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**rev2025 –
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Efficient Vehicles
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Preface

It is with great pleasure that we present the electronic proceedings of the 2nd Resource Efficient Vehicles Conference (rev2025). rev2025 followed the theme *Shaping the Future of Sustainable Transport and Circular Solutions*, and was held from September 23rd to 25th, 2025, in the city of Graz, Austria. Organized by the Department of Environmental Systems Sciences at the University of Graz, this vehicle-centric conference brought together participants from academia, industry and public agencies to discuss research from all relevant fields connected to resource efficiency in all motorised modes of transport and interdependent surrounding systems.

The rev2025 conference was a unique platform for interdisciplinary collaboration, featuring 11 sessions packed with cutting-edge insights and 45 inspiring contributions. With 64 participants from various fields, the event fostered meaningful discussions and innovative ideas at the intersection of sustainability, technology, and societal impact.

These proceedings serve as a comprehensive collection of all submitted contributions to rev2025 (i.e., full papers and extended abstracts). They aim to provide a valuable resource for the scientific community, industry professionals, and policymakers, fostering further exploration and collaboration in the pursuit of sustainable and resource-efficient transportation systems.

We extend our deepest gratitude to our financial supporters, our scientific board members, as well as to all participants, for their enthusiasm, insights, and collaborative spirit – without you rev2025 would not have been possible.

As we reflect on the success of rev2025, we are reminded of the power of collaboration and the importance of shared vision in addressing the pressing challenges of our time. We hope these proceedings will inspire continued innovation and cooperation in shaping a future where resource-efficient vehicles and sustainable transport solutions become a reality.

The organizational committee

Rupert J. Baumgartner, Josef-Peter Schöggl and Katharina Berger

Scientific board

The development of *rev2025* was supported by the scientific board and its members in terms of

- developing submission formats and procedures
- advertising the conference in respective scientific board member networks
- support of the peer-review process
- developing the conference programme

support during the conference by taking over the function as session chairs

The organizing committee wants to express their deepest gratitude to the scientific board members, who are listed below.



Rupert J. Baumgartner

Professor of Sustainability Management, University of Graz and Director of the Christian-Doppler-Laboratory for Sustainable Product Management enabling a Circular Economy, Graz, Austria.



Josef-Peter Schöggel

Assistant Professor of Sustainability Assessment and Management, University of Graz, Graz, Austria.



Katharina Berger

Postdoctoral Researcher, Christian-Doppler-Laboratory for Sustainable Product Management enabling a Circular Economy, University of Graz, Graz, Austria.



Ciarán O'Reilly

Associate Professor in Conceptual Vehicle Design, Centre for ECO2 Vehicle Design, KTH Royal Institute of Technology, Stockholm, Sweden.



Jenny Jerrelind

Associate Professor in Vehicle Dynamics, Centre for ECO2 Vehicle Design, KTH Royal Institute of Technology, Stockholm, Sweden



Johann Bachler-Udier

Global R&D Coordinator AVL List GmbH, Graz, Austria.

**Sophie Isaksson Hallstedt**

Professor of Product Development, Industrial and Materials Science, Chalmers Tekniska Högskola, Sweden.

**Mario Hirz**

Associate Professor of Virtual Product Development and Head of the Department Automotive Mechatronics, Graz University of Technology, Austria.

**Morgane Fritz**

Professor of Sustainable Supply Chain Management, Excelia Business School, Research Center in Managerial Intelligence and Innovation (CERIIM) and Institute for Societal Responsibility through Innovation (IRSI), La Rochelle, France.

Keynote speakers

rev2025 hosted four exceptional keynotes, comprising two keynotes from industry experts, one keynote from policy makers on the European level and one expert roundtable discussion.

Keynote 1 by Johanna Nylander (GKN Aerospace)



Johanna Nylander has a PhD in product development and a focus on circular economy and sustainable product development. With over a decade of experience in the aerospace industry, her work has been focused on sustainability since 2015. As a sustainability specialist at GKN Aerospace Engines, she has developed several methods and tools to assess products from a sustainability perspective across various phases of the development process. She is involved in several research projects related to sustainable product development, as well as national and international networks for sustainable transition within the aerospace and defense sector. Focusing on sustainability from a strategic perspective she is guiding GKN Aerospace to become the most sustainable partner in the sky.

Her keynote was entitled “**Make sustainability happen in industry!**”. This speech explores the challenges and complexities of driving sustainability in industry. It reflects on why progress has been slow despite growing awareness, touching on trade-offs between climate, resources, poverty, safety, and ethics. It outlines how companies can evolve from compliance to visionary leadership. The message is: to make sustainability happen, we must dare to take on the fight, be brave enough to lead, and envision a sustainable future together.

Keynote 2 by Matthias Asplund (Trafikverket)



Matthias Asplund holds a PhD in the field of condition monitoring, with a focus on efficient measurement of railway wheels and utilizing data to improve maintenance decision-making for infrastructure managers. He currently works as a Senior Specialist and leads both national and international research initiatives at Trafikverket, the Swedish Transport Administration. In addition, Matthias serves part-time as a researcher at Luleå University of Technology. Over the past years, he has authored more than 30 research articles published in conferences and scientific journals.

Matthias gave the keynote entitled “**Green Sustainable Railway Systems**”. In his keynote Matthias emphasized the system perspective and it being essential for achieving green and sustainable transportation, especially in the railway sector. The keynote described the system and highlights the importance of considering the system perspective to deliver sustainable transport solutions. Ongoing projects will also be presented, showing how they can support the development of a green and sustainable railway system.

Keynote 3 Round table discussion “7 years CD-Lab for Sustainable Product Management”

The round table discussion “7 years CD-Lab for Sustainable Product Management and its made contributions to sustainable transport solutions and systems” comprised the following panelists:



Rupert J. Baumgartner, University of Graz

Rupert J. Baumgartner is professor of sustainability management at the Department of Environmental Systems Sciences, University of Graz, Austria. Since November 2018 he is the director of the Christian-Doppler-Research Laboratory for Sustainable Product Management enabling a Circular Economy. He published more than 90 journal papers in leading academic journals, 3 books and more

than 25 book chapters. His main research interests are corporate sustainability management, sustainability assessment, lifecycle assessment, and circular economy. His research achievements include the development of an integrated model for corporate sustainability management combining maturity levels of sustainability strategies with organizational culture and operative implementation, the joint development of a framework for sustainable business excellence based on Hoshin Kanri, the definition of second-order sustainability performance, the joint development of a checklist and implementation framework for sustainable product development and the publication (together with colleagues) of the first scientific concept for a digital product passport from a sustainability perspective.



Josef-Peter Schöggl, University of Graz

Josef-Peter Schöggl is an Assistant Professor of Sustainability Assessment and Management at the University of Graz, where he focuses on data-driven sustainability assessment and management. He holds a PhD in Environmental Systems Sciences from the University of Graz and has worked as a Full Professor of Sustainability Analytics at Modul University Vienna and as a postdoctoral researcher at KTH Royal Institute of Technology and the University of

Graz. His research focuses on sustainability assessment, circular economy, sustainable product development, inter- and intra-organizational collaboration, and the utilization of digital technologies to advance sustainability-related decision-support methods.



Johann Bachler-Udier, AVL List GmbH

Johann Bachler-Udier received his diploma in mechanical engineering and economics from Technical University, Graz, Austria (1995). Between 1989 – 1995, he worked at the Institute for Internal Combustion Engines & Thermodynamics, Prof. Dr. Rudolf Pischinger, TU Graz as scientist and project manager. In 2000 he joined AVL List, and headed the Diesel Calibration for 10 years. For 8 years he was responsible for the monitoring of the global R&D activities in the business unit ‘Powertrain Engineering’ of AVL List, since 2016 he is responsible for

the program ‘Life Cycle Engineering’. He is involved in, coordinating and leading research projects on ‘sustainability and circularity’ on national and EU level. He has a record of more than 20 publications as author or co-author. He participates as Expert Group Member in initiatives on national and EU level on topics sustainability, circular economy, LCA.

Andreas Schiffleitner, iPoint-systems GmbH



Andreas Schiffleitner is Product Manager for Sustainability Solutions at iPoint-systems, a leading provider of digital solutions for sustainable product development and compliance. Since joining iPoint-Austria in 2004, he has held key roles including Head of R&D Sustainable Product Development, Product Manager for various sustainability solutions, and Director of iPoint-Austria. He brings deep expertise in ecodesign, life cycle assessment, and regulatory requirements such as conflict minerals.

Andreas contributed to international projects like the EU-funded SustainHub and led the innovation project Live LCA, which laid the foundation

for today’s “Product Sustainability” solution. He studied Electronics at the University of Applied Sciences Technikum Wien.

Topic of this round table was to discuss 7 years of research conducted within the CD-Lab for Sustainable Product Management, taking into consideration the scientific perspective (i.e., scientific contribution to the field of sustainability research), as well as the perspective of involved industry partners (i.e., iPoint-systems GmbH and AVL List GmbH), highlighting the importance of transdisciplinary research.

First, Prof. Rupert J. Baumgartner and Prof. Josef-Peter Schögggl presented 7 years of research conducted within the CD-Lab for Sustainable Product Management, elaborating its contribution in the fields of sustainable product management and development, with particular focus on the transportation and transport sector. This was enhanced by the industry perspectives of the CD-Labs core industry partners iPoint systems GmbH and AVL List GmbH, represented by Andreas Schiffleitner and Johann Udier-Bachler, regarding the impact of research conducted within the CD-Lab and respective knowledge exploitation by the industry partners.

Keynote 4 by Beatriz Ildefonso (European Commission – DG Research & Innovation)



Beatriz Ildefonso is a Policy Officer at the European Commission’s DG Research & Innovation (Unit C3 – Clean Transport Transitions), where she works on the 2ZERO partnership and contributes to advancing circular economy initiatives in the mobility sector. With a background in energy and environmental engineering, Beatriz has built her career at the intersection of sustainability, research, and industry policy. Prior to joining the Commission, she served as Circularity & Materials Manager at CLEPA, the European Association of Automotive Suppliers, where she led regulatory and innovation work on

materials circularity, sustainable batteries, and product carbon footprint methodologies. She also worked as a researcher in the Laboratory of Energy Policy of Ljubljana.

In her keynote “**Advancing Circular Economy in Road Mobility: Horizon Europe and 2ZERO R&I Actions**” Beatriz outlined ongoing research and

innovation activities supporting the transition to a circular economy in the road transport. Beatriz will present relevant ongoing initiatives under Horizon Europe, and specifically the 2ZERO Partnership, that address eco-design, end-of-life management, and sustainable use of critical raw materials in vehicles, to enhance resource efficiency and resilience across the European mobility value chain.

Structured sessions and proceedings

rev2025 comprised in total 11 sessions and 45 contributions.

In this section, the submitted contributions (i.e., extended abstracts, full conference papers) are presented.

The contributions are presented based on the structured sessions.

Day 1 Session: Advancing Sustainable Battery Design: Materials, Circularity and Environmental Impact

An innovative and sustainable battery case design made from wood, steel and cork

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EXTENDED ABSTRACT

The global transition towards electro-mobility is a pivotal strategy in addressing climate change and reducing the environmental footprint of transportation. However, while electric vehicles (EVs) are widely recognised for their lower operational emissions compared to conventional vehicles, their production introduces new sustainability challenges, particularly regarding the sourcing and processing of materials. Currently, much attention is focused on the environmental and social impacts of raw materials used in EV batteries, such as lithium, cobalt, and nickel. However, sustainability concerns related to structural materials—those used throughout the vehicle, including the battery housing—are increasingly significant. These materials contribute substantially to the vehicle's overall carbon footprint and resource consumption.

Current state of the art battery housings are typically fabricated from high grade aluminium alloys like EN AW 6061-T4 [1]. While aluminium offers advantages in terms of weight reduction and crash safety, its production is energy-intensive and a major source of CO₂ emissions, contributing significantly to the environmental footprint of EVs. Further, these alloys are typically not recycled in a sorted fashion, resulting in lower aluminium qualities after the recycling process [2]. This down cycling does necessitate the need

for further primary aluminium production and therefore an increase in carbon emissions.

To address this issue, the preceding research project BioLIB! introduced a novel battery housing architecture that replaced aluminium structures with bio-based hybrid materials. Specifically, a wood-steel hybrid battery housing was proposed. The housing further incorporated a cork-based cell holder in order to substitute synthetic foams and resins. Overall the concept offered a significantly reduced environmental impact [3] while still satisfying critical safety requirements related to mechanical integrity [4], crash resistance and noise, vibration and harshness requirements [5].

Building on these findings, the research project SMADBatt (**S**ustainable **MA**-terials and **D**esign for electric vehicle **B**atteries), aims to further enhance both the sustainability and functionality of such hybrid battery housings.

The present aims to optimise both the ecological and economic performance of the battery housing by integrating secondary biobased materials. The proposed concept features a cell holder made from recycled cork material. Further, wood gathered by forest thinning, which is currently an underutilised resource and traditionally designated only for energy recovery through combustion, is explored as a structural filler to reinforce thin-walled steel profiles. This hybridisation is evaluated through three point bending experiments in order to assess the mechanical potential of secondary wood products for reinforcement purposes within a vehicle structure. The hybridisation strategy seeks to adopt low-value by-products for high-performance applications in the automotive sector, thereby increasing material circularity and reducing reliance on virgin resources.

Moreover, improved recyclability at the end-of-life is enabled through modular design and ease of disassembly of the battery housing. This is facilitated through detachable mechanical connections and advanced adhesive systems that can be separated or “triggered” to allow for clean disassembly of parts. Multiple triggered adhesives are assessed for their suitability for their mechanical properties as well as their trigger mechanism, such as thermal, UV, magnetic and solvent separated adhesives. This design-for-disassembly strategy supports future reuse, recycling, and recovery of both structural and electronic components, enabling circular economy.

In addition to structural design, this work addresses another key contributor to battery efficiency and longevity with an optimised thermal management system. Since batteries operate within narrow temperature ranges for optimal performance and longevity (15-35°C) [6], improved heat dissipation and

control are crucial. A combination of passive and active thermal management solutions is investigated through simulations for different thermal loads. This includes the novel utilisation of cork, as a cell holder material, which is also saturated with a Phase Change Material (PCM), which allows for function integration of two safety relevant properties. Mechanical impact can be mitigated through the cellular structure of the cork material, while short time temperature peaks, which can lead to lithium plating and accelerated aging of the battery [7], can be prevented by the inclusion of PCM. Further, the fire retardant properties of cork [8] are investigated in an approximated experiment which replicates the highly abrasive flames which occur in battery fires through spark emission.

The innovations proposed within the presented work are expected to deliver a battery housing that matches with conventional metal solutions in terms of safety, durability, and thermal performance, while dramatically lowering its environmental footprint. Preliminary results suggest that the incorporation of recycled and natural materials can lead to significant reductions in CO₂ emissions generated during the production processes. Additional benefits in end-of-life and potential cost savings through the utilisation of secondary materials are expected. The integration of sustainable materials, triggered disassembly, and thermo-functional optimisation into a battery housing exemplifies circularity in electromobility. In conclusion, the project contributes to the broader transformation of mobility systems by aligning vehicle design with environmental goals and circular resource use, paving the way for a more sustainable and climate-friendly future in transportation.

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Design for disassembly: The influence of EV battery pack designs on environmental impact and circularity beyond the first life cycle

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EXTENDED ABSTRACT

In recent years, lithium-ion (Li-ion) batteries have become essential to the global automotive industry, transforming vehicle power solutions. As the market for these batteries continues to grow, battery disposal has become a significant concern (Ding et al., 2019). In light of the climate crisis and resource scarcity, the traditional linear economic model of "take-make-dispose" is becoming unsustainable (Mayyas et al., 2019). This practice is increasingly being replaced by the restorative framework of the Circular Economy (CE). To effectively implement CE principles, an eco-design strategy, such as designing for disassembly, can be integrated at the beginning of product development of Li-ion battery packs. This approach ensures that battery packs can be dismantled efficiently, facilitating sustainable practices—such as recycling, repair, and reuse—at the end of their life cycle (El Jalbout & Keiv-anspour, 2024). Battery packs used in certain applications are subject to a higher risk of damage, particularly in electric two-wheelers, where accidents are reported to be 6 to 13 times greater than that of other vehicle types (Yousif et al., 2020).

To address this increased risk, the present study incorporates a crash scenario within the first product life cycle stage, thereby extending the scope of environmental impact assessment beyond conventional phases—design, use, and end-of-life—to include the potential for repair. The objective is to examine the environmental benefits and trade-offs associated with design for disassembly, particularly as they manifest across different life cycle stages and environmental indicators. A comparative analysis is conducted on three battery pack configurations with varying degrees of dismantlability: a non-dismantlable sealed housing and two dismantlable alternatives (exchangeable lids and liquid-filled battery). The product system of the LCA is given in Figure 1.

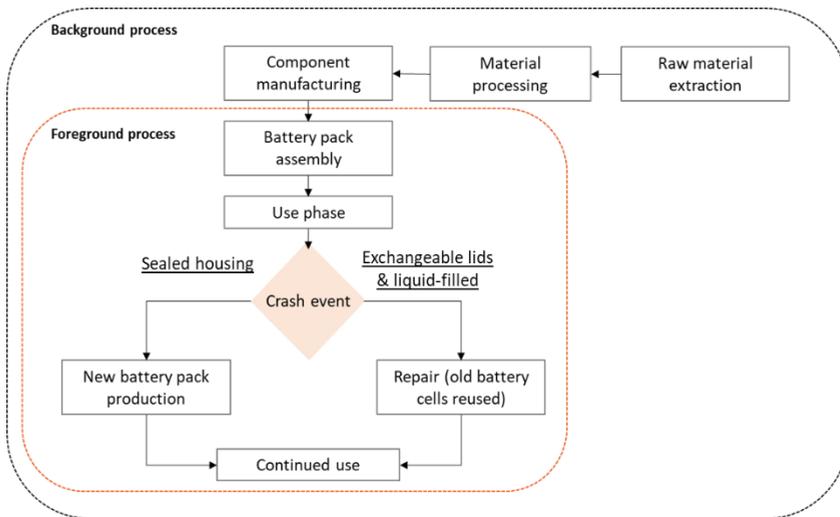


Figure 1. Production systems of the three battery packs, crash and replacement scenario included

Given that the focus of LCA is to evaluate environmental impacts, circularity assessments will be conducted to quantify the effects of different design-for-circularity measures. Our analysis is driven by the following key research questions:

1. How does the level of dismantlability in electric two-wheelers battery pack designs influence environmental impacts across multiple life cycles?
2. What are the trade-offs between circularity and environmental impact within the different designs?

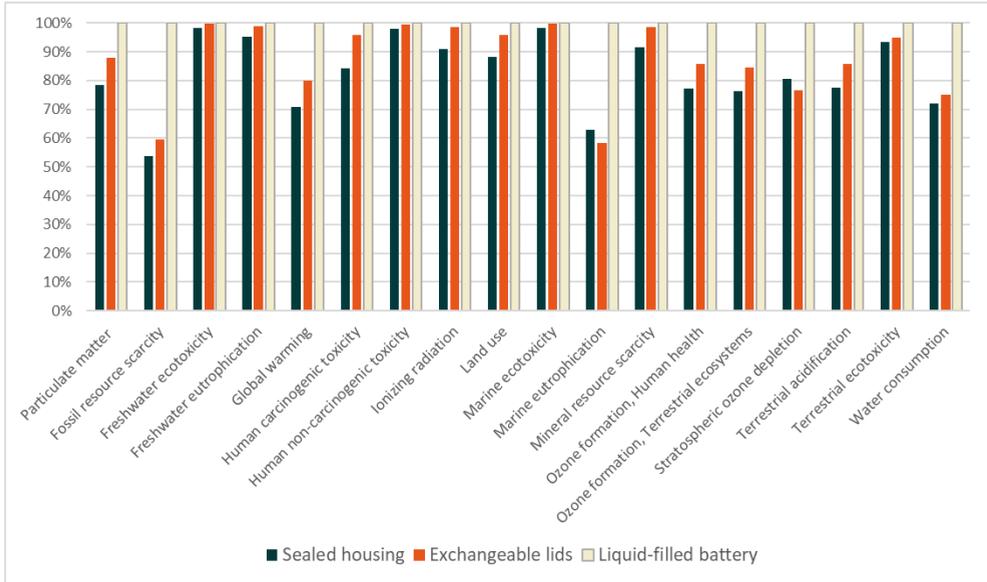


Figure 2. Relative environmental impact of the production phase for three battery pack designs, evaluated across multiple impact indicators - in relation to the highest contributor (set as 100%)

The outcome of this study provides an overview of the environmental impact and circularity of design for disassembly not only on the first product life cycle but also on the potential second life cycle considering repair. The results show that, during the initial life cycle, battery packs designed for disassembly are associated with higher environmental impacts, as illustrated in Figure 2. This suggests that enabling reparability in this context incurs additional material usage and environmental burden related to the battery housing and the choice of gap filler. However, the environmental impacts are reduced following a crash, when reparability becomes relevant primarily due to the reuse of battery cells. Although the environmental impacts increase, design for disassembly aims to ultimately improve the sustainability of the new battery packs by enhancing the circularity. Emphasizing the use stage, the added weight of dismantlable battery packs results in greater energy demands for motorcycle operation, illustrating how design decisions influence performance in later stages. To assess the benefits of enhanced circularity, suitable circularity metrics, such as circularity indicators which assess materials and/or products, need to be identified and applied. A variety of circularity indicators are proposed in the literature, ranging from indicators which consider environmental, economic and/or social aspects. Suitable indicators, which are able to capture

the consequences of a design for disassembly will be applied to the case study in this work. This study highlights the environmental trade-offs and circularity benefits of design for disassembly in electric two-wheeler battery packs. While dismantlable designs show higher initial impacts, their potential for repair and reuse after damage supports long-term sustainability and resource efficiency in line with circular economy goals.

