. applied a logarithmic barrier function to penalize configurations approaching the engineering constraints to optimize a vehicle's roof panel (2019), Wolff et al.

incorporated the genetic optimization algorithm NSGA-II to optimize the sizing of the main vehicle components according to engineering requirements (2021), and Hung et al. used a linear programming algorithm to minimize life cycle impacts of fleet utilization requirements during vehicle stock transitions (2022).

The result is a framework that embeds the LCE logic into an iterative optimization loop, enabling the automatic search for improved product system configurations when coupled with optimization algorithms. Further, it introduces development phase-specific tailoring of the design space and assessment logic, aligning the optimization depth and resolution with the data maturity and decision-making needs of each development stage. While the development of HDVs typically progresses through four engineering phases—Task Clarification, Concept & Technology Development, Embodiment Design, and Detailed Design—the proposed LCO framework applies a series of optimization stages mapped onto these phases. Each optimization stage introduces a tailored, life cycle-based assessment loop, embedded within the respective development phase, to ensure environmentally informed design decisions are made in alignment with the data availability and decision-making needs of that phase. This part is based on our previous work, investigating the applicability of impact characterizations based on the alignment of data availability and spatiotemporal precision along the HDV development process (Katzner et al., tbd.).

### 3.3 STRUCTURE AND APPLICATION ACROSS DEVELOPMENT PHASES

For each optimization stage of the LCO framework for HDVs, we propose a standardized structure built around six core elements, of which the central five form an iterative optimization loop:

- x.1 Functional needs & design requirements: These define the system boundaries and performance expectations of the vehicle at a given development stage. They become more specific and data informed as the development process advances.
- x.2 Optimization algorithm: Based on the engineering context, the most suitable algorithm is selected and configured. It receives optimization targets (e.g., minimum climate change impact), variables (e.g., drivetrain configuration and scaling options), constraints (e.g., performance indicators based on engineering requirements), and the ultimate results for each design configuration from step *x.6*.

- x.3 HDV product system design: The design space is defined, ranging from conceptual system layouts in early stages to detailed, component-level specifications and relations to the connected system levels (e.g., background system configuration) in later stages.
- x.4 Life cycle inventory (LCI): Each design configuration is translated into inventory flows reflecting material use, energy demand, emissions, waste streams, and other systemic exchanges with the environment.
- x.5 Life cycle impact assessment (LCIA): The inventory flows are translated into environmental impacts using established characterization methods (e.g., climate change, resource depletion, etc.). The characterization methods are hereby selected in accordance to the established spatiotemporal precision of step x.5.
- x.6 Evaluation of target fulfilment (optional): In eco-efficiency contexts, the optimization aims to minimize impacts compared to alternative configurations. When targeting eco-effectiveness, solutions are evaluated against absolute environmental thresholds (e.g., planetary boundaries) to assess whether the product system is in a sustainable state itself.

The outputs of the loop feed back into the optimization algorithm (step x.2), which determines whether further improvements are possible, or if an optimal solution has been reached. Once a satisfactory configuration is found, the development process proceeds to another engineering challenge and eventually the next stage in correspondence to the development phases and their respective goal and scope settings. Thus, the LCO framework mirrors the typical HDV development process and is composed of four sequential optimization stages, each aligned with the specific data realities and decision context:

1. Task Clarification: During this phase, the optimization operates on the vehicle level with broad life cycle scenarios. There is low data granularity but a broad design space flexibility, mostly with the goal to decide upon the most optimal powertrain technology for the targeted use case with potential sizing of main components.
2. Concept & Technology Development: In this phase component-level simulations and optimizations support targeted refinement and narrowing of viable vehicle configurations. The scope shifts from the vehicle to the (sub-)component level. However, the optimization goal is still centred around the overall vehicle's life cycle, achieved via multi-level optimization approaches.
3. Embodiment Design: This phase introduces real-world constraints such as integrating performance and longevity results of prototypes and simulation, as well as supplier offerings. The focus traditionally shifts toward the supply chain actors and more generally to

interactions with stakeholders of the background system to fulfil defined requirements.

4. Detailed Design: Finally, this phase delivers optimization focused on fine-tuning compliance, and product system validation. The focus returns to the vehicle level, but the optimization goal is to improve in much more detail various small specific aspects of the HDV's product system, as most details have been defined and tailored in the previous development stages.