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The potential of reducing greenhouse gas emissions of lithium-ion battery production in different geographic scenarios

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ABSTRACT

Battery electric vehicles (BEVs) have emerged as a promising solution for the transition towards sustainable mobility, offering the potential to decrease greenhouse gas (GHG) emissions and reducing dependence on fossil fuels. However, while BEVs offer the potential for reduced emissions during operation, battery manufacturing processes are associated with considerable carbon footprints. Furthermore, the choice of cathode material significantly influences the environmental impact created by lithium-ion battery production. The current state-of-the-art route of production of lithium-ion batteries occurs mainly outside of Europe and to a large extent in countries owning a greenhouse gas-intensive electricity mix, resulting in a significant quantity of emissions generated. As the European Green Deal promotes sustainable production and use of batteries within the EU, this paper investigates GHG emissions generated by a hypothetical battery manufacturing scenario occurring in Europe, using the framework of Life-Cycle Assessment, and compares them to the conventional production route occurring globally and mainly in Asia. The results are retrieved for different battery types and for both, a hypothetical European Route and a Conventional Route, per 1 kWh of battery pack produced. The cathode chemistries under scope are NMC111, NCA and LFP, representing the state of the art of today's automotive battery technology. The outcomes of this paper highlight that the European production route shows a significant potential for greenhouse gas reduction (approximately 40 % for all

battery chemistries) in comparison to the Conventional Route. Besides highlighting the high relevance of local material sourcing and battery production, the results also outline the necessity of using renewable energy sources for the entire process of lithium-ion battery production. In this way, a holistic consideration of influencing factors supports a detailed discussion and derivation of recommendations with the target to make the production of lithium-ion batteries more sustainable.

1. INTRODUCTION

The transition towards sustainable mobility has gained increasing importance in recent years, driven by the urgent need to reduce greenhouse gas (GHG) emissions and mitigate climate change. Battery electric vehicles (BEVs) have emerged as a key solution in this transition, offering the potential to reduce emissions and decrease reliance on fossil fuels. However, while BEVs produce lower emissions during operation compared to internal combustion engine vehicles (ICEVs), the environmental impact of their production—particularly the manufacturing of lithium-ion batteries (LIBs)—remains a significant concern.

LIBs, essential for powering BEVs, are responsible for considerable GHG emissions during their production. Figure 1 illustrates this dynamic by comparing the lifecycle emissions of a BEV and an ICEV. To achieve an early break-even point in terms of emissions, both using a high share of renewable energy in the Use-Phase and employing a low-emission battery production process are crucial.

A key factor influencing the environmental impact of LIB production is the choice of cathode materials. Various cathode chemistries have been developed, each offering distinct advantages and disadvantages in terms of performance, cost, and sustainability. The material selection plays a critical role in determining the overall emissions associated with battery manufacturing.

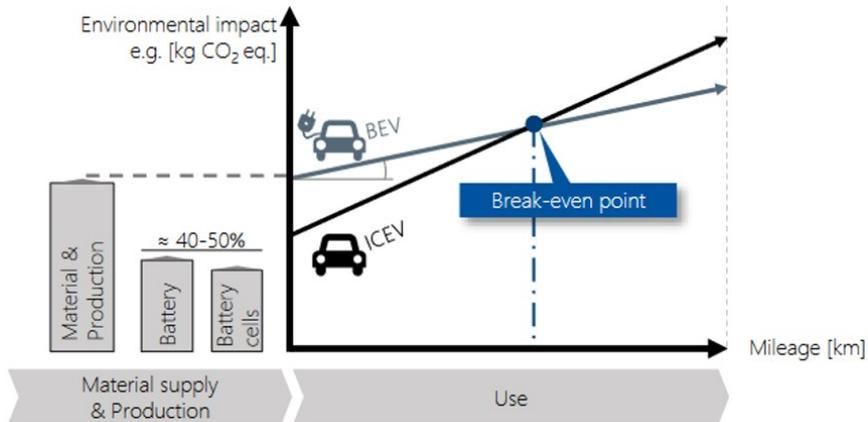


Figure 1: Comparison of generated GHG emissions over lifetime for a BEV and an ICEV. Adapted from [6].

Currently, most LIB production takes place outside of Europe, often in regions with carbon-intensive electricity grids, leading to significant emissions. Additionally, the reliance on global supply chains for critical raw materials – such as lithium, cobalt, and nickel – poses sustainability challenges, including ethical concerns related to mining practices and resource extraction. Addressing these issues requires a comprehensive approach that integrates environmental and social considerations into battery production and supply chain management.

Recognizing these challenges, the European Union has introduced regulatory measures aimed at promoting sustainable and responsible battery production. Initiatives such as the Circular Economy Action Plan - one of the main building blocks of the European Green Deal, seek to establish a circular economy, reduce carbon emissions, and enhance the sustainability of LIB manufacturing within Europe [4].

Against this backdrop, this study assesses the greenhouse gas emissions generated during lithium-ion battery production in Europe, using a Life Cycle Assessment (LCA) framework, per 1 kWh of battery pack produced. The results are then compared to the conventional global production route. Given

the diversity of LIB chemistries available, the study focuses on three common cathode types: NMC111, NCA, and LFP.

2. METHODOLOGY

Life Cycle Assessment is the methodology applied in this study, based on DIN EN ISO 14040/44, which can be used to evaluate the environmental impacts and resource consumption associated with a product's entire life cycle, from raw material extraction through production, use, and waste management. An LCA study consists of the following four phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation [5].

The goal and scope of this study is assessing and comparing the amount of greenhouse gases generated by the production of 1 kWh energy storage capacity of an NMC111-type, an NCA-type and an LFP-type lithium-ion battery pack, taking place in two different production routes. The first route involves the conventional production process, wherein all materials incorporated in the battery pack and the battery pack itself are manufactured in locations that represent the state of the art (e.g., China, Australia, Congo, etc.). The second route involves the production of materials included in the battery pack and the battery pack itself in a hypothetical "European Route", with the majority of production occurring in Europe. The emissions generated by transportation processes occurring in the production of the Cathode Active Materials (CAMs) are determined as well for both routes.

The system boundary is limited to the production of the battery pack, which encompasses the sourcing of raw materials, processing and refining to form materials, and battery manufacturing. This system boundary represents a cradle-to-gate approach and is employed to facilitate a comparative analysis of the NMC111-, NCA- and LFP-type batteries. The assumed energy densities for the battery packs are 158 Wh/kg for NMC111, 170 Wh/kg for NCA and 133 Wh/kg for LFP [2]. The production stages of the following constituents are included: NMC111-CAM, NCA-CAM, LFP-CAM, synthetic graphite, natural graphite, electrolyte, current collectors, constituents made of copper and aluminum, separator, constituents made of polymers, constituents made of steel and stainless steel, binder, thermal insulation, coolant, battery management system (BMS), NMP, aluminum oxide and the battery assembly process. Furthermore, the transport processes occurring in the cathode active material are considered.

All data for the LCI was collected from the GREET 2022 model [8], reports/publications from Argonne National Laboratory and other scientific literature sources. All assumptions and their respective sources used in order to produce a functioning LCA model can be found in detail in [2]. The information used for creating the modelling the European Route primarily stems from [3]. The GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) is used as an LCA tool, for modelling of both scenarios. It was developed by the Argonne National Laboratory, designed to evaluate energy and environmental effects (emissions of greenhouse gases, water consumption, emissions of air pollutants) of transportation fuels, vehicle technologies, energy systems and other end-use sectors [1].

A visual representation of production locations and transportation routes occurring in the production of the CAMs, for the conventional and the hypothetical European Route, is given below in figure 2 and figure 3. Country-specific electricity mixes are used for each production activity in the respective location, except for some specific components in the European Route for which the European average electricity mix is used.

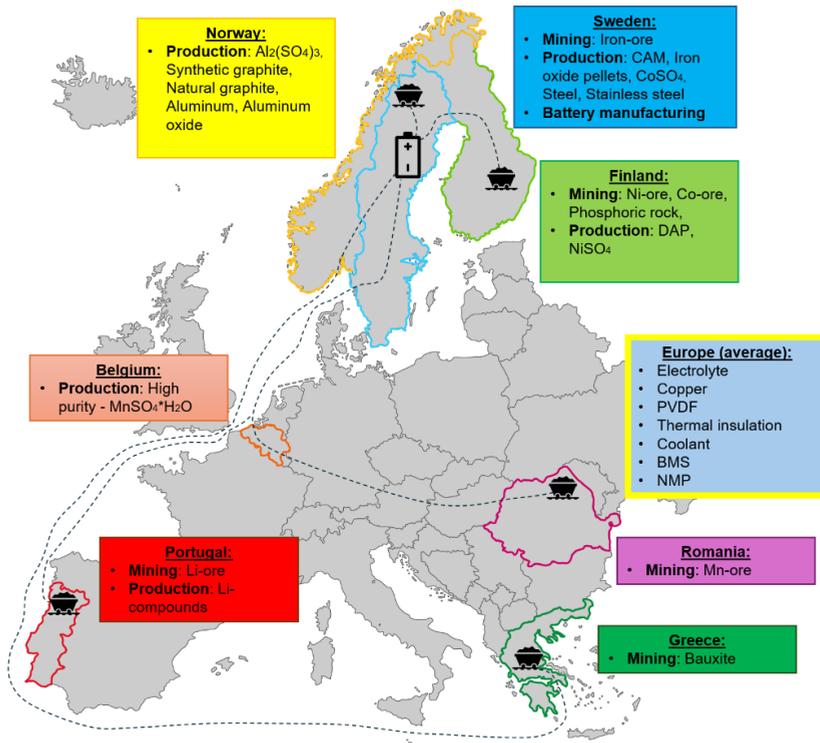


Figure 2: Visual representation of potential production locations and transportation routes occurring in the production of the CAMs, for the European Route.

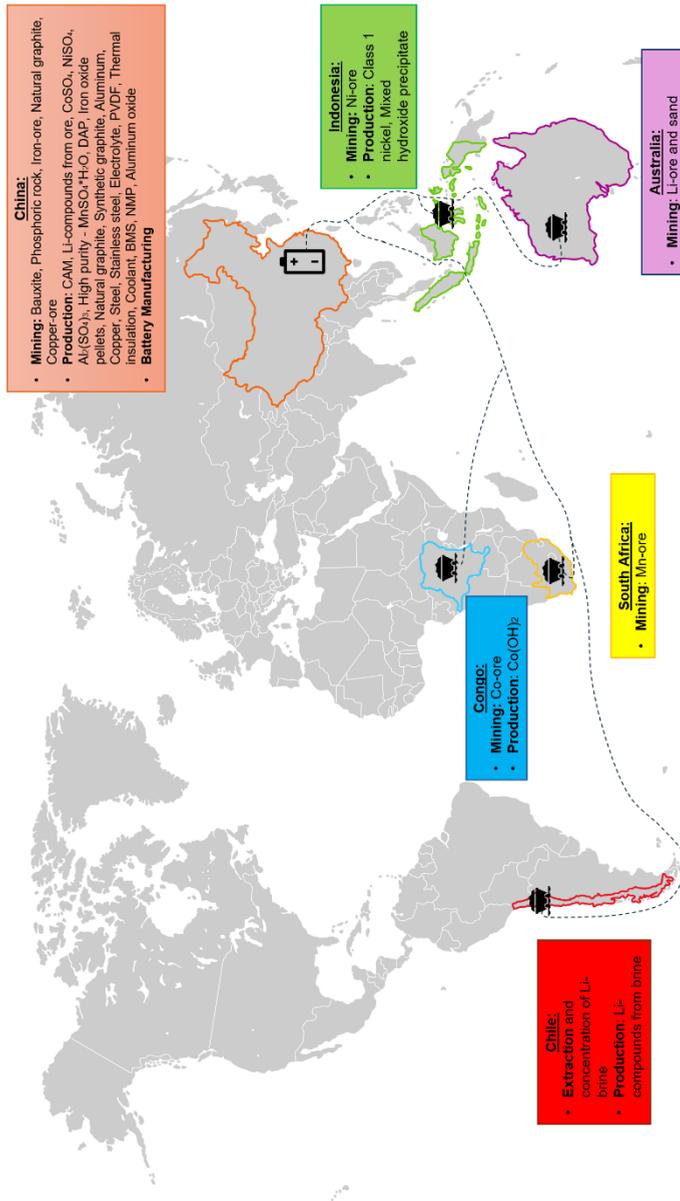


Figure 3: Visual representation of production locations and transportation routes occurring in the production of the CAMs, for the Conventional Route.

3. LCIA-RESULTS AND INTERPRETATION

Since lithium compounds are needed to produce the cathode active materials, GHG emissions generated by their production are calculated and presented in figure 4, for the Conventional Route and the European Route. For CAMs with high nickel concentrations, such as NMC811 and NCA, typically $\text{LiOH}\cdot\text{H}_2\text{O}$ is used as a lithium compound for its production. In contrast, CAMs without or with low nickel concentrations, like NMC111 and LFP, use Li_2CO_3 [7]. Li_2CO_3 and $\text{LiOH}\cdot\text{H}_2\text{O}$ can both be produced either from lithium-rich brine or lithium-containing ores, such as spodumene.

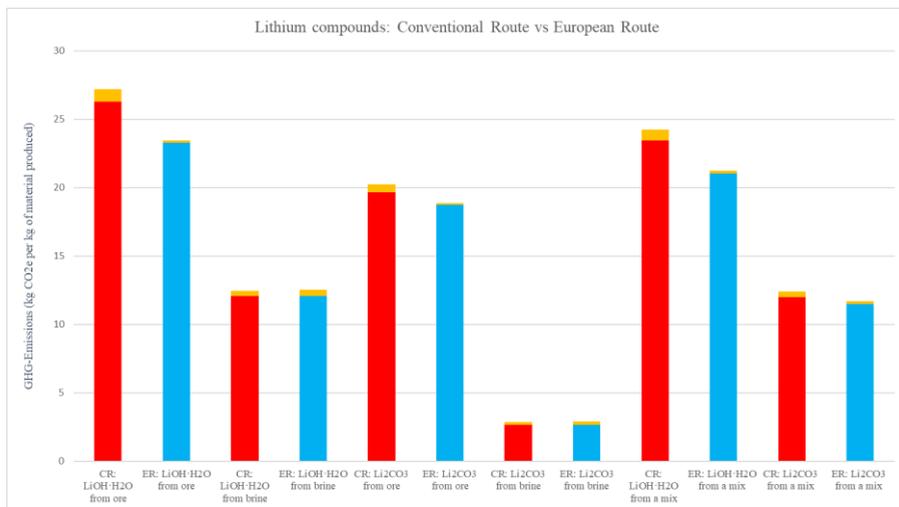


Figure 4: GHG emissions generated by the production of 1kg of lithium compound from different Li-feedstocks and a Li-feedstock mix, represented for the Conventional Route (CR) and the European Route (ER). Red/blue bars: GHG emissions from material production; Orange bars: GHG emissions from transport

Figure 4 illustrates that $\text{LiOH}\cdot\text{H}_2\text{O}$ production from ore has the highest global warming potential, followed by Li_2CO_3 from ore, then $\text{LiOH}\cdot\text{H}_2\text{O}$ from brine, and finally Li_2CO_3 from brine. A reduction in GHG emissions of approximately 14% can be observed in the European production route of lithium hydroxide from ore in comparison to the Conventional Route, which is attributed to the less GHG-intensive electricity mix in the European Route. Additionally, shorter distances for transportation are utilized. The same appears for Li_2CO_3 production from ore, although the reduction is less significant. The GHG emissions generated due to the production of the lithium

compounds made of brine are marginally higher for the European Route. This is due to the fact that the road transport distance for trucks is greater for the European Route. $\text{LiOH}\cdot\text{H}_2\text{O}$ and Li_2CO_3 made from brine are already produced in Chile for both routes, thus their production cannot benefit from the electricity mix in Portugal. The production of lithium compounds from a lithium-feedstock mix, representing the production of lithium compounds the best, exhibits a reduction in GHG-emissions of approximately 12% for $\text{LiOH}\cdot\text{H}_2\text{O}$ and 6% for Li_2CO_3 , when comparing the European Route to the Conventional Route.

Figure 5 presents a comparison of cathode active materials production for both routes. Here, NCA is responsible for the greatest quantity of GHG emissions. This is due to the fact that lithium hydroxide is employed in the manufacturing process, which is more emission-intensive than lithium carbonate, which is utilized in the production of the CAMs NMC111 and LFP. Furthermore, NCA exhibits the highest nickel-ratio among the other CAMs, indicating that a high quantity of nickel sulfate is utilized in its synthesis. Nickel sulfate and cobalt sulfate are the most GHG-intensive precursor chemicals per kg of product, among all batteries under scope (for both routes) [2]. Both chemicals are necessary for the synthesis of NCA and NMC111. Additionally, aluminum sulfate is needed for the synthesis of NCA and manganese sulfate for NMC111 – being, together with iron oxide and diammonium phosphate (DAP), the least GHG intensive precursor chemicals for both routes of CAMs [2].

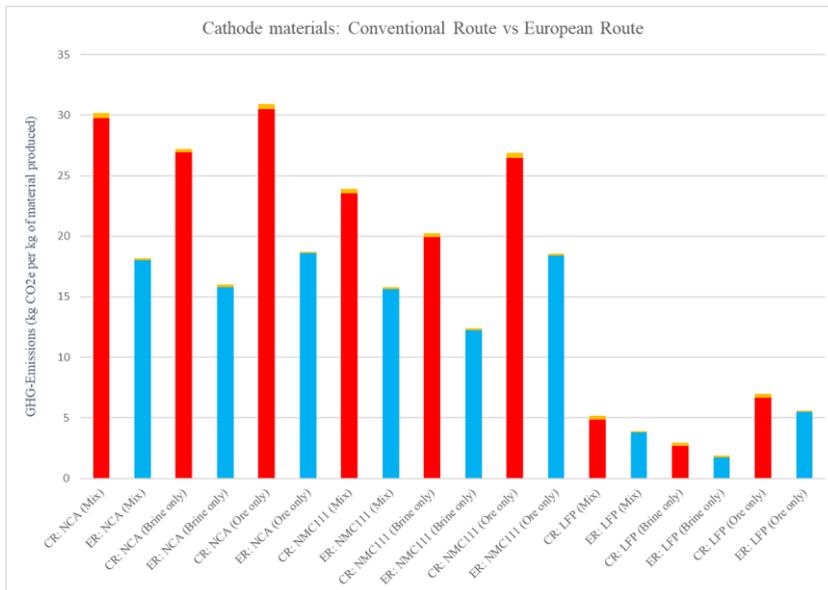


Figure 5: GHG emissions generated by the production of 1kg of CAM from different Li-feedstocks and a Li-feedstock mix, represented for the Conventional Route (CR) and the European Route (ER). Red/blue bars: GHG-emissions from material production; Orange bars: GHG emissions from transport

NMC111 exhibits a lower nickel ratio, which means a lower quantity of nickel sulfate and a higher quantity of cobalt sulfate and manganese sulfate are used in its synthesis than for NCA. Furthermore, lithium carbonate is used in its production instead of lithium hydroxide. These facts result in a lower global warming potential for NMC111 compared to NCA.

LFP employs iron oxide, DAP and lithium carbonate in its synthesis, which accounts for the CAM's superior performance in terms of low GHG-emissions (approximately six times less GHG intensive than the NCA CAM). Nevertheless, it is not the case that the LFP battery pack causes also six times less GHG than the NCA battery (see figure 6). This is because the specific energy density of LFP batteries is lower than that of NCA batteries, which means that a greater amount of CAM is required to reach the same energy capacity.

For NCA and NMC111, the transport emissions account for approximately 1% of the total emissions, due to their emission-intensive production. In contrast, for LFP, the transport emissions represent approximately 10% of the

total emissions, given that its production is less emission-intensive than that of the other CAMs.