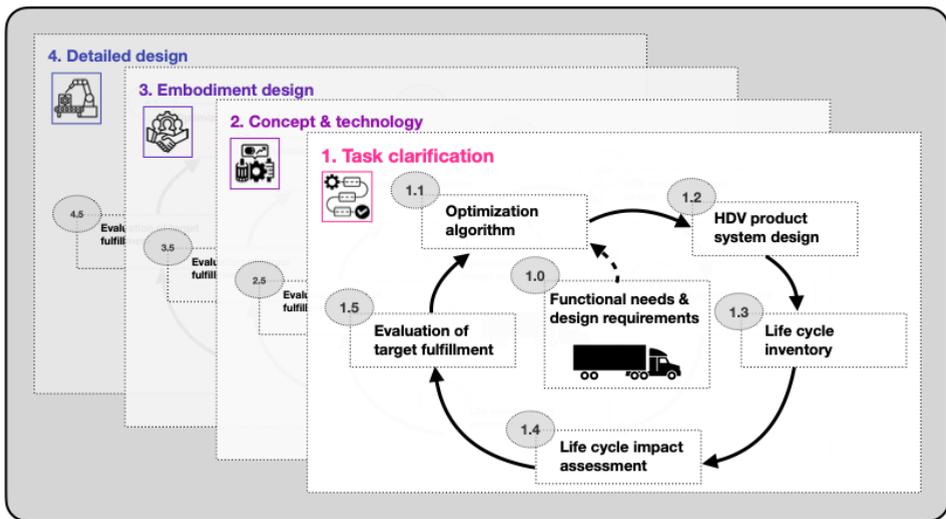


Figure 2: The life cycle optimization (LCO) framework for heavy-duty vehicles (HDV).

This progression ensures that also the spatiotemporal specificity is aligned with the information availability: both the spatiotemporal context (e.g., electricity mixes, use scenarios) and the maturity of technical data are explicitly reflected in each iteration. As such, the framework enables a dynamic, sustainability-oriented design process that evolves in parallel with the technical development, empowering informed trade-offs and targeted interventions at each stage of HDV design.

#### 4. HEAVY-DUTY VEHICLE CASE STUDY

To demonstrate the applicability and functionality of the proposed LCO framework for HDVs, a realistic case study is defined based on the the expert

workshop, outlining a generic HDV development process. An optimization is applied sequentially for the first two development phases *task clarification* (Section 4.1) and *technology & concept development* (Section 4.2) to improve environmental performance across the vehicle's life cycle. At each phase, optimization objectives, input assumptions, and design-specific challenges are aligned with the specific data granularity and evolving system requirements. The latter change according to new insights gained along the HDV development process, progressively rendering engineering requirements for vehicle sub-structures or specific life cycle application/implementation aspects. The presented results and conclusions represent actual findings of our ongoing research.

In contrast, Section 4.3 provides a brief outlook on how the LCO framework for HDVs may be applied to the subsequent development phases of *embodiment design* and *detailed design*.

## 4.1 TASK CLARIFICATION PHASE: POWERTRAIN SELECTION

The case study focuses on a 40-ton HDV intended for long-haul transport. The vehicle is expected to enter the market in 2028 and primarily operating in Central Europe. Its unique selling points are supposed to lie in reduced environmental impacts and maintained leading quality for a mid-range HDV. The vehicle shall be designed for an overall lifetime mileage of 1,5 Mio kilometres.

Thus, generic vehicle models are rendered for each powertrain technology (battery electric (BE), fuel cell electric (FCE), plug-in hybrid electric (PHE), and internal combustion engine (ICE)), fulfilling these conditions. Accordingly, their main components are appropriately sized, and prospective European electricity mixes, fuel compositions and projected usage patterns introduced to compare the various HDV configurations over their life cycle. Due to the very limited data availability and spatiotemporal precision, only environmental impact categories with global effects (e.g., global warming or ozone depletion) were assessed. Also, proxies like life cycle energy would have been applicable. However, it is important to state that the development of follow-up generations may have far more and detailed data available at this stage, enabling a more detailed impact characterization.

In this instance, this comparison was conducted manually. An automated approach could have been applied following the optimization structure of Wolff

et al. (2021), incorporating the generic scaling of main vehicle component to optimise e.g. the vehicle's climbing ability against environmental impact. The result of this early-stage optimization identified the battery electric powertrain as the most environmentally advantageous solution across a range of scenarios, due to an already relative high share of renewables in the European electricity mix but comparatively low share of e-fuels. This choice sets the foundation for subsequent design and development decisions.

## 4.2 CONCEPT AND TECHNOLOGY DEVELOPMENT: COMPONENT DESIGN

With the battery-electric configuration selected, the second optimization stage focuses on refining component-level specifications. I.e., the battery system design is optimised, but any other design trade-off (typically at the component-level for this development phase) may be optimized as well, like e.g., the roof panel design (Bouchouireb et al., 2019). The now further defined design space narrows down the locations of use with 80% of operation occurring in Austria and 20% in Germany and Switzerland. The unique selling points are also specified: A 600 km driving range is determined as target, which is on par with the current generation. However, also considering the infrastructure, the vehicle is shall build on a 800 V nominal system voltage system optimized for fast charging. Additional technical constraints include 1) a minimum 450 kW power output paired with a three-speed gearbox to ensure sufficient climbing ability, and 2) the use of a specific cell model from a predetermined battery supplier (i.e., a prismatic LFP cell of 2,8 kg with a maximal voltage of 4,2 V and a nominal energy of 580,8 W).