Figure 6 illustrates an overview of the differences in GHG-emissions generated in the production of the battery types under scope, for the Conventional and the European Route. It can be seen that the NCA and NMC111 - type batteries show approximately the same quantity of GHG-emissions per kWh (1,8% lower emissions for NMC in the CR compared to NCA; 2,1% lower emissions for NCA in the ER compared to NMC111), despite the fact that NMC111 uses less intensive CAM upstream materials than NCA. The reason for that is the lower energy density provided by the NMC-battery, which leads to a higher amount of material in the battery. Thus, energy density is an important parameter, significantly influencing the resulting GHG-emission intensity of batteries.

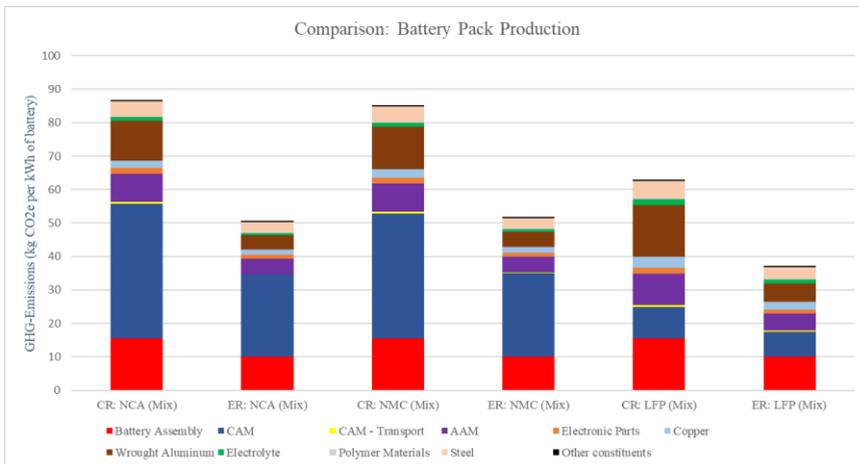


Figure 6: Comparison of results of all battery types, for the Conventional Route (CR) and the European Route (ER) in the Li-feedstock mix scenario.

The LFP-type battery exhibits a reduction in GHG emissions of 27.6% in comparison to NCA and 26.3% in comparison to NMC111, when utilizing the Conventional Route. With regard to the European Route, LFP is observed to result in a reduction in GHG emissions of 26.6% in comparison to NCA and 28.2% in comparison to NMC111. Consequently, the low emission level generated by the production of its upstream materials outperforms the lower energy density of LFP. However, LFP can be produced through either the hydrothermal or solid-state synthesis method. The solid-state synthesis route, which is employed in the model, is considerably less energy-intensive in its

production, resulting in relatively low GHG emissions for the LFP battery. In other life cycle assessment studies, LFP has been found to exhibit a global warming potential that is comparable to that of NMC and NCA. This observation can be attributed to the fact that LFP is produced using the hydrothermal synthesis route in those studies. However, solid-state synthesis is the well-established route for producing LFP commercially [1] and therefore considered in the present investigation.

4. CONCLUSION

It is possible to reduce the GHG emissions generated by LIB battery production by approximately 40% for all battery chemistries, by employing production in Europe. In addition, the applied lithium feedstock in CAM manufacturing has a relevant impact. If lithium brine is applied for manufacturing of lithium compounds, the emissions are significantly lower compared to production from lithium ore. Additionally, it has been found that producing Li_2CO_3 is less GHG intensive than $\text{LiOH}\cdot\text{H}_2\text{O}$, if the same type of feedstock is used for its production. Nevertheless, this does not necessarily imply that Li_2CO_3 should be employed in preference to $\text{LiOH}\cdot\text{H}_2\text{O}$, given that $\text{LiOH}\cdot\text{H}_2\text{O}$ is typically utilized in cathode chemistries that provide a high energy density, which subsequently also reduces the total GHG emissions of battery production, related to the energy storage capacity. The CAM pre-chain materials exhibit varying levels of generated GHG emissions. The pre-chain materials of LFP typically demonstrate significantly lower emissions than the pre-chain materials of NMC111 and NCA. For NMC and NCA, the highest carbon footprint is attributed to NiSO_4 and CoSO_4 . Transport emissions generated by the production of the CAMs are negligible in comparison to the production processes occurring in CAM production, despite the transportation distances being very high for the conventional route.

The study shows that the most GHG emission-intensive processes are CAM production, battery manufacturing, AAM production and aluminum production (the sequence depends on the investigated battery-type). The LFP-type battery pack generates the least quantity of GHG emissions for both routes. The NCA- and the NMC111-type battery show similar results for both the conventional and the European route.

In conclusion can be stated, that if LIBs for BEVs shall generate low levels of GHG emissions during production, lithium brine should be used as a feedstock (regardless of whether Li_2CO_3 or $\text{LiOH}\cdot\text{H}_2\text{O}$ is produced). In addition, LFP should be chosen as a CAM and produced by solid-state synthesis, and

finally, all processing steps should be executed at locations with low GHG emission - electricity mixes. Even if a production in the Europe-only Route may not be entirely realistic, the paper demonstrates the potential for climate change mitigation of a hypothetical production scenario of LIBs in Europe. Furthermore, for production of next generation batteries, such as solid-state batteries or sodium ion batteries, the above-described findings can potentially be valid, too.

Not considered in the study, but also of relevance are strategic and economic factors. Automotive battery production in Europe not only has potential to lower the GHG emissions, but also represents a relevant factor for the local industry. In this context it is important to expand the European battery production with the target to intensify the involvement of local supplier industry, engineering services and research institutions. Considering the global market situation of battery production today, the Europe-only route would not be capable of delivering 100% supply of raw materials and production capacity for the European demand within competitive economic boundary conditions. Nevertheless, an increase of European contribution to automotive battery production can support both, reduction of greenhouse gas emissions and transferring relevant shares of value creation into the European market.

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Influence of early-stage design choices on the environmental performance of repurposed lithium-ion batteries

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ABSTRACT

Lithium-ion batteries (LIBs) are a key technology in decarbonisation, particularly for their use in electric vehicles (EVs) and battery energy storage systems (BESS). Nevertheless, their production is associated with significant environmental impacts. Repurposing LIBs after their use in EVs for less demanding applications, such as BESS, has the potential to reduce these impacts. However, current repurposing efforts face several technical challenges, often requiring the replacement of key components. For example, the module casing might be damaged during disassembly, while the battery management system (BMS) is typically replaced because it is not programmed for stationary applications and contains sensitive data belonging to original equipment manufacturers (OEMs). This study examines how specific early-stage design choices influence the environmental impacts of second-life applications. A life cycle assessment (LCA) of a BESS equipped with repurposed LIBs was conducted, evaluating different repurposing scenarios based on the reuse or replacement of the BMS and module casing. The results revealed a superior environmental performance of second-life BESS compared to new systems in four out of five analysed impact categories. The lowest impacts were identified when both the module casing and the BMS were reused, while the highest impacts were observed when both components were replaced. These results underscore the importance of designing LIBs to enable component reuse and facilitate a more sustainable repurposing process. A “circular by design”

approach could involve avoiding adhesive connections to prevent damage to battery components, particularly the module casing, while maintaining safety. Additionally, integrating a BMS reset function, as suggested in the EU battery regulation 2023/1542, could enhance the sustainability of repurposed LIBs without compromising data confidentiality.

1. INTRODUCTION

In accordance with the European Green Deal, the European Union has formally committed to achieving climate neutrality by the year 2050 (European Commission, 2019). As part of the ongoing efforts to reduce carbon emissions, lithium-ion batteries (LIBs) are regarded as a pivotal technology. Consequently, the demand for LIBs is continuously increasing, primarily driven by the expansion of the electric vehicle (EV) fleet. However, LIBs also play a crucial role in battery energy storage systems (BESS), which facilitate the widespread integration of renewable energy sources (Bielewski et al., 2022). Despite their importance in decarbonisation efforts, the production, use, and recycling/disposal of LIBs are associated with significant environmental impacts and supply chain risks due to critical raw materials (CRMs), such as cobalt, lithium, and graphite (Buchert et al., 2017; Windisch-Kern et al., 2022).

Integrating circular economy strategies, such as repurposing and recycling at the early-design stage of LIBs, has the potential to improve their environmental performance. Repurposing end-of-life (EoL) LIBs from EVs for use in BESS extends their lifespan and reduces pressure and dependencies on CRM supply chains, before ultimately enabling the recovery of valuable materials through recycling (Kotak et al., 2021).

However, existing efforts face several technical challenges, often requiring the replacement of key components (Prenner et al., 2024b). For instance, module casings may need replacement for safety reasons due to potential damage sustained during disassembly. The battery management system (BMS) is typically replaced because it is not configured for stationary applications and may contain proprietary data belonging to original equipment manufacturers (OEMs) (Bobba et al., 2018b; Börner et al., 2022). This study investigates how specific early-stage design choices influence the environmental impacts of second-life applications.

2. METHODOLOGY

A life cycle assessment (LCA) of a BESS utilising repurposed LIBs (i.e., second-life BESS) was conducted. The goal of the LCA was to identify potential environmental benefits of second-life BESS, assuming different repurposing strategies. The system boundary is displayed in Figure 1.

Four repurposing strategies were assessed, each taking a different approach to the reuse of battery components, i.e., the module casing and BMS in the second life. All cases included the repurposing and testing of the battery cells. The summarised assumptions can be found in Table 1.

Table 1: Repurposing assumptions

	Testing	Reuse battery cells	Reuse module casing	Reuse BMS
Base case	x	x		
Case 1	x	x	x	
Case 2	x	x		x
Case 3	x	x	x	x

A BESS equipped with new batteries served as a reference scenario for comparative analysis. For both systems, a capacity of 14.4 kWh and nickel manganese cobalt oxide (NMC 111) battery chemistry were assumed. The functional unit was 1 kWh of energy delivered by the battery to meet the electricity demand of an average German household until it reaches a lower capacity than the daily household demand. A two-person household was considered with an average daily electricity demand of 8.7 kWh (Statistisches Bundesamt, 2023). The capacity loss due to ageing processes during each cycle was determined using an equation based on Han et al. (2014). More details can be found in Spindlegger et al. (2025).

LCA for Experts (Sphera, 2024) was used as a software, *Ecoinvent 3.8* (Wernet et al., 2016) served as a database, and *ReCiPe 2016* (Huijbregts et al., 2017) was chosen as an impact assessment method. The results are presented for five selected impact categories: Climate change (CC), Ecotoxicity freshwater (ET_{fw}), Human toxicity, cancer (HT_c), Metal depletion (MD) and Terrestrial acidification (TA). By choosing these categories, a comprehensive

coverage of all three endpoint categories (damage to human health, ecosystems, and resource availability) was ensured.

To address the multifunctionality of the repurposed components, allocation was applied to distribute the environmental impacts of production and EoL treatment between their first life in an EV and second life in a BESS. It was assumed that 25% of the impacts were allocated to the battery's second life and 75% to its primary function in the car, in accordance with the literature (e.g., Bobba et al., 2018a; Wilson et al., 2021).

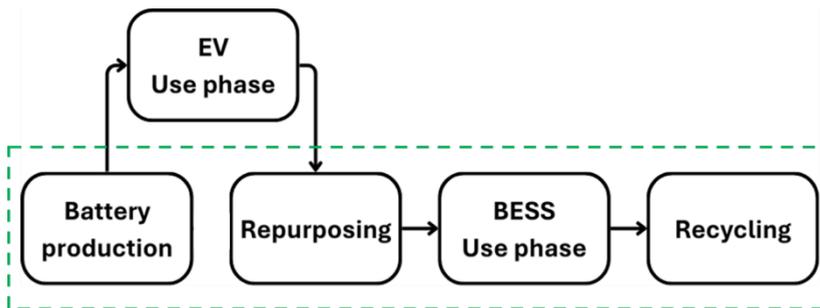


Figure 1: System boundary

3. RESULTS

The results highlight the substantial environmental benefits of second-life BESS across various impact categories and repurposing scenarios. Figure 2 presents the normalised LCA results for the second-life BESS across the assumed cases. Compared to a BESS with new LIBs, the second-life BESS consistently demonstrates superior environmental performance for MD, CC, HT_c , and TA. The most favourable outcome is observed in Case 3, where both the module casing and BMS are reused, achieving the highest reductions of 61% for MD. For HT_c and MD, reusing only the module casing (Case 1) proves more advantageous than reusing only the BMS (Case 2), with savings of 32% for HT_c and 61% for MD. This is attributed to the significant environmental impacts associated with steel production for the module casing. Conversely, Case 2 is more beneficial for CC and TA with reductions of 40% and 50%, respectively. For ET_{fw} , environmental benefits are only observed in the Base case and Case 1. In contrast, Case 2 and Case 3 result in higher impacts, with increases of 22% and 20%, respectively, compared to the new BESS. This is primarily due to reduced recycling credits from BMS treatment in the EoL phase, as a portion of these credits is allocated to the battery's first life. A

sensitivity analysis demonstrated that fully allocating the EoL impacts, including the environmental credits, to the battery’s second life eliminates these drawbacks and significantly enhances environmental savings (Spindlegger et al., 2025).

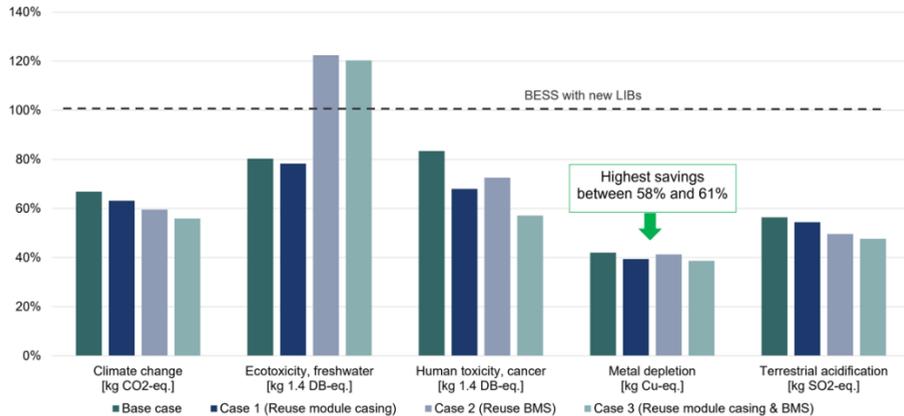


Figure 1: Normalised environmental life cycle impacts of a second-life lithium-ion battery storage system compared to a new lithium-ion battery storage system, which is the reference scenario

4. DISCUSSION AND CONCLUSIONS

LCAs can be a versatile tool for decision-making in battery design, enabling the consideration of environmental aspects in the early development stage. However, from a methodological perspective, our LCA study highlights the substantial influence of allocation procedures on overall environmental impacts, underscoring the need for more explicit methodological guidance on how to allocate environmental burdens between different life cycle stages. In other words: How should the credits be distributed among the different sectors (e.g., cell producers, car manufacturers, repurposing companies, recyclers, etc.)? To address this, the Circular Footprint Formula (CFF) represents a harmonised method for calculating a product’s environmental footprint and provides a structured approach to allocating environmental burdens and credits in the EoL phase (European Commission, 2021). However, applying the formula to second-life batteries remains challenging due to its methodological complexity and numerous parameters involved. Alternatively, multifunctionality problems in LCAs could also be addressed through system expansion.

This approach provides a more comprehensive view of environmental effects by considering all battery life stages in one LCA model.

From a practical standpoint, the results provide actionable recommendations for improving the environmental performance of BESS and offer valuable input for integrating repurposing strategies early in the innovation phase of new LIB systems. Furthermore, these findings show the potential of early-stage design considerations to improve the environmental impacts of LIBs by extending their lifespan and contributing to their circularity. Specifically, re-using both the module casing and BMS proved to be environmentally beneficial. However, implementing such strategies requires a change in battery design practices. Current battery designs are highly diverse and often rely on adhesives and welding techniques, which pose substantial challenges to the disassembly process. Likewise, enabling the reuse of the BMS requires safeguarding OEM data (Prenner et al., 2024b). To address such challenges, the battery regulation (Regulation 2023/1542) recommends developing standards for design and assembly techniques that facilitate repurposing. For instance, a modular design would improve repairability, reuse and repurposing. Moreover, the replacement of adhesive connections with mechanical options, such as screws, would improve manual or automated disassembly processes. Incorporating a reset function in the BMS, as suggested in the battery regulation, could provide a practical solution to ensure OEM data protection while allowing for reuse. Such standards could provide guidance for battery manufacturers in designing LIBs that are optimised beyond their first life, enabling more efficient resource utilisation and supporting circular economy actions. To ensure the feasibility and acceptance of design standards, without imposing overly restrictive design constraints, their development should involve relevant stakeholders, including OEMs, policymakers, repurposing operators, and researchers (Prenner et al., 2024a). Incorporating these early in the design phase can help overcome technical barriers and, consequently, reduce the costs associated with LIB disassembly and component replacement (Prenner et al., 2024b). This, in turn, renders repurposing and recycling more technically and economically viable.

Overall, battery design choices should not be limited to the initial application but should instead embrace a life cycle perspective in the sense of the 9R strategy of the circular economy (Potting et al., 2017). Such “circular by design” approaches, similar to eco-design principles, could effectively integrate repair, refurbish, reuse and repurposing considerations into the design phase, ultimately supporting the transition to more sustainable battery value cycles. However, future research is still required to evaluate the economic feasibility,

as well as the suitability across different battery types and applications of the proposed design strategies.

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Day 1 Session: Enhancing Resource Efficiency and Circularity in the Transport System

Promoting Electrification of Regional Rail Transport through Shared Charging Infrastructure with Road Vehicles

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EXTENDED ABSTRACT

Electrification of regional railway systems constitutes a promising strategy for reducing greenhouse gas (GHG) emissions and improving air quality in the transportation sector. While full electrification via overhead line equipment (OLE) is technically viable for high-density corridors, it is often not economically justified on low-traffic routes due to high infrastructure costs relative to usage levels. Battery-electric trains (BETs) have therefore emerged as a potentially cost-effective and operationally flexible alternative. However, the reliance on large onboard battery systems—required to span extended un-electrified segments—brings about several drawbacks, including significant capital and lifecycle costs, and notable environmental impact related to battery manufacturing and charging facilities. To address these challenges, this study proposes a shared charging infrastructure model for both rail and road vehicles, combining static and dynamic charging strategies. Static charging refers to energy transfer while the train is stationary, usually at stations, and can be implemented with relatively low capital investment. Dynamic charging involves supplying energy during motion via Electric Road System (ERS) technologies. Solutions developed by companies such as Alstom [1],

Electreon [2], Honda [3], and Elonroad [4]—originally intended for road applications—utilize conductive strips or inductive pads embedded along the vehicle path, and are proposed here for potential investigation and adaptation in shared rail–road contexts. A MATLAB-based simulation model is developed based on the Borlänge–Malung railway corridor in Sweden, a 129-kilometre regional line with 12 intermediate stops. The train modeled in the study is 15 meters long, weighs approximately 30 metric tons, and has an average auxiliary power demand of 15 kilowatts (kW) (These parameters are based on data provided by Flagship Project 6: FUTURE [5].). The estimated energy consumption for a full round trip—factoring in route topography, driving profiles, and stop patterns—is around 230 kilowatt-hours (kWh). Two battery charging configurations are evaluated. In the first, the train is equipped with a 300 kWh battery charged once at the origin, resulting in deep discharge cycles and associated accelerated battery degradation. In the second, a smaller 210 kWh battery is supported by three intermediate static charging sessions—each lasting two minutes—at selected stations. The simulations suggest that this distributed static charging approach can help reduce battery capacity needs, lower battery-related manufacturing emissions by up to 30%, and extend battery life by reducing depth of discharge (DoD). In same scenario, a hybrid setup is investigated, in which short dynamic charging segments (500 meters before and after selected stations) supplement the static chargers. Although this approach offers further reduction in DoD and could potentially halve the environmental impact and cost related to battery manufacturing, it requires significantly higher upfront investment. Elonroad’s pricing data indicate that the capital cost of rail-compatible dynamic charging infrastructure scales significantly with the total length of deployment, making extensive implementation economically challenging without shared usage. As such, dynamic charging may be more viable when deployed in contexts where its use is shared with multiple vehicle types and rail applications represent a relatively small share of total demand. A design of the shared road-rail infrastructure would obviously be subject to the regulation guaranteeing safety of rail system and train operations. To assess the overall cost-benefit trade-off, a sensitivity analysis is performed. It shows that increasing the number of static charging stations leads to battery cost reductions, primarily due to improved battery longevity, until a saturation point is reached. Beyond this point, the marginal benefits taper off. In one example, operating a train with a 300-kWh Lithium Iron Phosphate (LFP) battery and a single static charger yields a life-cycle battery and charging infrastructure cost of approximately €0.017 per kilometer. However, when six static chargers are shared with other electric vehicle users (with rail usage representing only 20% of the total charging load), the cost per kilometer is reduced below the baseline case. This improvement is not only attributable to cost-sharing but also to shallower DoD, which

enhances battery longevity and, correspondingly, reduces the environmental impact linked to battery manufacturing and associated carbon dioxide (CO₂) emissions. Although dynamic charging may offer some operational flexibility, its cost-effectiveness depends on widespread cross-sector participation. If trains only account for a small fraction, e.g. 1%, of the total energy transferred by a shared ERS system, and dynamic segments are deployed at multiple points along the route (e.g., six segments of 1 km each), the total system cost can still be lower than for a train relying solely on a large battery and a single static charger. Nevertheless, this relies heavily on external demand and coordinated infrastructure planning. From a system-level perspective, shared charging infrastructure, whether static or dynamic, may contribute to a more resilient and efficient transport energy network. Such developments are consistent with the European Union's broader strategic objectives for sustainable mobility and emissions reduction, as outlined in long-term climate and energy policy frameworks [6]. The proposed infrastructure-sharing approach could therefore represent one promising pathway toward more affordable, scalable, and sustainable regional rail electrification. In summary, this study suggests that integrating shared charging infrastructure into regional rail operations may help address the technical and economic challenges of battery-electric trains. A balanced deployment of static and dynamic charging, particularly when utilized by both rail and road vehicles, can reduce battery size requirements, mitigate CO₂ emissions from battery production, and lower total system costs. While further research and real-world trials are needed, the findings highlight the potential of shared, multimodal energy infrastructure as a viable enabler for cleaner and more sustainable transportation.

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Exploring the landscape of circularity indicators: A systematic review with focus on nano- and micro indicators for the assessment of biobased materials and products

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EXTENDED ABSTRACT

The transition towards a circular economy necessitates reliable metrics for evaluating the effectiveness of circularity measures (e.g., reuse, re-manufacturing, or recycling) employed in products and technologies (Peña et al., 2021). Various metrics and indicators have been proposed to measure circularity; however, due to their consideration of different aspects in their assessment, these tend to give varied results (Corona et al., 2019; Vural Gursel et al., 2023). To assess circularity on a sound basis, it is necessary to identify and utilize circularity indicators fit for a given context. Therefore, this paper aims to systematically explore proposed circularity indicators by classifying them according to multiple criteria, with a focus on their suitability for assessing specific R-strategies (as defined by Reike et al., 2018) and their ability to account for the use of biobased materials. In a second step, a set of suitable indicators will be applied to a case study of a novel wood-hybrid battery compartment (Krassnitzer et al., 2025; Wagner et al., 2024) for battery electric vehicles (BEV).

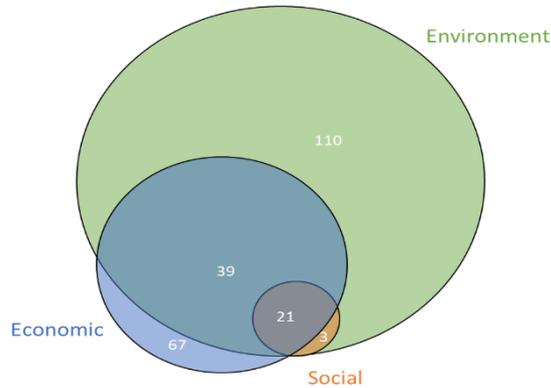


Figure 1: Dimensionality of the circularity indicators. The environmental dimension includes aspects such as the share of renewable materials, material waste, and emissions of a material or a product. Economic aspects include durability and utility, as well as value added. Social aspects may be the creation of jobs and social well-being.

This research is part of an ongoing effort to understand and enhance the circularity of renewable materials in contemporary manufacturing and product design. Therefore, a literature review has been conducted to identify relevant circularity metrics. Through the snowballing technique, circularity indicators have been extracted from previously conducted reviews on circularity metrics (Corona et al., 2019; Harris et al., 2021; Oliveira et al., 2021; Saidani et al., 2019; Vural Gursel et al., 2023). Additionally, a literature search within the date range of 2022-2025 with relevant search terms has been conducted. The identified indicators have been evaluated based on multiple criteria, such as their consideration of R-strategies, the consideration of biobased materials, the scale on which the indicator assesses circularity (material, product, companies or regional areas), the dimensionality (economic, environmental, and/or social) of the indicators, and more. The systematic literature search yielded 303 circularity indicators, of which 120 were deemed eligible for our study. These indicators are displayed in Figure 1 and are clustered by their dimensionality. As can be seen, 21 indicators were found that consider the environmental, economic, and social dimensions. Most of the indicators considered solely the environmental dimension (47), followed by indicators that account for both the economic and environmental dimensions (39), and a smaller fraction considered only economic aspects (7). From all investigated indicators, 69% assess circularity on a product level, 20% on the material

level, and the remaining 11% can assess on both scales. Figure 2 shows the number of indicators that account for a specific R-strategy.

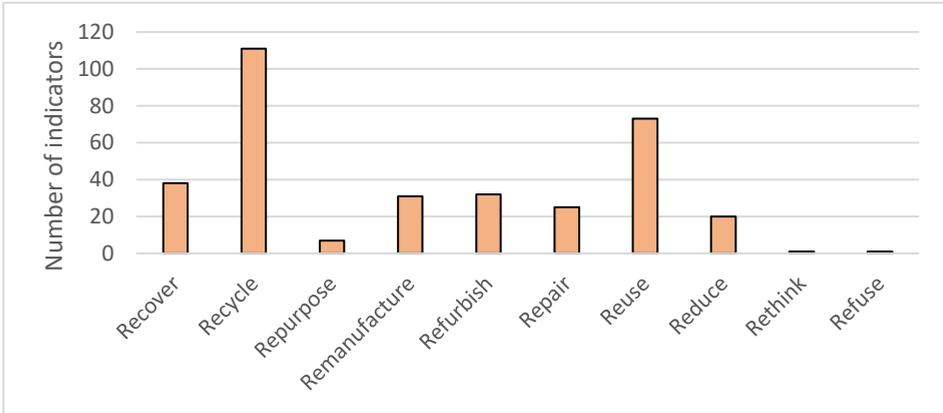


Figure 2: Indicators and their consideration of different R-Strategies

As can be seen, most indicators are able to account for the R-strategy Recycle (111), followed by Reuse (73) and Recover (38). Some indicators also account for different R-strategies such as Remanufacture (31), Repair (25), and Reduce (20). However, only two indicators account for the strategies Rethink and Refuse. Figure 3 displays the number of R-strategies that circularity indicators account for.

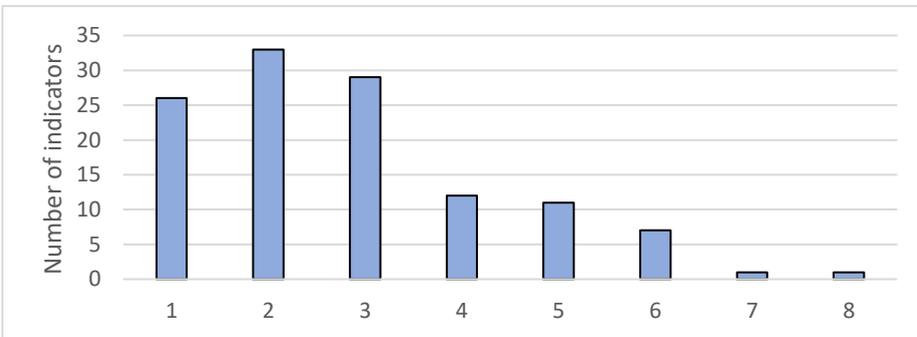


Figure 3: Number of R-Strategies covered by the indicators

It is apparent that most indicators account for a small number of R-Strategies; for example, 33 indicators account for 2 R-Strategies, and 29 indicators

account for 3 R-Strategies. A notable fact is that approximately 70% of the indicators consider only 3 R-strategies or fewer. However, two indicators stand out in this context: the 9R-Index (Muñoz et al., 2024) and the L&C indicator (Figge et al., 2018). These account for 8 and 7 R-strategies, respectively. The results indicate that assessing circularity is multifaceted, demonstrating the variability of aspects, scales, and scopes that need to be considered when evaluating circularity on various levels. Interestingly, many indicators do not even consider an environmental dimension and rely solely on economic and/or social aspects. This is somewhat unexpected, as circularity and the circular economy are closely tied to the concept of sustainability (Stahel, 2016). The focus on assessing established and well-known R-strategies, such as Recycle, and the lack of strategies like Refuse or Rethink, is also apparent in our results. The preliminary results of our study show that many indicators focus on the recyclability of materials and products. Since Recycling is considered the least preferred option from an environmental perspective, besides Recovery (Reike et al., 2018), the nature of those indicators may lead to a bias in attributing products a more circular character than they have. In other words, by not considering more preferable R-strategies than Recycling, the more effective R-strategies are not being credited enough in the face of a necessary transition towards a circular economy. Further work includes investigating the eligibility of the indicators to account for biobased materials and applying a set of indicators to the case study of a novel wood-hybrid battery compartment to benchmark them.

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Multi-Regional Input-Output analysis to improve Resource Efficiency in traction battery value chains

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ABSTRACT

Battery Electric Vehicles (BEVs) are seen as important contributors to the decarbonization of human mobility and therefore undoubtedly provide significant value. However, BEVs are also highly resource intensive throughout their life cycle, with various options for improvement, from material extraction to End of Life (EoL). This is especially true for the battery, where much of the resource use is obscured within its complex value chain. Providing the same value to humanity with fewer resources would be highly beneficial on a global scale. The idea of Resource Efficiency (RE) is to generate the most monetary benefit (e.g., GDP, value added) from the utilization of a unit of resource. This concept appears in various policy areas related to the circular economy, bioeconomy, and the United Nations Sustainable Development Goals (SDGs). To answer the research question, 'What are the potentials to increase the RE in traction batteries?', the research consists of several distinct steps: The final demand for electric equipment is isolated from other demands, represented in the Multi-Regional Input-Output (MRIO) tables of Exiobase 3 and its impacts on resource consumption are analysed. After that, the status quo RE is presented. Finally, the RE is tested on its sensitivity to modifications of the driver of its denominator as identified by Pothen (2017) by setting up an alternative scenario. Due to the sectoral resolution, the research doesn't differentiate between different chemical elements, however the results offer valuable guidance on the drivers of resource consumption in the traction battery value chain and the potentials for achieving higher RE. More specifically, this research provides insights such as preferred manufacturing locations and “material hotspots” for policymakers and industry stakeholders aiming to improve the RE of BEVs in general and batteries in particular.

1. INTRODUCTION

To reduce traffic-related emissions, electric vehicles powered by traction batteries are a promising alternative to conventional vehicles with combustion engines. This leads to an expected increase in demand for Lithium-Ion Batteries (LIBs). Depending on the scenario, even a tenfold increase of LIB demand until 2030 seems realistic (Usai et al., 2022). It is also possible that future material demand for LIBs in electric vehicles will exceed raw material production (Maisel et al., 2023). These challenges, including the scarcity of raw materials and the generation of waste, necessitate effective resource efficiency (RE) improvement strategies throughout the entire life cycle of batteries.

The emergence of potential sustainability trade-offs underlines the challenges in traction battery value chains. Sustainability trade-offs refer to the complex and often interrelated decisions that are made in the pursuit of sustainable outcomes, where improvements in one area may come at the expense of another (Morrison-Saunders & Pope, 2013). New Europe-centred recycling processes can improve the RE in certain countries (e.g., through resource efficient machinery). However, this could also lead to negative effects in other countries or inefficiencies in the global economy. The use of MRIO analysis can be a promising approach to analysing sustainability trade-offs and the associated impacts (Zimek et al, 2022). Recent literature that applied environmentally extended and socially extended MRIO analysis can be complemented using RE focused MRIO as in this research.

2. RESOURCE CONSUMPTION FOCUSED MRIO ANALYSIS

MRIO tables represent economic relationships both within and between different regions or countries. MRIO analysis can be used to assess various aspects such as outsourcing, environmental impacts, and value generation in global trade systems (Miller and Blair, 2009). Generally, the tables consist of monetary values dependent on country (or region) and economic sector (e.g., agricultural activities, mining, manufacturing etc.) (ibid.). Further intermediate and final demand is distinguished (ibid.). Examples for final demand are expenditure by households or the government (ibid.). Their demand in the different sectors causes also intermediate demand (and therefore impact) in other regions and sectors (ibid.). This enables the tracing of impacts throughout (complex) value chains (ibid.). Since all MRIO data is in monetary units,

material consumption is also expressed in monetary units, not in mass units (ibid.). For this research, the MRIO tables from the Exiobase 3 database (Stadler et al., 2025), with the most recent year 2022, are used. In addition to major economies and several European countries, the database provides data for five aggregated world regions, as shown in Figure 1 below.

region	EU	Advanced/Emerging	region group	region name
WA	FALSE	Emerging	Non-EU Emerging	RoW Asia and Pacific
WL	FALSE	Emerging	Non-EU Emerging	RoW America
WE	FALSE	Emerging	Non-EU Emerging	RoW Europe
WF	FALSE	Emerging	Non-EU Emerging	RoW Africa
WM	FALSE	Emerging	Non-EU Emerging	RoW Middle East

Figure 1: Exiobase world regions and abbreviations (according to Stadler et al., 2025)

A final advantage of using MRIO tables for resource efficiency is the inclusion of integrated value-added data. This means that no third-party source is needed to obtain value-added data. Value added can be obtained by simply subtracting the aggregated intermediate demand from the aggregated total output (Aslam et al. 2017). Detailed knowledge about batteries is not essential for this research due to the macro scale of the database and the method used.

The application of the research method consists of several distinct steps starting with goal and scope definition, followed by impact calculation, resource efficiency evaluation and scenario analysis for further interpretation (see Figure 2 below):

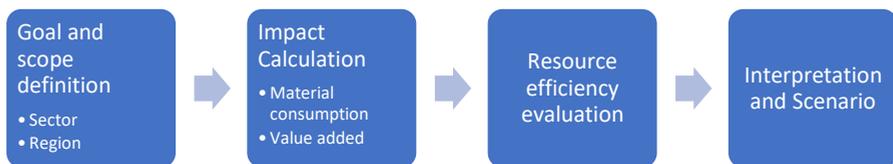


Figure 2: Research design (own illustration)

For the goal and scope definition (see figure 2), the sector and region are selected, in which the final demand for batteries occurs. In this case WE for RoW Europe was selected (meaning smaller European countries that are not

explicitly mentioned otherwise in the MRIO database, see figure 1). Then, the final demand in this sector was kept but the final demand for all other sectors and regions was set to zero. This enables the tracing of impacts caused solely by the final demand for electric equipment in smaller European countries without interference of other value chains.

Second, the impact of this selected final demand is calculated. Since this research focused on resource efficiency the following impact categories, inspired by Pothen (2017), are selected and graphically presented:

- Figure 3: Material consumption by region
- Figure 4: Material consumption by type of material (sectors)
- Appendix: Value added by region
- Figure 5: Imports and exports relative to its overall material consumption (only for one type of material)

The resource efficiency is then calculated through dividing the material consumption by region by the value added by region. This results in an overview of more and less efficient regions.

Lastly a scenario with final demand consumption in China instead of WE was set up and the changes are presented in figure 7.

3. RESULTS

In the case of the status quo, all demands are set to zero except the demand for electrical equipment from the region WE. It is therefore no surprise that the region WE has the highest material consumption, in figure 3 below. Much of the demanded materials can be fulfilled by WE itself. However, through intermediate demand, material is also consumed in China, Russia and to a lesser extent, in many other countries.

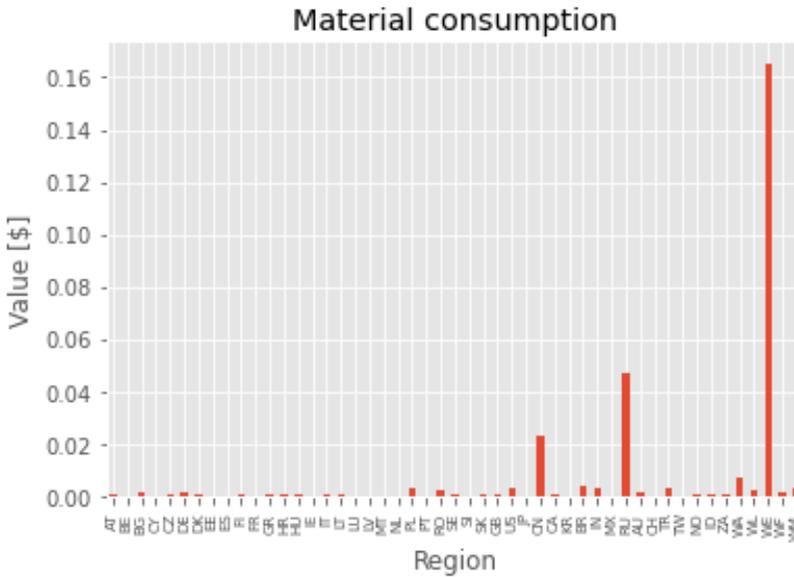


Figure 3: Regional material consumption caused by status quo final demand

Next, the same analysis is conducted for material type instead of regional level. This is comparable to the structure effect described in Pothen et al. (2017). The results are shown in figure 4 below. For improved clarity of the figure, only the 10 material types with the highest values were selected. It can be observed that “Non-Metallic Minerals - Sand gravel and crushed rock for construction” is the sector that contributes most material to the battery production (or rather electric equipment as the general sector). This is followed by natural gas for energy and various other minerals and energy carriers.

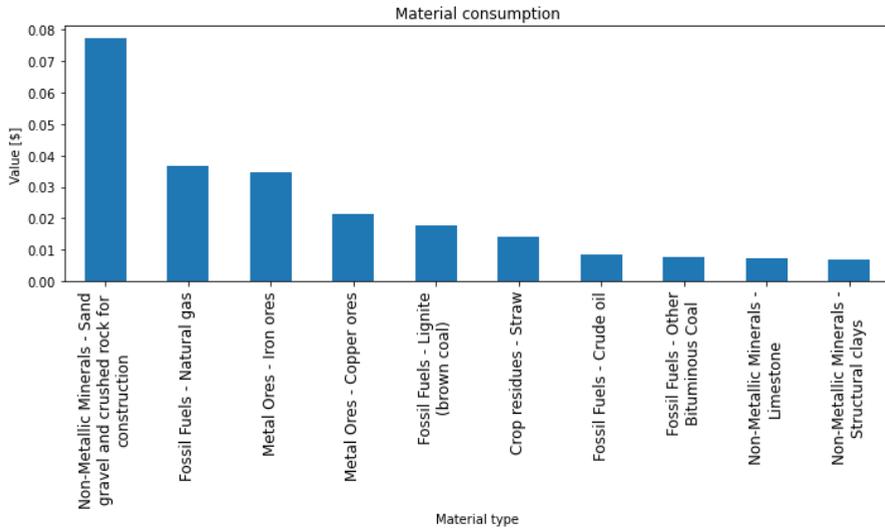


Figure 4: Sectoral material consumption caused by status quo final demand

The analysis for imports and exports is only done (exemplary) for the most used material, “non-metallic minerals”. The results in figure 5 show that the footprint in red consists of imports from China, and (to a lesser extent) of several other countries. However more than half of the material consumed comes from WE itself. Overall, the impacts of the status quo are not very high in absolute numbers. This confirms the findings of figure 3 and provides more detailed insights for this specific material. Since the units of this figure are in kilotons (kt) rather than monetary units, one can gain an understanding of the material intensity of these processes.

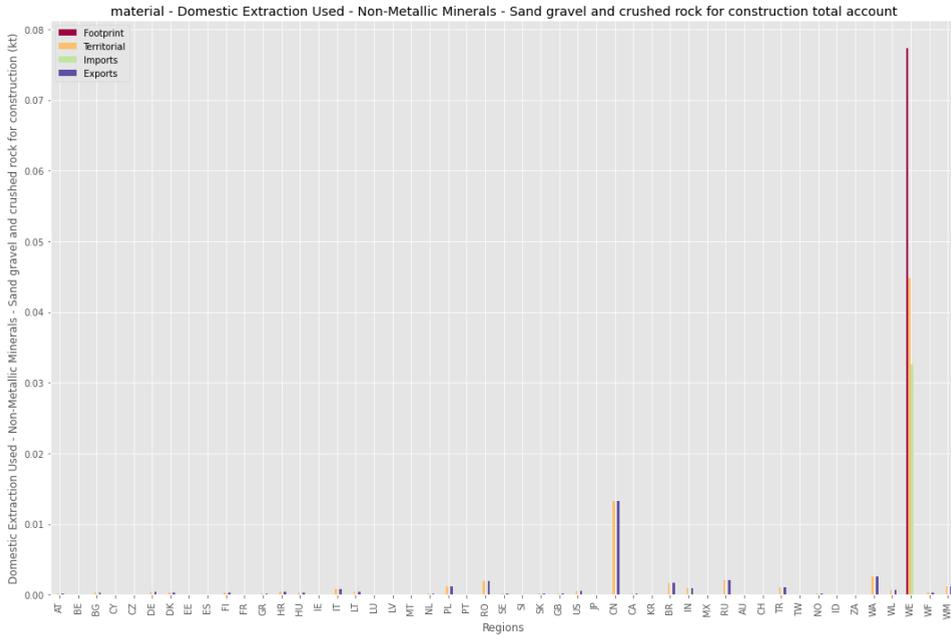


Figure 5: Non-metallic minerals import export balance

Apart from material consumption, the second important “ingredient” for calculating the resource efficiency is the value added. To conserve space, the figure depicting the value added by region is located in the appendix. Figure 6, shown below, directly presents the final result of resource efficiency. Here, Japan stands out as the most resource efficient country. It is worth noting that Japan does not have exceptionally high value added or extremely low resource consumption but beats all other regions with the combination of both factors. The resource efficiency in Japan is more than twice as high as that of the runner-up, South Korea.