Correspondingly, the central design decision is in this case structured around the degree of battery modularity - an optimization is conducted (i.e., based on the genetic NSGAI algorithm) to evaluate environmental trade-offs between integrated and modular battery architectures – an integrated installation of components improves gravimetric energy (thus reducing the overall mass and electricity requirements during use), while a modular installation enables replaceability (thus improving value retention in case components break).

Six components on the module level and ten components on the pack level were integrated in the battery structure to model its electrical performance and necessary replacements during the vehicle's lifetime. The optimization algorithm was configured to find: 1) the number of modules in series and in parallel, 2) the module design (five distinct designs with distinct housing materials and thermal runaway mitigation strategies), 3) and the installation type

(integrated or replaceable) of six module-level and eight pack-level components.

The results are structured around impact categories with global to regional effects despite known shortcomings to represent impacts at End-of-Life and for the background system in general. The results suggest a hybrid approach:

- Overall, the battery design seems to perform environmentally better with many replaceable modules.
- Battery modules and their internal components should be installed in a replaceable manner to extend system longevity by enabling replacing defect components.
- Pack-level components, however, should be installed permanently to preserve gravimetric energy density and reduce the corresponding operational energy requirement.
- The preferable module design is highly dependent on the corresponding applicable cell-to-cell clearance.

### **4.3 OUTLOOK ON POTENTIAL APPLICATION IN SUBSEQUENT DEVELOPMENT PHASES**

Due to limited no testing and results limited to the first two development phases, the operationability of the LCO framework for HDVs remains to be determined and is subject of upcoming research. However, a first brief outlook on their potential application can be provided:

- Embodiment design: While Tier 1 production and final assembly are eventually secured to take place in Germany, several suppliers across different regions may be considered for battery pack and Tier 2+ components. Service providers during the use phase may be determined according to the targeted use scenario. Environmental optimization could thus be applied to evaluate upstream production processes, material sourcing patterns, and transport distances. The optimization results would identify environmentally preferable supply chain configurations, providing actionable guidance for procurement negotiations and assembly planning.
- Detailed design: This optimization stage potentially focuses on use phase services and end-of-life management, though the design space depends on the freedom to introduce adjustments to the targeted

business model. The optimization approach might thus focus on optimizing maintenance, remanufacturing, recycling, or material recovery implementation pathways with real-world stakeholders. This would allow the environmental benefits defined in early-phase targets to be refined and materialized in the actual life cycle setup

## 5. DISCUSSION & CONCLUSION

This paper proposed and demonstrated a life cycle optimization (LCO) framework tailored to the environmental sustainability-driven design of heavy-duty vehicles (HDVs). The LCO approach adapts HDV-specific complexities by embedding iterative optimization loops across four optimization stages—each aligned with a conventional development phase.

The framework introduces three key advancements to current sustainability design methodologies in the HDV sector, namely 1) flexibility across system levels: The modular structure allows application at the component, vehicle, and background system levels, enabling multi-level sustainability trade-off analysis, 2) the temporal and spatial specificity: It aligns life cycle assessment and optimization depth with the data availability and engineering needs of each development phase, and 3) the integration into design process: Optimization loops are embedded directly within the development process, targeting real-world design decisions as they emerge. These features allow the framework to operate within the constraints of HDV engineering while maintaining methodological integrity for robust life cycle assessments.

The case study demonstrated how the LCO framework for HDVs can guide sustainability decisions throughout early HDV development. In particular, it showed that the framework successfully addresses challenges of handling trade-offs (e.g., regarding powertrain selection or component design) its stage-wise structure alleviates data constraints. Together, these outcomes validate the potential of the framework to guide HDV development toward more eco-efficient—and potentially eco-effective—designs.

While the framework is promising, two major limitations remain. First, it has not yet been fully implemented in an industrial development context and thus its usefulness remains uncertain. And second, the optimization potential remains highly dependent on how the optimization targets and design space are set up and which background system structures may be feasible in the real world. Thus, future research should address these limitations and explore the integration to digital engineering tools (e.g., digital twins, model-based systems engineering) to support real-time feedback on environmental

sustainability optimization —helping steer the transport sector toward genuinely sustainable transitions.

## ACKNOWLEDGEMENTS & DECLARATIONS

The financial support provided by the Austrian Federal Ministry for Digital and Economic Affairs, the National Foundation for Research, Technology, and Development, the Christian Doppler Research Association, the Austrian Research Promotion Agency (FFG), and the University of Graz is gratefully acknowledged. The support of the participating HDV experts, especially Johann Bachler-Udier and Franz Hofer, is highly appreciated.

Parts of this manuscript, including language refinement and the structuring of individual sections, were supported using artificial intelligence. The content, methodological design, case study development, and critical interpretation were conducted by the authors.

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