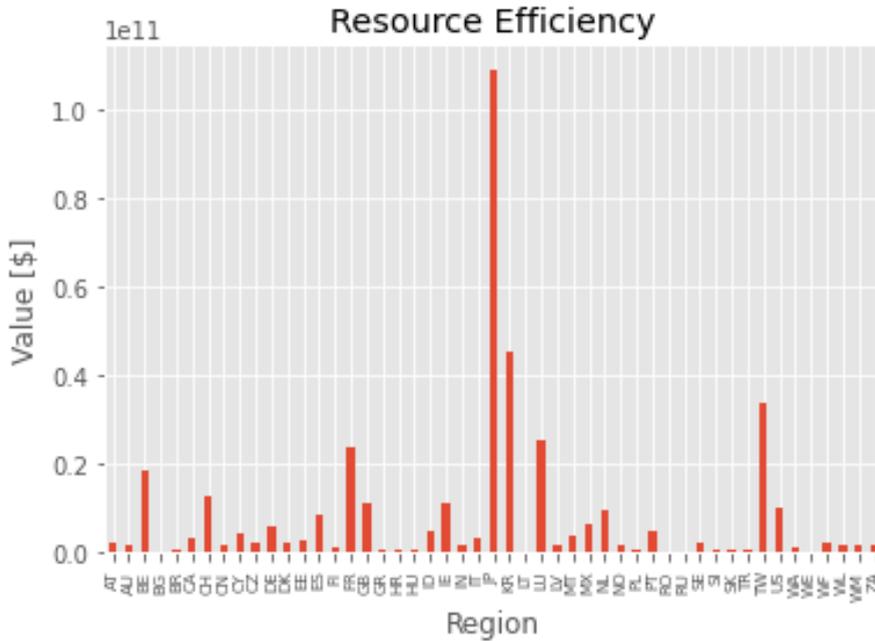


Figure 6: Resource efficiency by region (own illustration)

As a last step, the scenario of switching the sourcing from Europe to China led to various changes (see figure 7) with Taiwan emerging as the main beneficiary in terms of RE improvement, while Japan lost its lead in RE from the baseline scenario.

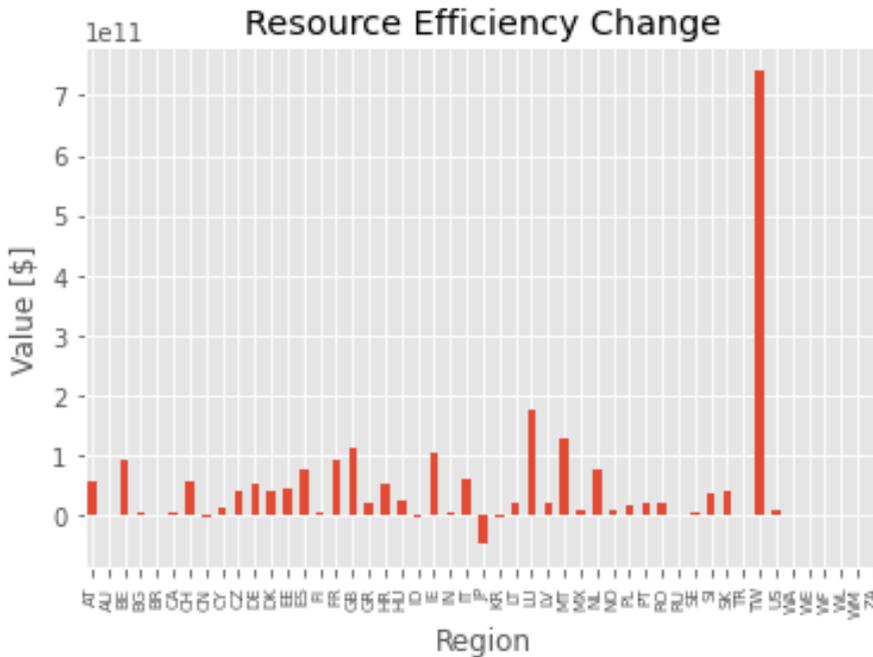


Figure 7: Change of resource efficiency when switching final demand from Europe to China

4. DISCUSSION AND CONCLUSION

The results of this research provide a valuable overview on the drivers of resource consumption and potentials for achieving higher RE in the traction battery value chain. For this, various economic sectors and regions that are involved in the battery value chain are identified and assessed using the consumption-based MRIO method. For example, depending on whether demand for batteries is fulfilled by European countries or China, different quantities of “ingredients” are needed for the battery production. This can be metals, but also services like the manufacturing and assembly of the different parts as well as transportation.

The findings offer insights into the countries and sectors that are important for the traction battery value chain production. These countries and sectors have the greatest leverage in increasing RE through targeted measures. The scenario analysis suggests that neighbouring countries of the demand-

originating country are more involved in the value chain, while China is always involved.

Regarding RE, the results suggest that high-income countries may achieve more material-efficient production despite higher production costs. The way RE is defined here, this approach effectively enhances resource efficiency. Conversely, relocating production to low-income countries tends to reduce resource efficiency. Regarding practical implementations: Policymakers and industry stakeholders aiming to improve the RE of BEV's in general and batteries in particular can benefit from the insights.

Typical limitations of MRIO analysis also apply to this research. The sectors have a limited level of detail and don't allow for assessments on (battery) component level. This research doesn't differentiate between different chemical elements, and the sector "electrical equipment" is not used for batteries exclusively.

Further research could examine trends over multiple years instead of focusing on a single year. Additionally, if e.g., metal treatment is observed as material-consuming, further research could target the identification of which exact part of the process is causing the material consumption, and which measures can help. Different methods might have to be applied for this. Further research could also explore methods to adjust or control for differences in income levels in order to ensure that comparisons are equitable. This research explicitly includes income levels by how resource efficiency is defined here. This research does not examine circular economy strategies, such as the R-strategies, and their impact on resource efficiency. Future studies could investigate the connections between these topics.

ACKNOWLEDGEMENTS

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Launching circular pilot lines in the Meuse-Rhine region to boost circularity of electric vehicle production

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EXTENDED ABSTRACT

On the way to a cleaner environment, circular approach requires inverting material resources from various waste flows. Such flows might be of different origin and occurring at different stages of a product life cycle: starting from a resource extraction, followed by a transportation, manufacturing, usage, and ending with a product End-of-Life (EoL) in linear economy. In advanced scenario, when circular strategies are coming into play, at the EoL, the product is recycled and some materials are recovered (in a current way of practice, even in most advanced scenarios, some waste is generated anyway; although it may be incinerated at the very end, which is still influencing environmental pollution). Practically, industrial actors with the best circularity intends are aiming to decrease various waste flows at different levels within various processes. Within this publication, we discuss and explore some circularity questions within automotive sector in EU and Meuse-Rhine region. Most recent data (ACEA, 2024) shows that in 2023 in EU, a car production generated about 800000 tons of waste per year, which results in about 85 kg of waste per single car production on average. Although numbers for European car recycling (ACEA, 2023) are pretty optimistic: 85% of materials are recycled at the EoL, majority of cars are transported out of EU when approaching EoL. Real numbers and what is happening to the cars afterwards is not fully tracked nowadays. To improve circularity (decrease overall waste flows), joint

synchronized actions are needed at different levels. At the highest EU level, upcoming circularity actions for automotive sector are outlined within

- Industrial Action Plan for the European automotive sector (European Commission, 2025),
- Proposal on circularity requirements for vehicle design and on management of end-of-life vehicles (European Commission, 2023).

Looking from a single company perspective: none can achieve circular economy alone. A new value creation requires either a new business model or a new industrial ecosystem. A transition towards circular economy impacts the entire value chain and requires collaboration and coordination across multiple actors. For businesses to thrive along any new circular material loop, a new non-disruptive value chain has to be envisioned, implemented and maintained. This involves creating interconnected systems that rely on such material resources as either products after their first use, or sorted waste streams. Currently such resource streams are yet not well established, so the opportunities are open for SMEs to explore and benefit from. New business ecosystems based on intensive collaboration of stakeholders may help to overcome economic and technological barriers towards circularity. Running until mid-2027, the CYPRESS INTERREG project will establish a highly circular and resource-efficient supply chain within electric vehicle production that spans a cross-border ecosystem within the Meuse-Rhine region. The goal is to reduce the ecological footprint and promote long-term sustainability in the automotive sector by fostering collaboration among SMEs and larger enterprises within the value chain, from material supply and recycling to manufacturing and testing. CYPRESS is creating a collaborative platform for over 150 companies and regional stakeholders, driving innovation in circular materials, processes, and business models. The project will co-develop three pilot production or remanufacturing lines for key automotive components, including (1) a battery module of an electric car tailored for refurbishment and repair; (2) a hydrogen tank for the fuel cell electric vehicle that is partly produced with recycled carbon fibre; and (3) a gearbox for electric vehicle drivetrains. The project aim is to establish at least one physical pilot production line through cross-border cooperation, leveraging regional private investments through a grant scheme. As part of the transition, the project will also focus on developing assessment studies, technological toolkits, and training programs for technicians, engineers, and managers. By boosting a circular economy that is efficient in usage of materials and energy, this project effectively promotes the Green Transformation. The regional SMEs that are often innovation drivers forms the main project target group, but also larger enterprises

will benefit. The targeted companies are those active in the automotive value chain: material supply and recycling, design, simulation and engineering, manufacturing, assembly and testing. In addition, SMEs in circular materials, processes and business models may grow their business in the automotive sector. A strong involvement of the regional industry is embedded within each activity of this project.

ACKNOWLEDGEMENTS

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Day 1 Session: Life Cycle Management in early-vehicle design: Frameworks and Life Cycle Optimization approaches

The energy consumption of a heavy-duty ground vehicle subjected to extreme crosswind

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ABSTRACT

The road transport sector, a major consumer of global energy, relies predominantly on oil-based fuels and contributes significantly to greenhouse gas emissions. Enhancing fuel efficiency through improved vehicle aerodynamics is essential for sustainable mobility. However, crosswind disturbances compromise aerodynamic performance by increasing drag and rolling resistance, particularly for heavy-duty vehicles. This study investigates the impact of extreme crosswind on vehicle energy consumption and dynamic behaviour by considering driver steering response under extreme conditions at different delay times. A two-way coupled aerodynamic and vehicle dynamic simulations framework is employed to capture these interactions. The findings highlight the critical role of driver skills, i.e., prompt steering by driver effectively mitigates energy losses, whereas delayed or abrupt corrections exacerbate rolling resistance through pronounced tyre slip angles. For example, delayed steering response of the driver (e.g., 1.0 second delay) increases energy consumption by 77% when compared to 44% maximum increase for prompt steering of the driver. These results underscore the complex interplay between aerodynamic forces and driver-induced dynamic forces in shaping vehicle energy efficiency under crosswind conditions.

1. INTRODUCTION

The transportation of humans and goods using ground vehicles is one of the major consumers of the energy sources in the world that is accompanied by undesirable air pollution, safety issues, and other problems. According to the International Energy Agency (2024), the transportation sector consumes approximately 27% of global energy with around 90% of its energy consumption coming from oil-based fuels. Additionally, road transport accounts for approximately 75% of total transportation energy consumption, with passenger cars and heavy-duty trucks being the primary contributor.

According to the Jaramillo et al. (2022), the transportation sector contributes approximately 15% of total global greenhouse gas (GHG) emissions, making it a significant driver of climate change. Additionally, road transportation dominates among all transportation modes and accounts for nearly 74.5% of total transportation emissions. This is primarily due to the passenger vehicles such as cars and buses, which alone contribute around 45.1% of the sector's emissions, while freight trucks add another 29.4% (Ritchie, 2020). These figures underscore the urgent need to transition to cleaner transportation alternatives, such as electric vehicles, sustainable aviation fuels, and improved freight logistics, to mitigate the transportation sector's environmental impact (Jaramillo et al., 2022; Ritchie, 2020; U.S. Environmental Protection Agency, 2022).

Therefore, fuel efficiency of vehicles, in general, is crucial for multiple reasons, including economic, environmental, and performance-related factors. As fuel prices fluctuate and environmental concerns grow, the need for fuel efficient vehicles has become increasingly critical. Studies indicate that improving the vehicle aerodynamics can lead to savings of up to 25% in fuel costs for heavy-duty trucks, which often face high fuel consumption due to their size and load (Mohamed-Kassim and Filippone, 2010). Additionally, from environmental perspective, previous studies have shown that the relationship between fuel efficiency and CO₂ emissions is directly proportional. Thus, improvement in fuel efficiency can lead to a reduction in CO₂ emissions, making it a vital area of focus for both manufacturers and policymakers (Gao et al., 2023). Moreover, from the perspective of performance, fuel efficiency is closely linked to the vehicle design. Vehicles with improved aerodynamic performance experience less drag, which not only improves fuel efficiency but also enhances stability and handling, particularly at high speeds or in adverse weather conditions (Huang et al., 2017).

In designing fuel efficient vehicles, the impact of crosswinds is critical because crosswinds can significantly affect the aerodynamic performance of vehicles, for example the aerodynamic drag force acting on the vehicle can increase substantially (Zhang et al., 2020). Moreover, the stability of vehicles under crosswind conditions is crucial for maintaining fuel efficiency. Vehicles that are more stable in crosswinds can maintain a straighter path, thereby reducing the need for corrective steering inputs that can lead to reduced fuel consumption (Forbes et al., 2016; Salati et al., 2019).

The present study investigates the fuel consumption of a heavy-duty vehicle which is subjected to the crosswind by incorporating its drag force and tyre-slip angles into the driving resistances. The investigations are conducted using the ground transportation system, GTS, as the simplified heavy vehicle model together with the two-way coupled simulation between the vehicle dynamics and aerodynamics. Thus, a method for more realistic and accurate estimation of the fuel consumption of a vehicle in extreme crosswind conditions can be suggested.

2. METHODS

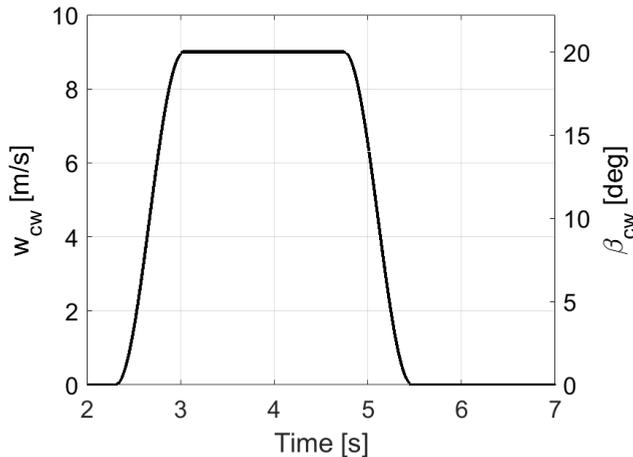


Figure 1: The extreme crosswind profile used in the investigations.

The single-track vehicle dynamics equation including roll degree-of-freedom was used to simulate the dynamics of the vehicle. Additionally, IDDES turbulence model was used for the calculation of the unsteady aerodynamic forces acting on the vehicle, e.g., drag and lift forces, due to the crosswind. The driver model used in the present study involved proportional gain

parameters on lateral displacement, k_y , yaw angle, k_ψ and the preview distance, k_l , i.e., $k_y = 2.0$, $k_\psi = 50$, $k_l = 1.5$. The two-way coupled solution method of the vehicle dynamics and aerodynamics equations were employed in order to get an accurate and a realistic simulation of the crosswind-vehicle-driver interaction. The details of the dynamic, aerodynamic and driver models are given in (Tunay et al., 2021; Tunay, 2023; Tunay et al, 2024). The crosswind profile, shown in Figure 1, was used to simulate the extreme weather condition on roads, i.e., the maximum crosswind velocity, $w_{cw} = 9$ m/s and the reduced frequency, $k = \frac{2\pi fL}{u} = 1.3$ (Tunay et al, 2024). Here, f is the frequency of the crosswind (Hz) and u is the vehicle velocity (m/s) which was 25 m/s. The details of the geometrical and mass properties of the vehicle used in the present study are given in Table 1.

Table 1: Geometrical and mass properties of the vehicle employed in the study.

Vehicle's Parameter	Sym- bol	Data	Unit
Length	L	12.2	[m]
Height	h	3.6	[m]
Width	w	2.6	[m]
Track width	T	2.25	[m]
Length of the wheelbase	L_{wb}	5.9	[m]
Distance between front axle to CG	L_f	3.7	[m]
Distance between rear axle to CG	L_r	2.2	[m]
Mass	m	13,650	[kg]
Linear cornering stiff- ness for the front tyre	$C_{\alpha,f}$	250	[kN/rad]
Linear cornering stiff- ness for the rear tyre	$C_{\alpha,r}$	450	[kN/rad]
Roll damping of the sus- pension	C_ϕ	100	[kN/rad]
Roll stiffness of the sus- pension	K_ϕ	1,000	[kNm/rad]
Yaw moment of inertia	I_{zz}	200,000	[kgm ² /rad]
Roll moment of inertia	I_{xx}	30,000	[kgm ² /rad]

3. DRIVING RESISTANCES

The total driving resistance of a vehicle is calculated by summing the aerodynamic drag forces, F_D , rolling resistance forces, F_R , forces due to the grade resistance, F_H , and forces due to the acceleration, F_B , as given in Eq. (1).

$$F_T = F_D + F_R + F_H + F_B \quad (1)$$

In the present study, F_H and F_B forces were zero due to the zero-grade road condition and the constant velocity in the axial direction of the vehicle. The aerodynamic forces, F_D , were obtained directly from the results of the coupled simulation between the aerodynamics and vehicle dynamics of the vehicle. Finally, the rolling resistance, F_{R0} , of a vehicle can be calculated using Eq. (2) as suggested by (Schuetz, 2015).

$$F_{R0} = \mu_R (m \cdot g - F_{a,z}) \quad (2)$$

In Eq. (2), F_{R0} is the rolling resistance at zero sideslip angle, μ_R is the rolling resistance coefficient, which was $\mu_R = 0.005$ in the present study, m is the vehicle weight (in kg), g is the acceleration of gravity (9.81 m/s^2) and $F_{a,z}$ is the aerodynamic lift force applied by wind on the vehicle.

Furthermore, the rolling resistance, $F_{R\alpha}$, in the case of the tyre slip angles, α , can be calculated using the relation given in Eq. (3) as suggested by LaClair (2006).

$$F_{R\alpha} = F_{R0} + C_\alpha \cdot \alpha^2 \quad (3)$$

In Eq. (3), $F_{R\alpha}$ is the rolling resistance at a certain tyre slip angle, α , and C_α is the cornering stiffness. Thus, the total F_R is calculated using Eq. (4).

$$F_{R\alpha} = \mu_R (m \cdot g - F_{a,z}) + C_\alpha \cdot \alpha^2 \quad (4)$$

Using Eqs. (2)-(4), one can obtain the Eq. (5) in which the effects of lift forces, $F_{a,z}$, front and rear tyre slip angles, α_f and α_r , contribute to the calculation of the rolling resistances, $F_{R\alpha}$.

$$F_{R\alpha} = \mu_R(m \cdot g - F_{a,z}) + C_{\alpha,f} \cdot \alpha_f^2 + C_{\alpha,r} \cdot \alpha_r^2 \quad (5)$$

Thus, the total power, P , needed to overcome the driving resistances of the vehicle when there is crosswind can be calculated by multiplying the total driving resistances with the vehicle velocity, u , as given in Eq. (6).

$$P = [F_{a,x} + \mu_R(m \cdot g - F_{a,z}) + C_{\alpha,f} \cdot \alpha_f^2 + C_{\alpha,r} \cdot \alpha_r^2]u \quad (6)$$

Additionally, the power needed to overcome the driving resistances of the vehicle when there is no crosswind is calculated by assuming the tyre slip angle, α , is zero and the drag, $F_{a,x}$, and lift, $F_{a,z}$, forces were constant.

4. RESULTS AND DISCUSSION

The present study investigates the energy consumption characteristics of a heavy-duty vehicle operating under the extreme crosswind condition. In particular, the influence of the driver's steering inputs on the vehicle's energy consumption is analysed for various delay times in the driver's steering response to the crosswind disturbances.

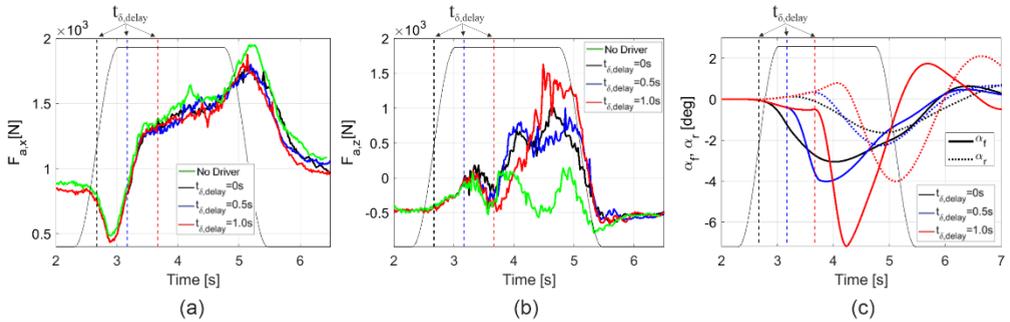


Figure 2: The aerodynamics forces (a) in the longitudinal direction (or drag forces), $F_{a,x}$, and (b) in the vertical direction (or lift forces), $F_{a,z}$, and (c) the tyre slip angles, α_f and α_r , at different delay times of driver's steering inputs.

Fig. 2 illustrates the longitudinal and vertical forces (i.e., drag, $F_{a,x}$, and lift, $F_{a,z}$, forces) acting on the vehicle at different delay times of driver's steering inputs aimed at counteracting extreme crosswind disturbances. The

corresponding vehicle dynamic responses, including the tyre slip angles at the front and rear axles (i.e., α_f and α_r , respectively), are also presented. For comparative analysis, the figure includes results for a scenario without any steering input from the driver. Note that $t_{\delta, delay}$ is the time at which the driver’s steering input starts after the crosswind hits the vehicle. As shown in Fig. 2(a), the peak drag forces, $F_{a,x}$, under different steering responses demonstrate only minor deviations from the no-steering case. Moreover, the temporal evolution of the drag force remains nearly indistinguishable across different delay times of driver inputs. In contrast, the lift force, $F_{a,z}$, profiles in Fig. 2(b) reveal a notable divergence. That means when steering corrections are applied, the lift force, $F_{a,z}$, assumes predominantly positive (upward) values, whereas it remains negative (downward) or approximately zero in the absence of steering intervention. This upward lift induced by steering in extreme crosswind conditions may be advantageous from an energy consumption perspective by reducing the normal load and thus rolling resistance. However, it also poses potential challenges to vehicle handling and stability due to reduced tyre contact forces. Fig. 2(c) shows that the peaks of all slip angles increase with the latency of the steering response. This effect is most pronounced when the steering input is delayed by $t_{\delta, delay}=1.0$ second that highlights the strong interplay between reaction timing and control authority in mitigating crosswind-induced instabilities.

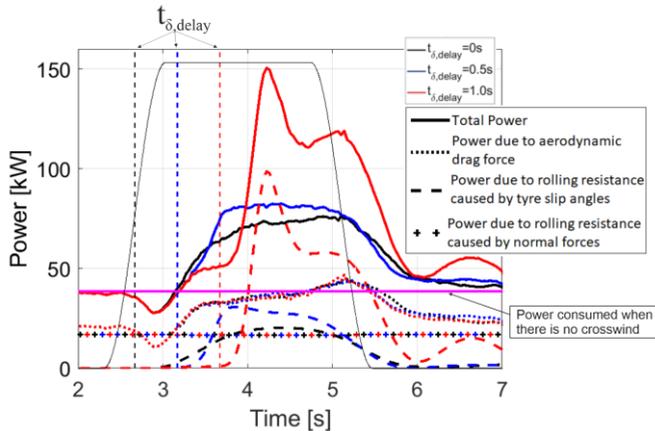


Figure 3: The power, P , consumed by the vehicle to overcome the driving resistance for various driver’s steering inputs against the extreme crosswind.

The results presented in Fig. 3 indicate that the power required by the vehicle to overcome the driving resistance under the extreme crosswind condition increases with longer delays in the initiation of steering input, $t_{\delta, delay}$. This trend can be attributed to the abrupt escalation in both front and rear tyre slip angles associated with the initiation of driver’s steering correction, as previously illustrated in Fig. 2(c). In contrast, the component of power demand, attributed to aerodynamic drag, exhibits comparatively lower sensitivity to the variations in steering delay time. This finding suggests that while aerodynamic resistance plays a consistent role, the dynamic tyre response induced by delayed or aggressive steering is a dominant contributor to the observed increases in power consumption.

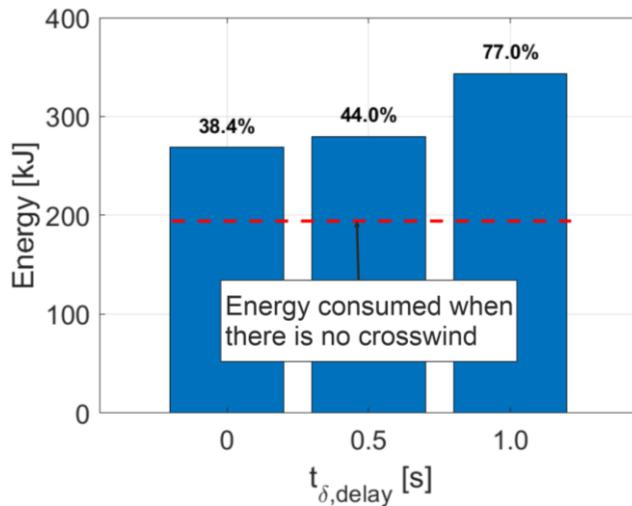


Figure 4: The energy consumed by the vehicle to overcome the driving resistance for various driver’s steering inputs.

The substantial increase in the vehicle’s energy consumption under extreme crosswind conditions is clearly illustrated in Fig. 4. For steering inputs initiated at $t_{\delta, delay}=0$ s and 0.5 s, the energy consumption rises by maximum 44%. However, when the steering input is delayed to $t_{\delta, delay}=1.0$ s, the increase in energy consumption reaches 77% which indicates a pronounced sensitivity to steering response timing. These findings emphasize the critical interplay between the driver skill and the steering response time in mitigating the energy inefficiency caused by the extreme crosswind disturbances.

5. CONCLUSION

The present study examined the impact of extreme crosswind scenario on the energy consumption and dynamic response of a heavy-duty vehicle. The results of study provided detailed insights into the energetic consequences of crosswind-vehicle-driver interactions by evaluating the delays in the driver's steering response.

The role of driver's steering input in the extreme crosswind conditions was investigated in detail using the representative extreme crosswind profile. The findings revealed that the delay in initiating a steering response play crucial roles in shaping the vehicle energy demand. While the prompt reaction of driver demonstrates more effective control thereby minimizing energy losses, the delayed response of the driver contributes to the highest energy penalty when the steering response is delayed. This is primarily due to the rapid onset of large slip angles which leads to the sharp increases in rolling resistance. In the extreme crosswind scenario studied, the energy consumption increased by 77% for a delayed steering response of 1.0 second, compared to the maximum 44% increase for a timely response by the driver.

In conclusion, the study underscores two main implications. First is that the crosswinds significantly deteriorate vehicle energy efficiency, with the extent of impact strongly dependent on the driver's behavioural response. The second is that the energy losses are not solely governed by aerodynamic drag; dynamic tyre responses and slip-induced resistances, particularly under delayed or abrupt steering actions, emerge as dominant contributors to power surges and cumulative energy demand.

Future research based on the motivations of present study could investigate the influence of variety of aerodynamic scenarios that have different maximum velocities and frequencies of the single crosswind events on the energy consumption of heavy-duty vehicles. Furthermore, future research could focus on evaluating the cumulative effects of prolonged crosswind exposure over extended driving distances. In particular, persistently windy environments may impose significant long-term impacts on overall system performance and durability, making this an important area for further investigation. For instance, in the context of electric vehicles, repeated crosswind-induced power surges may accelerate battery degradation, thereby shorten the service life, and reduce the operational efficiency.

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Advanced high-temperature PEM fuel cells for heavy-duty applications: Performance, sustainability and life cycle assessment insights from the MEASURED project

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ABSTRACT

The EU-funded Horizon 2020 project “MEASURED” aims to enhance the performance and durability of high-temperature proton exchange membrane fuel cells (HT PEMFC) for heavy-duty vehicle applications by integrating experimental research with advanced simulation-based modeling. One part of the project is to evaluate the environmental impact of existing FC technologies and explore how systems operating at higher temperatures can offer a cleaner and more sustainable alternative. To assess these benefits, a meta-study on FC sustainability, synthesizing literature on resource consumption, greenhouse gas emissions, recyclability, and circularity is performed. This study provides a quantitative evaluation of the current status of the environmental footprint of PEMFC systems. By consolidating data from previously conducted life cycle assessment (LCA) studies, the meta-study establishes benchmark values for key environmental indicators, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and abiotic depletion potential (ADP). These benchmarks together with the LCA on a reference HT PEMFC in the present study form the baseline for evaluating the sustainability advancements of Advent Technologies HT PEMFC systems during the MEASURED project. The LCA results show high indicator

values for GWP and EP, and low values for AP and ADP compared to the literature benchmarks. Impact reduction potentials which can be harnessed through reaching MEASURED KPIs, including reduced platinum loading and increased power density, are found to be significant. Drawing on Advent Technologies expertise, the project will refine critical technical parameters to define a high-performance HT PEMFC that meets economic and environmental sustainability objectives. The project aims to deliver an improved system of up to TRL 4. Through these efforts, the MEASURED project contributes to the broader adoption of FC technology, supporting its integration into sustainable mobility solutions and advancing clean energy innovations in transport.

1. INTRODUCTION

Fuel cells are a crucial technology for the decarbonisation of the transport sector (Ajanovic & Haas, 2021). They provide the opportunity for much higher gravimetric energy density than commercial EV batteries through the high energy density of compressed hydrogen (Lei, 2024). This makes them especially attractive for the heavy-duty vehicle (HDV) sector, where batteries are suboptimal due to their high weight and cost and there is sufficient room for large hydrogen tanks (Cunanan, et al., 2021). Multiple PEMFC systems are readily available on the market for a host of applications (Asif Jamil, 2022). Novel systems aim to improve on the useful lifespan, fuel compatibility and cost of these systems (Asif Jamil, 2022). The MEASURED project aims to improve on these aspects in the context of high temperature HT PEMFC systems for the HDV sector by expanding on existing Advent Technologies' membrane electrode assembly (MEA) technology. The assessment of the environmental consequences of these novel products consists of three main steps. First, a literature review of relevant LCA studies is conducted. This review provides baseline values for environmental impact indicators that can serve as a benchmark for comparison for later assessments. In addition, valuable insights on various aspects of FC systems sustainability and circularity are gathered. Secondly, an LCA study on a current Advent Technologies HT PEMFC system is carried out. This assessment provides a reference point to show improvements along the development timeline of the MEASURED project. Finally, an LCA study of the final product will be carried out to assess the impacts of the fully developed (TRL 4) system. The final LCA is not included in this paper as the project is still ongoing, but an outlook is provided and improvement potential of the current technology is discussed. During all

stages of the assessment, crucial leverage points for impact reduction and improved circularity are identified.

2. METHODS

The LCA methodology applied in this study is based on the ISO 14040 (International Organization for Standardization, 2006) and ISO 14044 (International Organization for Standardization, 2006) norms, which establish a standardized framework for the systematic evaluation of the environmental impacts associated with products, services or firms. It comprises four interdependent phases that together ensure consistency and transparency throughout the assessment process. Additional guidance is taken from the ILCD handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) and relevant documentations from the applied software and database.

2.1 GOAL AND SCOPE DEFINITION

The objective of the LCA is to quantify the environmental impacts associated with the production of a reference 1kW FC stack. The goal is to identify the main environmental hotspots related to the production of the system. The system boundaries include the production phase (raw material extraction, component manufacturing, stack assembly). The use phase and the end of life (EoL) are not included due to severe uncertainties and data constraints. The methodological framework adopted in this study enables consistent comparison with literature cases, while also supporting future scenario analyses based on MEASURED KPIs and project objectives.

2.2 STACK SPECIFICATIONS AND DATA SOURCES

The bill of materials (BoM) for the reference HT PEMFC stack is set up based on literature, AVL expert interviews and data from Advent Technologies. The original structure of the BoM is based on Usai et al. (2020) and is adapted to represent typical material contents of a HT PEMFC system. Data for a 100W HT PEMFC system is provided by Advent Technologies and incorporated into the BoM. The system size is then scaled up to fit the chosen functional unit of 1kW FC power. Sublinear scaling is applied to specific components to

reflect the requirements for some parts like housing materials, endplates and cooling fans. The specifications for the resulting stack are shown in Table 2.

Table 2: Stack Specifications

Stack Power [kW]	Stack Weight [kg]	Active Area [m ²]	Pt loading [g]
1	31	0,765	1,64

The main differences compared to the original BoM from Usai et al. (2020) lies in the simplified air, water and heat management, the heavier housing and endplates, the higher platinum (Pt) load and the membrane and bipolar plate materials. The heavier housing and endplates are typical for HT PEMFC systems as they are designed for stationary application. The higher Pt load and different membrane materials are also typical for HT systems (Zuconni, et al., 2024). As many material and weight specifications as well as detailed process data and information on production locations is incomplete, the LCA model exhibits uncertainty.

2.3 LIFE CYCLE INVENTORY (LCI)

The inventory phase involves the quantification of inputs and outputs for each component. The LCI data for the PEMFC stack is based on primary and secondary data. As a proxy for data on the production processes and missing data on materials, the Ecoinvent 3.11 database is used as is common practice in recent LCA studies on FC-technologies (Gulotta et al., 2024).

2.4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The potential environmental impacts of the assessed system are quantified using the Environmental Footprint 3.1 (EF 3.1) method. This method allows a consistent and policy relevant assessment of environmental performance across 16 impact categories. In this study, emphasis is placed on the GWP indicator, expressed in kg of CO₂ equivalent emissions (kgCO₂eq.) as a key metric for climate related burdens (Sala et al., 2018). A sensitivity analysis is conducted for key parameters such as Pt loading to assess their influence on overall impact variability. Indicators for AP, ADP and EP are also evaluated.

This selection aligns with common practice of LCAs of PEMFCs and allows for direct comparison with literature benchmarks.

3. RESULTS

This section elaborates on the results of the meta-study and the LCA. The LCA results are compared to the previously determined benchmarks and crucial leverage points for impact reduction are discussed. An outlook regarding the future LCA of the novel system will be provided based on a sensitivity analysis conducted on the LCA model at hand and the MEASURED KPIs and development objectives.

3.1 META-STUDY RESULTS

Quantitative data regarding the potential environmental impacts of FC systems was collected for four impact indicators: GWP, AP, EP and ADP. These indicators are evaluated separately for three parts of the FC life cycle: the production, the use phase and the EoL. Results regarding the production of FC systems are of the highest availability and were therefore focused upon.

The observed literature review showed an extensive amount of assessments regarding environmental implications of the production phase of FC systems. Figure 3 shows the distribution of observed GWP values for a selection of PEMFC systems.

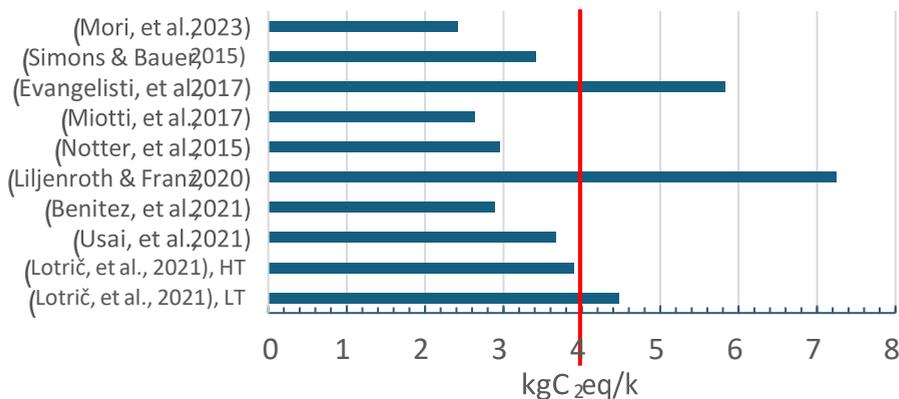


Figure 3: Distribution of the observed GWP values by source. The average of 40 kgCO₂eq/kW is indicated by the vertical red line.

The observed indicator ranges for all assessed impact indicators are shown in Table 3. The shown results are a narrowed down selection of the observed study results. A few studies were omitted due to limited comparability of the analyzed systems (e.g. SOFC or stationary systems). Even though Lotrič et al. (2021) conduct an LCA on stationary systems, the results were deemed important for the objective of the literature review. This is due to the fact that a comparison of low and high temperature systems within one LCA study is conducted in the respective study, which enables a high degree of comparability between the two systems as methodological choices are homogenous.

Apart from the system and component assessment, the impacts and criticalities that are associated with the employed materials are also of interest. The analysis in Mori et al. (2023) shows that the Pt loading of the catalyst layer is responsible for most of the environmental burden across all impact indicators which is confirmed by many other studies. The assumed Pt loads in the screened studies differ quite substantially. Benitez et al. (2021) use 0.2 g/kW for the current scenario (0.06 g/kW for the future scenario) while Miotti et al. (2015) use 0.45 g/kW. Evangelisti et al. (2017) even use 0.925 g/kW. Other, less severe environmental hotspots in PEMFC materials are found in stainless and chromium steel as well as glass fiber reinforced plastic. Criticality assessments as in Gramc (2024) and Mori et al. (2023) point towards significant criticalities concerning a multitude of materials that are typically used in PEMFC systems.

During the use phase, the majority of environmental impacts are caused by hydrogen production. An estimate of impacts from hydrogen production during the use phase, evaluating GWP and AP based on data from Acar & Dincer (2022), indicated that the respective impact indicators are much higher regarding the use phase than production. Some additional impacts arise from maintenance activities. To reduce these impacts in tandem with the FC system's expected lifespan, attention should be given to separability during system design. This is especially important regarding gasket design. Gasket design is important to limit adhesion and enable a higher degree of reparability during maintenance as well as EoL dismantling.

The EoL phase itself is currently found to be of rather low impact compared to the preceding life cycle stages. Ferreira et al. (2021) for instance find the impact of the EoL to be less than 1% of production and transport emissions. Gramc et al. (2025) report similar results, where the EoL makes up less than 2% of the combined manufacturing and EoL impacts for all assessed impact indicators apart from ADP where the EoL accounts for 7,4%. The EoL is still crucial as recycling offers an opportunity to reduce FC system's

environmental footprints through the provision of secondary materials. Especially Pt recycling is found to offer the potential for significant impact reductions in all assessed impact indicators. Lotrič et al. (2021) find reduction potentials of up to 35% of production GWP (60% for ADP, 71% for AP and 65% for EP respectively) for a 76% platinum group material (PGM) recovery rate for a stationary HT PEMFC system. Without PGM recovery, the production related EoL impact reduction potential is found to be below 10% for all of the above indicators. Gramc et al. (2025) evaluate the environmental benefits of eco-design for PEMFC manufacturing and EoL. With regards to EoL, they use Pt recycling rates of 30% for their short- and long-term scenarios. The optimistic and disruptive scenarios use Pt recycling rates of 70% and 95% respectively. For the short- and long-term scenarios, 34% and 39% in potential GWP reductions through recycling are reported.

Many studies point towards significant improvement potential regarding the environmental performance of FC systems. Most studies attribute this to the potential of increased secondary material use, improved energy mixes and technological advancements regarding Pt load and system size. These potentials can be realized during the design process by following available eco-design guidelines and incorporating existing knowledge on reparability and recycling. The improvement potential pointed out in Gramc et al. (2025) is based on a host of eco-design measures including reuse and recycling of components, reductions in Pt loadings and lightweighting. In the short term they find a GWP reduction potential of 31% (52%, 74% and 85% for the long term, optimistic and disruptive scenarios respectively), with similar or higher potentials for all other impact indicators. Note that this does not consider the additional potential for avoided impacts that can be achieved through EoL recycling. The only net environmental drawback of recycling is found in the short-term scenario for EP. An increase by almost 20% is found compared to the manufacturing and EoL without Pt recovery, which originates from the recycling process of Pt. For all other scenarios, changes in EP are still negative. Based on the values used in the short- and long-term scenarios in Gramc et al. (2025), a Pt recycling rate of 30% can serve as a goal for the MEASURED MEAs. Recyclability of other components should be considered during system design, albeit Pt recovery offering the biggest leverage point for impact reductions across most impact indicators.

3.2 LCIA RESULTS FOR THE REFERENCE PEMFC SYSTEM

The total GWP associated with the production of the 1 kW system amounts to 179.37 kgCO₂eq. The analysis reveals distinct impact contributions across component groups, highlighting critical hotspots primarily associated with material intensity and upstream processing emissions.

The largest share of emissions originates from other stack components contributing 87.35 kgCO₂eq which represents 48.7% of the total impact. This category includes non-core components such as aluminium and cast alloy housings, electronic control units, steel structures and cabling. The dominant impacts within this category stem from the use of aluminium cast alloys and wrought aluminium, which are associated with high embodied energy due to electrolysis based primary production. The catalyst is the second largest contributor with 74.90 kgCO₂eq, which equates to a 41.8% share of the total impact, primarily due to the use of Pt, as well as chemical inputs like formaldehyde, cobalt salts and fluorinated solvents. Despite its minor mass share, the upstream impacts from Pt mining, refining and chemical synthesis processes result in a disproportionately high environmental footprint. The membrane accounts for 6.35 kgCO₂eq (3.5% share of total GWP), linked mainly to the production of phosphoric acid and benzimidazole compounds used in polybenzimidazole (PBI) based membranes. While its share is modest, the membrane remains a hotspot due to the embodied energy of specialty chemicals. Bipolar plates (BPPs) contribute 4.27 kgCO₂eq (2.4%) and are typically based on coated graphite substrates. Graphite is a durable but highly energy intensive metal, requiring high temperature smelting and machining which is reflected in the upstream impacts. The gas diffusion layers, including carbon paper and microporous coatings, account for 1.97 kgCO₂eq (1.1%), with main inputs being graphite and carbon black. Auxiliary subsystems, such as fuel and heat management, together contribute less than 1%, with emissions of 0.64 and 0.22 kgCO₂eq, respectively.

In addition to the GWP, the environmental footprint assessment revealed critical contributions across ADP and EP indicators. Figure 3 presents the normalized environmental profile of the assessed HT PEMFC system, across six key EF 3.1 midpoint indicators: GWP, AP, ADP, freshwater eutrophication potential (FEP), marine eutrophication potential (MEP) and terrestrial eutrophication potential (TEP). The results highlight significant differences in component level contributions depending on the environmental mechanism under consideration. The Catalyst consistently emerges as the dominant

contributor across most categories particularly in AP, MEP and TEP, where it accounts more than 75% of the normalized impacts. This is attributable to the use of Pt, inorganic salts and fluorinated compounds, which are linked to acidifying emissions and aquatic nutrient loading during mining and chemical synthesis (Liu et al., 2023). In contrast, other stack components dominate in GWP and FEP, contributing 41.7% and 55.1% of the total impact in these categories respectively. This reflects the embedded emissions of aluminium, steel and electronics, as well as phosphate related discharges during upstream processing. The ADP shows a more distributed profile, while the catalyst still contributes a majority share (58.7%), auxiliaries and membrane components also have visible impacts (17.4% and 1.9%), likely due to the use of phosphoric acid, specialty polymers and metallic fittings. The ADP of fossil resources totals 2.34 MJ, mainly reflecting the embodied energy of aluminium and graphite production, as well as polymer processing. In parallel, the depletion of mineral resources (0.0006 kgSbeq) is driven by Pt, cobalt and copper inputs, all materials that carry high depletion factors due to intensive extraction requirements. BPP and GDL components consistently show a minimal contribution (<2.5%) across all categories, indicating their relatively low mass. The system's TEP, calculated at 6.88 molNeq, is largely attributable to upstream NO_x and NH₃ emissions, particularly from combustion related processes in aluminium and membrane precursor supply chains. FEP and MEP values are found to be 0.16 kgPeq and 0.51 kgNeq respectively, mostly arising from nitrate and phosphate rich emissions associated with chemical processing in the catalyst and membrane subsystems. Lastly, the AP, amounting to 6.69 molH⁺eq, is primarily caused by SO₂ and NO_x emissions originating from fossil fuel-based electricity and industrial processing of base metals and electronics.

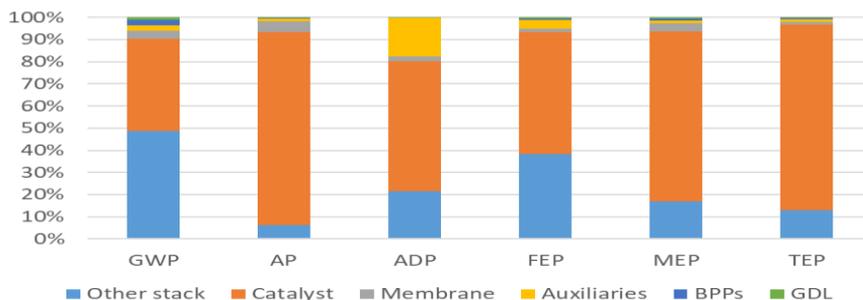


Figure 3: Normalized results of the LCIA of the HT PEMFC for the assessed indicators (EF 3.1).

3.3 BENCHMARKING

This section elaborates on the benchmarking of the LCA results against literature values which were obtained in the meta-study. The observed ranges from literature for all selected indicators are shown in Table 3. All values are scaled to the functional unit of 1 kW of FC power.

Table 3: Benchmark values and ranges for the selected impact indicators. *Original high value of the GWP range was at 724 kgCO₂eq/kW before narrowing down the results. **Values from Gramc et al. (2025).

Indicator	This Study	Literature Benchmark	Unit
GWP	179	24 – 73*	kgCO ₂ eq/kW
AP	6.7	0.8 – 23	kgSO ₂ eq/kW
ADP	0.006	0.0008 – 0.06	kgSbeq/kW
EP		0.09 – 2.7	kgPO ₄ eq/kW
TEP	6.88	0.34**	molNeq/kW
FEP	0.16	0.0001**	kgPO ₄ eq/kW
MEP	0.51	0.03**	kgNeq/kW

The benchmarking shows that the GWP of the reference product exceeds the narrowed down range of the literature results. Significant reductions in GWP will be necessary to reach the benchmark average of 40 kgCO₂eq/kW. However, compared to the original high end of the range, the result is still well sat inside the range. In terms of AP and ADP, the reference product places on the mid to lower end of the range. To enable a meaningful comparison with regards to EP, the results from Gramc et al. (2025) are chosen as a reference point. This is due to the fact that different indicators are used to express EP which makes comparison between the EF 3.1 method and the meta-study results impossible in this regard. Compared to the chosen reference, the reference product performs significantly worse in all three measures of EP. Additional challenges arise when comparing this study to literature results. Many studies assess different FC technologies and system applications, like focusing on LT PEMFC or stationary systems. LT PEMFCs do not use steel as housing material but rather plastics, as there is no need for heavy housing. The Pt loading is also generally lower for LT systems (Zucconi, et al., 2024).

This explains largely, why this reference HT PEMFC LCA shows much higher GWP values than the literature baseline.

3.4 OUTLOOK AND IMPROVEMENT POTENTIAL

The upcoming LCA of the novel HT PEMFC system will build upon the baselines that are established in the meta-study as well as the results presented in this paper. This LCA not only assesses the environmental impacts but also reflects on how technical advancements in the MEASURED project can potentially contribute to their reduction.

Several improvements are expected to help with impact reduction as defined by the KPIs of the MEASURED project. The new system is designed to last 20000 hours and deliver greater power density of 1.2 W/cm² at 0.65 V, both of which directly influence the environmental performance of the FC by extending its operational lifetime and improving energy output per unit of material. In addition, the Pt load shall be reduced to 0.3 mg/cm². This planned Pt reduction addresses one of the major environmental hotspots identified in this study. Lower Pt use reduces the environmental burden associated with resource extraction and catalyst production. Furthermore, the manufacturing process is being streamlined to use less energy and produce less waste, while ensuring consistent batch-to-batch quality.

To quantify the impacts of expected improvements the LCA model is adapted to evaluate potential scenarios. As the MEASURED project KPIs aim to reduce the impact of the materials significantly, the inputs are downscaled to assess the impact of these goals. Reducing the Pt loading from 1.64 g to 0.27 g lowers the GWP by about 35%. Changing the employed electricity mix to wind energy from Greece lowers the overall GWP result by less than 1%. The energy consumption during production is however subject to uncertainties. Increasing the power density to 1.2 W/cm² reduces the overall GWP by about 44%, assuming that the cell related material demand is reduced accordingly. Changing the BPP material from synthetic graphite to stainless steel reduces the overall GWP by about 1.2%, albeit the weight of the stainless steel BPPs being slightly higher.

As emphasized by Gramc et al. (2025), embedding LCA early in the design process supports the proactive identification of environmental hotspots and guides targeted improvements in material choice, durability and recyclability. Their eco design framework demonstrates how integrating life cycle thinking during technology development can significantly lower cumulative environmental burdens across all product life cycle stages. Finally, the MEASURED

project aims to develop a PEMFC system in the 80 kW range. Comparatively speaking, the larger system size will most likely lead to an improved environmental performance with regards to a 1 kW functional unit due to sublinear scaling advantages.

All together, these improvements are expected to yield significant reduction in the overall environmental impact of HT PEMFCs, offering a cleaner and more sustainable option for HDV applications. Regarding to the critical material issues, a next generation HT PEMFC with Ion Pair technology, offering higher power density and lower Pt use, needs to be analyzed and conducted. The upcoming novel HT PEMFC LCA will capture these advancements, showing optimised design and production options for future FCs. In addition, the upcoming LCA should also take the use phase into consideration, as significant environmental advantages could be found with regards to the HT PEMFC systems capability to operate on less pure hydrogen which potentially benefits impacts from the use phase.

4. CONCLUSION

This paper presents an environmental assessment within the broader scope of the MEASURED project, which aims to improve the performance, durability and sustainability of HT PEMFCs for HDV applications. Through a combination of a literature review and an LCA study, this paper evaluates both the current environmental impact of an Advent Technologies HT PEMFC system as well as the improvements expected through ongoing research and development.

The meta-study revealed that reported potential environmental impacts vary widely across published PEMFC LCA studies and ranges for the impact indicators GWP, AP, ADP and EP were derived as a benchmark for the LCA studies in the context of the MEASURED project.

The LCA conducted on the current PEMFC stack is based on a 100 W laboratory-scale system which is scaled up to 1 kW for comparability to the meta-study. The results for GWP are 179 kgCO₂eq/kW, which is above the identified benchmark average. Indicators for EP are found to be higher than the established benchmarks. Indicator values for AP and ADP on the other hand are placed on the lower end of the benchmark ranges. Notably, the highest contribution to the GWP value stems from the stack housing and endplates. Another hotspot are the catalyst layers due to the Pt loading. In addition, the inefficiencies and high material intensity resulting from small-scale systems, as well as data uncertainties coming from limited primary data and necessary

modelling assumptions explain the high results. These findings should therefore be interpreted as estimates, rather than being representative of the system's potential at higher TRL.

Despite the environmental challenges observed in the LCA, the outlook for the novel HT PEMFC system is highly encouraging. The upcoming LCA will reflect the benefits of key technological advancements, including an improved stack lifetime and reduced Pt loading, which directly improves the environmental performance. Additionally, the enhanced power density leads to more compact and efficient designs and optimized ionomer formulations reduce energy use, improve batch consistency and enhance recyclability. Lastly, the capability to utilize hydrogen of lower purity is not part of the LCA at hand, despite it being one of the expected key advantages of HT PEMFC systems in environmental terms compared to current high TRL systems when considering their full life cycle.

In summary, while the HT PEMFC LCA highlights the environmental challenges associated with early stage, small-scale FC stacks, it also provides a valuable baseline for identifying key points for improvement. The results of the upcoming LCA on the TRL 4 system are expected to show substantial reductions across several environmental indicators, demonstrating the MEASURED project's potential to deliver cleaner, more efficient FC solutions for the HDV sector. This supports the broader project goals of climate-neutral mobility, circular design and resource-efficient energy technologies.

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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

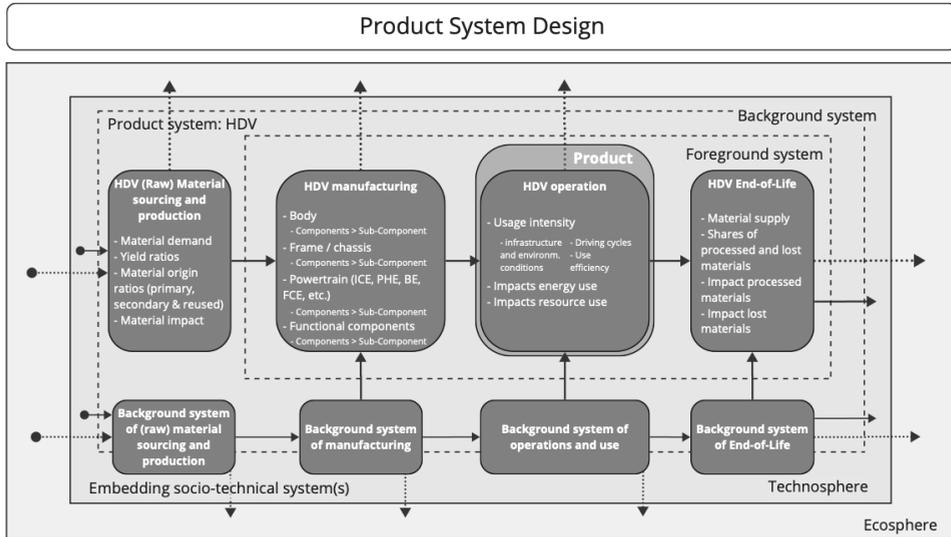
The development of heavy-duty vehicles (HDVs) involves a sequence of distinct engineering phases, each characterized by different challenges, decision-making logics, and levels of data availability and precision. Findings from the structured literature review and the expert workshop conducted as part 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.

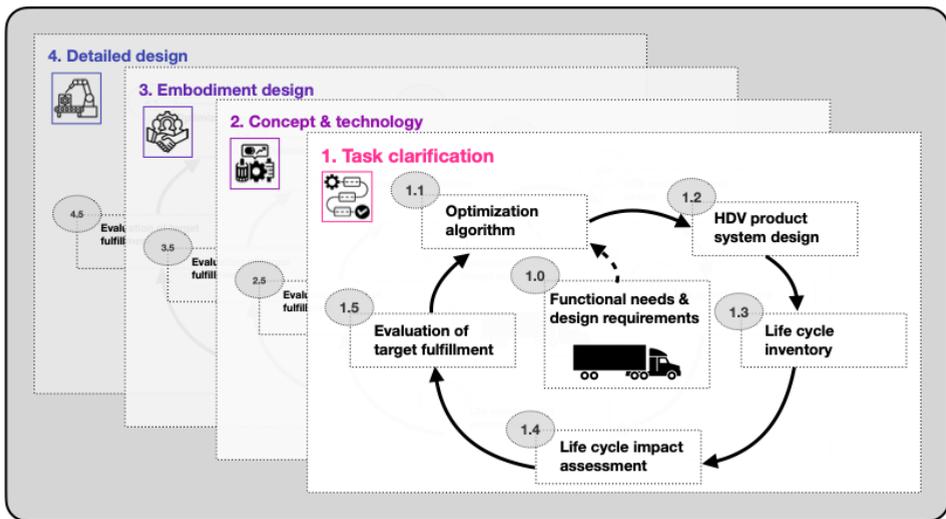


Figure 2: The life cycle optimization (LCO) framework for heavy-duty vehicles (HDV).

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.

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Investigation of new ion-pair-based membranes for carbon-neutral propulsion of heavy-duty vehicles

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EXTENDED ABSTRACT

Hydrogen fuel cells are a promising carbon-neutral technology for powering heavy-duty vehicles (HDVs) and could contribute significantly to the decarbonization of the transport sector. High-temperature proton exchange membrane fuel cells (HT-PEMFCs) are a class of fuel cells that can be operated with lower-purity and therefore cheaper hydrogen due to their elevated operating temperature. They require smaller heat exchangers than low-temperature (LT-) PEMFCs because the larger temperature gradient to the environment increases the cooling rate [1]. The current state-of-the-art membrane electrode assemblies (MEAs) are based on phosphoric acid-doped polybenzimidazole (PBI) membranes, which exhibit good performance at the beginning of life (BoL) but experience performance degradation over prolonged operation due to phosphoric acid leaching [1]. To mitigate this, new materials such as ion-pair-based membranes (IPMs) have been developed [1, 2].

In this study, novel IPM-based MEAs and reference PBI-based MEAs were evaluated using 100-hour accelerated stress tests (ASTs) at 160 °C, designed to simulate real-world operating conditions in heavy-duty vehicles (HDVs) [3]. The performance evaluation of the membrane material in the cell was carried out using in-situ measurement techniques, such as polarization curves and electrochemical impedance spectroscopy (EIS), which were performed in

25-hour intervals. The ex-situ characterisation of the material was performed with scanning electron microscopy (SEM).

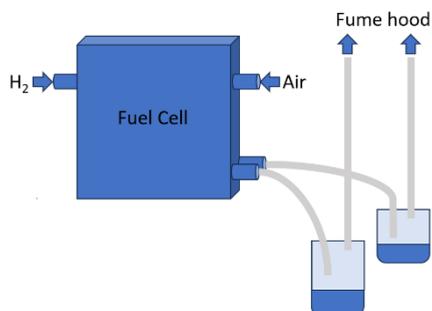


Figure 1: Schematic display of the sample collection during the AST measurement.

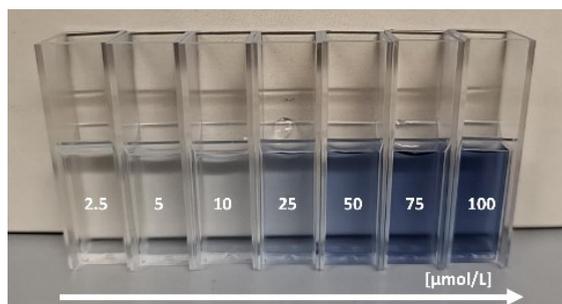


Figure 2: Molybdenum blue standards in the measuring cuvettes.

To investigate phosphoric acid (PA) loss from the two membrane types, the effluent water generated during operation was collected in a sample container connected to the cell via PTFE tubing (Figure 1) and analyzed via the molybdenum blue method [4]. In this method, a molybdenum-containing color reagent is added to the effluent, forming a blue colored complex with phosphate. The phosphate quantification was subsequently performed spectrophotometrically using a calibration curve with standards (Figure 2) and applying the Lambert-Beer law. This analytical method for the detection of phosphoric acid offers a simple and fast analysis of the effluent water sample with low limit of detection ($\text{LOD} = 0.3 \mu\text{mol L}^{-1}$) and limit of quantification ($\text{LOQ} = 1.0 \mu\text{mol L}^{-1}$), which are close to the values achieved by commercial ion

chromatography measurements ($LOD \approx 0.1 \mu\text{mol L}^{-1}$, $LOQ \approx 0.3 \mu\text{mol L}^{-1}$ [5]). The results of the molybdenum blue method were cross-validated using ion chromatography to ensure accuracy and reliability.

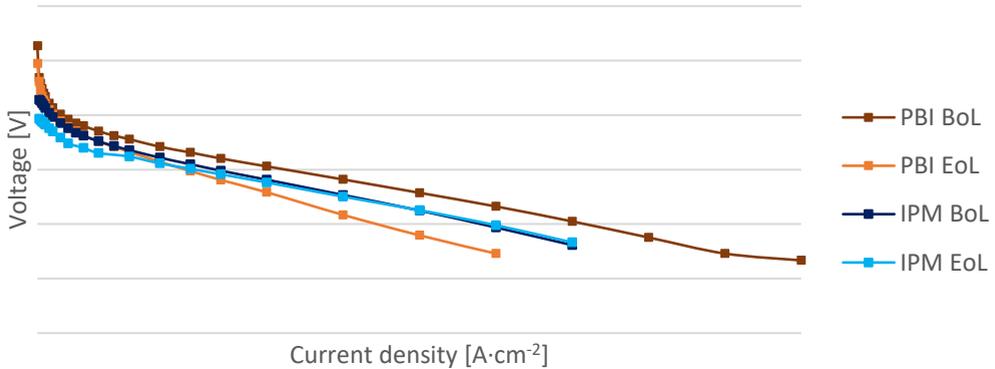


Figure 3: Comparison of BoL and EoL performances of PBI and IPM at 160 °C

At the beginning of life (BoL, 0 hours AST), the PBI-based membrane showed higher performance compared to the IPM (Figure 3). However, over the duration of the 100-hour AST, the PBI membrane experienced a more significant decline in performance, whereas the IPM demonstrated stable performance. By the end of life (EoL, 100 hours AST), the IPM-based membrane outperformed the PBI membrane.

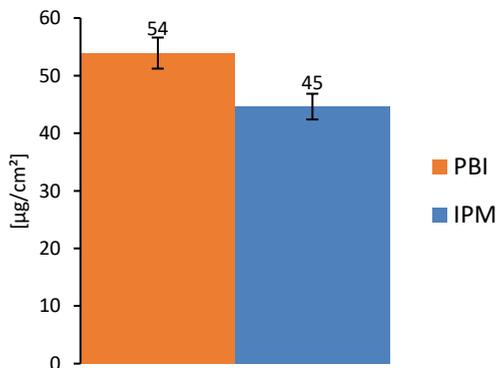


Figure 4: Determined phosphoric acid in effluent water for PBI and Ion-pair membranes after 100 h AST at 160 °C. Values given as mass of phosphoric acid, normalized for membrane area [$\mu\text{g}_{\text{PA}} \text{cm}^{-2}$]

Furthermore, the total phosphoric acid loss observed over the 100-hour test period was higher for the PBI membrane ($54 \mu\text{g}_{\text{PA}} \text{cm}^{-2}$) than for the IPM ($45 \mu\text{g}_{\text{PA}} \text{cm}^{-2}$) shown in Figure 4. This highlights the stronger phosphoric acid retention of the IPM, due to the stronger interaction with phosphoric acid, as indicated by the higher calculated interaction energy (PBI: 17 kcal mol^{-1} ; IPM: $105 \text{ kcal mol}^{-1}$ [6]). The values obtained with the molybdenum blue method are largely in line with literature values. For the IPM, the determined phosphoric acid loss rate was in the range of 0.45 to $1.30 \mu\text{g}_{\text{PA}} \text{cm}^{-2} \text{ h}^{-1}$, and for the PBI membrane, it was in the range of 0.54 to $2.11 \mu\text{g}_{\text{PA}} \text{cm}^{-2} \text{ h}^{-1}$. Literature values report for IPM-based MEA a loss rate of $1.30 \mu\text{g}_{\text{PA}} \text{cm}^{-2} \text{ h}^{-1}$ [6], whereas for PBI-based MEAs, they reported 0.24 to $61.2 \mu\text{g}_{\text{PA}} \text{cm}^{-2} \text{ h}^{-1}$ [7,8].

These results suggest that the novel IPM technology is a promising alternative to conventional PBI membranes, with the potential to improve acid retention and durability of HT-PEMFCs in HDV-related operating conditions.

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Day 1 Session: Digital Product Passports for Sustainable Mobility Solutions

From literature to practice: Understanding researcher perspectives towards social issues in digital battery passports

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ABSTRACT

The Digital Product Passport (DPP) is a cornerstone of the 2024 Ecodesign Regulation for Sustainable Products. It is an innovative tool designed to improve the transparency and sustainability of product value chains. The DPP acts as a digital identity card that promotes the circularity of products and strengthens compliance with legal standards and regulations. In response to the upcoming European battery regulation that will mandate digital battery passports (DBPs) for industrial and electric vehicle batteries (EVBs) from 2026, this study addresses the neglected integration of social aspects that are crucial for the sustainable management of the EVB value chain. DBPs are innovative tools designed to digitally document comprehensive details of EVBs, encompassing technical specifications, circularity data, and information on sustainability throughout their lifecycle. Although environmental aspects have been included in the conceptualization of DBPs, social factors have not been sufficiently analysed or incorporated, despite their importance for a holistic sustainability perspective in the transport sector. Therefore, this study uses a mixed-methods approach to investigate the integration of social issues into the value chain of EVBs in the context of DBPs. Through a systematic review of the scientific literature, coupled with insights from academic-led workshops, the present study identifies pressing social issues that are essential for a socially sustainable EVB value chain. The results highlight the most pressing social issues relevant to a DBP, e.g., health and safety issues of workers and local communities, fair wages, child labour, local

employment, and education and training of workers in the EVB value chain. In this case, the study highlights the researcher's view that social issues must be an integral part of DBP development to ensure that holistic aspects of sustainability are addressed, the overall management of EV value chains is improved, and ethical industry practices are supported.

1. INTRODUCTION

At the forefront of sustainability and circular economy initiatives, digital product passports (DPPs) have emerged as transformative tools that introduce a new era of product traceability and accountability (Berger et al., 2022). DPPs contain comprehensive product lifecycle data ranging from resource extraction to end-of-life (EoL) management. This facilitates the transition to a more sustainable, circular, and transparent global supply chain (Berger, Baumgartner, Weinzerl, Bachler, & Schögggl, 2023). As the European Union lays the groundwork for incorporating DPPs within its Ecodesign for Sustainable Products Regulation (ESPR), the Digital Battery Passport (DBP) is gathering particular attention (European Union, 2024). The DBP enhances the foundational concept of DPPs specifically within electric vehicle battery (EVB) systems. EVBs can be seen as an enabler of a low-carbon future, promising to replace combustion engines with clean, efficient electric power. In this case, the DBP can be promising to advance the EoL management of EVBs by providing essential information, for e.g., details regarding recycling processes (Ott et al., 2024). The introduction of DBPs is not only a technological novelty but an important channel for the collection and transmission of information critical to the legal, environmental, and ethical aspects of EVBs - a representation of the increasing overlap between digitalization and sustainability (Berger, Baumgartner, Weinzerl, Bachler, Preston, & Schögggl, 2023). In the DBP discourse, environmental sustainability and circularity aspects find great consideration (ibid). However, the social sustainability perspective has been neglected so far (Panza et al., 2023; Saari et al., 2022). Thus, there is a risk that the dynamic social issues associated with the EVB value chains are overlooked, resulting in DBPs that lack a holistic sustainability perspective.

In light of this discrepancy, this study seeks to extend the conceptual development of DBPs towards a holistic sustainability perspective by identifying and incorporating relevant social issues (social datapoints) into the conceptual framework of a DBP. Through a mixed-methods approach, using both primary data from targeted expert workshops and secondary data from a

comprehensive literature review, this study aims to develop a researcher-centred understanding of essential social issues relevant to DBPs (social datapoint requirements). The results are summarized based on the subcategories by UNEP (2020) or expanded to include further social issues in order to identify social datapoint requirements for DBPs. By breaking down these myriad social dimensions, the study highlights the need to develop DBPs that not only improve environmental performance but also promote social well-being and equity (Saari et al., 2022). In this regard, and considering the importance of this topic, this study answers the following research question:

Which social issues are central to the conceptual development of DBPs from the researcher's perspective to obtain a holistic sustainability perspective?

Consequently, the study describes an expanded perspective of sustainability that harmonizes with economic and environmental pillars, strengthens the integrity of DPPs and DBPs, and ultimately contributes to improving the holistic sustainability performance of global value chains of EVBs.

2. THEORETICAL BACKGROUND

The circular economy represents a system change, moving from a traditional linear framework for resource use to an innovative regenerative model that emphasizes the continuous recovery and reuse of resources to minimize waste and ensure improved sustainability performance (Moreno & Charnley, 2016; Suman & Rajak, 2025). The concept of circular value chains is crucial, especially in contexts such as the transport sector, where the life cycle of products has fundamental environmental and social impacts. EVBs are a great example of a product that can benefit from circular value chains, as they are made of different materials, and demand is growing rapidly as the world transitions to electric mobility (European Union, 2023).

Circular EVB value chains facilitate the efficient use of valuable and often scarce resources such as lithium, cobalt, and nickel, which are essential for battery production. By incorporating circular principles, value chains can minimize waste and reduce the need to extract new materials, which often leads to significant environmental damage and negative social impacts. Appropriate EoL management of EVBs ensures that these valuable materials remain in circulation for as long as possible, improving the overall sustainability performance of battery production (Rezaei et al., 2025). While a more circular EVB value chain has potential environmental benefits, it is important to note that greater circularity does not automatically equate to sustainability (Broman & Robèrt, 2025; Schögl et al., 2020).

For circular value chains to be effective, transparency and traceability are key (Berger et al., 2022; Centobelli et al., 2022; Wallat et al., 2024). This is where innovations such as DPPs come into play, potentially tracking the lifecycle impacts and facilitating the return and recycling of EVBs (Berger, Baumgartner, Weinzerl, Bachler, Preston, & Schöggl, 2023). DPPs are envisioned to create a closed-loop system, ensuring that every stage of the EVB value chain is documented, which is critical for enabling the circular economy (Zhang & Seuring, 2024). By providing accessible, reliable data on the origin, material composition, and environmental footprint of products, DPPs are set to become crucial in the tracking and optimisation of resource flows, thus fostering circularity across industries (Plociennik et al., 2022).

The DPP is a comprehensive digital identity card, analogous to a fingerprint for products, detailing the lifecycle information of products (Tabata & Tsai, 2025; Yasin et al., 2024). By integrating ethical and environmental information about a product, DPPs are structured to provide stakeholders, such as manufacturers, regulators, and consumers, with detailed data that enables informed decision-making that supports the goals of the circular economy (Berger, Baumgartner, Weinzerl, Bachler, & Schöggl, 2023; Berger et al., 2022). Not limited to ecological attributes, DPPs also have the potential to document and communicate the social impacts associated with product manufacturing, which is crucial from a holistic sustainability perspective (Berger et al., 2022; Panza et al., 2023; Saari et al., 2022). Although few, a handful of scientific studies have already investigated the integration of possible social issues in DPPs. In this regard, several studies point out that a DPP should include information on the social impact of a product. Still, no more detailed information is provided; see, e.g., the papers of Kebede et al. (2024), Langley et al. (2023), Panza et al. (2023), or Pohlmann et al. (2024). In some studies, social issues as relevant social datapoints in DPPs are already mentioned somewhat more specifically, such as in the study by King et al. (2023) and Plociennik et al. (2022), who name human welfare as one specific social topic. Other studies report more labour-related issues, such as labour conditions in general (Pohlmann et al., 2024; Stratmann et al., 2023) or position or salary information by gender, in particular for textiles and clothing (Alves et al., 2024). In their study, Panza et al. (2023) refer to five stakeholder groups and associated social topics and indicators relevant for DPPs in general, such as two social topics for the consumer stakeholder group, namely health and safety, and experienced well-being. One study focuses on batteries more specifically, namely Berger et al. (2022), who mention worker safety, fair wages, and forced labour as relevant social issues.

However, most scientific studies show that a too narrow or purely technical perspective in DPPs, or DBPs as in the present study, can obscure important data requirements. An integration of environmental and social issues is unavoidable in order to ensure sustainable product value chains. A well-structured DBP could provide critical insights into the ethical sourcing of raw materials, advance responsible production practices, and support efforts for extending battery life through an appropriate EoL management.

3. METHODS

The research adopts a mixed-methods approach in two sequential main phases (see Figure 1): 1. an exploratory literature review (secondary data) followed by 2. empirical primary data collection through workshops, leveraging the strengths of both qualitative insights and quantitative data from researcher workshops and quantitative data from the literature review. The literature review establishes a theoretical backbone, while workshops with researchers infuse the study with experiential knowledge and expert perspectives. A comprehensive systematic literature review serves as the first phase, aimed at constructing a theoretical foundation for identifying social issues associated with DPPs in general and DBPs. Therefore, relevant regulations, policy papers, and standards are being screened to identify possible relevant social issues in addition to the subcategories based on UNEP (2020) as preparation for the empirical work (workshops). Subsequently, academic databases (i.e., Scopus) are systematically searched using a combination of keywords related to social sustainability (issues), EVBs, DPPs, and DBPs. Articles, reports, and white papers are reviewed to identify social issues mentioned in research discourse. Records were excluded if they did not clearly relate to DPPs/DBPs and respective data content for Sustainable Product Management (SPM). The initial search led to 266 records identified for title and subsequent abstract screening. Based on the inclusion/exclusion criteria defined, 30 records are identified for full-text analysis. Of these 30 records, 15 relate to social sustainability information and respective data points in DPPs/DBPs. The other records predominantly discuss circularity or environmental sustainability-related data points represented via a DPP. Of those 15 records, nine ($n=9$) remain, as they explicitly specify social issues that should be represented in a DPP/DBP. The synthesis from the literature review not only identifies recurring themes but also highlights gaps in current research.

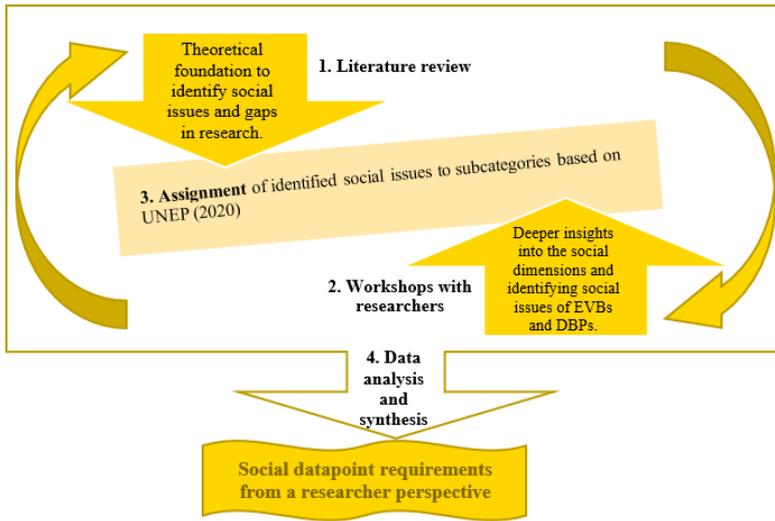


Figure 1: Methodical approach to identify social datapoint requirements from a researcher's perspective.

The literature review serves two purposes: firstly, it allows the relevance of individual social issues (social datapoint requirements) for DPP/DBPs to be identified based on secondary data. Secondly, the collection of social issues forms the basic scope for holding the workshops. Thus, the next main phase is to hold workshops with researchers ($n=64$) to gather primary data. These sessions bring together scientific experts from various fields, including sustainability, social sciences, and battery technology, to discuss and scrutinize the preliminary findings from the literature review. These workshops help to identify social issues (quantitative data) relevant as datapoints for DBPs and to gain deeper insights into the social dimensions of EVBs and DBPs, fostering an iterative dialogue that refines and enriches the themes identified in the literature. All identified social issues are assigned to the subcategories based on UNEP (2020) or have been added as additional social issues (e.g., training and education for the stakeholder group “worker”). Through an iterative process and several workshops, social datapoint requirements for DBPs from a researcher perspective are summarized, triangulated by the quantitative analysis (e.g., frequency of theme occurrence) and qualitative data, providing a conceptual basis for a holistically sustainable DBP development.

4. RESULTS

The results present social issues relevant to EVBs and the conceptual development of DBPs. The discussions draw attention to the complexity of these issues and their interconnections, emphasizing the need for their consideration in the design and implementation of DPPs.

4.1 RESULTS BASED ON SECONDARY DATA (LITERATURE REVIEW)

In total, 34 social issues were identified in the relevant literature (n=9). Based on the UNEP classification, the results show a clear preference for the "worker" stakeholder group, with a mean value of 2.50 (the sum of all mentions in the papers divided by the number of social issues per stakeholder group). Based on the mean values, the individual stakeholder groups are ranked in order: "value chain actors" (1.38), "local community" (1.09), "consumer" (1.00), "society" (0.20), and "children" (0.00). Social issues related to the stakeholder group "children" cannot be found in the respective scientific literature. When the number of social issues mentioned in the scientific papers is ranked, a focus on social issues for the stakeholder group "worker" is also evident, with the first eleven social issues related to the stakeholder group "worker" (see Table 1; Table 1 showcases only social issues with a #mentions ≥ 3).

The social issues "health and safety" (six times), as well as "child labour" and "fair salary" (five times), are mentioned most frequently. Other stakeholder groups only become apparent in 12th place, with "safe and healthy living conditions" for "local community" and "supplier relationships" and "wealth distribution" for "value chain actors". The results based on secondary data show a clear focus on the stakeholder group "worker". Overall, there is little heterogeneous discussion of social issues as a whole, with 34 social issues identified in the scientific literature, some of which are only mentioned once, such as social issues related to "local community" (e.g., cultural heritage or secure living conditions), related to "value chain actors" (e.g., fair competition or human rights due diligence), related to consumer (e.g., health and safety or feedback mechanism), and related to society (e.g., contribution to economic development or ethical treatment of animals).

Table 1: Social issues identified in scientific literature (n=9) as possible social datapoints

Rank	Stakeholder group	Social issue	Sum (#mentions)
1	Worker	Health and safety	6
2	Worker	Child labour	5
3	Worker	Fair salary	5
4	Worker	Working hours	4
5	Worker	Forced labour	4
6	Worker	Equal opportunities / discrimination	4
7	Worker	Employment relationship	4
8	Worker	Freedom of association and collective bargaining	3
9	Worker	Social benefits / social security	3
10	Worker	Sexual harassment	3
11	Worker	Smallholders including farmers	3
12	Local community	Safe and healthy living conditions	3
13	Value chain actors	Supplier relationships	3
14	Value chain actors	Wealth distribution	3

15	Consumer	Transparency	3
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4.2 RESULTS BASED ON PRIMARY DATA (WORKSHOPS)

The workshop results show that the stakeholder group “worker” is mentioned the most by the participants. Nevertheless, the distinction from the other stakeholder groups based on primary data is somewhat unclear, and the results show a heterogeneous picture of different social issues (see Table 2; Table 2 showcases only social issues with a #mentions by more than half of the participants). Based on the mean values, the individual stakeholder groups are ranked in order: “worker” (28.72), consumer (28.14), “local community” (28.00), “children” (26.50), “society” (23.80), and “value chain actors” (21.50).

The participants identified a total of 58 different social issues based on the three workshops. The social issue of health and safety is mentioned most frequently in relation to the stakeholder group “worker” (57 mentions), followed by safe and healthy living conditions for the “local community” (50 mentions). More than half of the participants mentioned a total of 27 topics relating to six different stakeholder groups. These include, for example, society-related issues (e.g., public commitments to sustainability issues or contribution to economic development), social issues related to consumers (e.g., health and safety or transparency) or social issues related to the stakeholder group “children” (e.g., education provided in the local community or health issues for children as consumers).

Table 2: Social issues identified in three workshops with sustainability researchers (n=64)

Rank	Stakeholder group	Social issue	Sum (#mentions)
1	Worker	Health and safety	57
2	Local community	Safe and healthy living conditions	50

3	Worker	Fair salary	49
4	Society	Public commitments to sustainability issues	48
5	Worker	Training and education	45
6	Worker	Child labour	44
7	Local community	Local employment	44
8	Society	Contribution to economic development	44
9	Value chain actors	Supplier relationships	43
10	Consumer	Health and safety	41
11	Consumer	Transparency	41
12	Consumer	End-of-life responsibility	41
13	Children	Education provided in the local community	41
14	Worker	Working hours	40
15	Local community	Secure living conditions	40
16	Children	Health issues for children as consumers	40
17	Worker	Forced labour	39

18	Value chain actors	Fair competition	38
19	Worker	Equal opportunities / discrimination	36
20	Local community	Community engagement	36
21	Value chain actors	Promoting social responsibility	36
22	Consumer	Feedback mechanism	36
23	Consumer	Consumer privacy	36
24	Worker	Social benefits / social security	35
25	Local community	Access to material resources	34
26	Local community	Respect of indigenous rights	33
27	Society	Technology development	33

5. DISCUSSION AND CONCLUSION

The development of DPPs and, more specifically, DBPs, represents a significant leap toward achieving transparency and accountability in the life cycle management of products, particularly in sectors such as transportation and mobility. The concept of these passports aligns closely with the goals of the CE and SPM, aiming to enhance resource efficiency, prolong product lifespans, and minimize negative sustainability impacts. While DPPs and DBPs have shown great promise in addressing the environmental and technical facets of sustainability, such as material circularity, carbon footprints, and recyclability, their contributions to social sustainability have so far been

limited. Social issues form an essential dimension of product lifecycles, particularly in globalized and resource-intensive industries like battery value chains. Failures to address these social considerations can exacerbate adverse outcomes such as unsafe labor conditions, human rights abuses, and economic inequalities. For instance, the mining of critical raw materials like cobalt and lithium, a cornerstone for lithium-ion battery production in EVs, has been associated with unethical labor practices and social displacement in different regions. Thus, the fair distribution of risks and benefits across the product life cycle is a prerequisite for a holistic, sustainable development within the context of circular economy principles. For DPPs and DBPs to contribute meaningfully to CE initiatives, they must incorporate social issues that align with not only resource management objectives but also the equitable treatment of all stakeholders. In the case of DPPs and DBPs, a more robust incorporation of social issues can provide several benefits, e.g., building trust within stakeholders through improved transparency, regulatory compliance, consumer empowerment, and supply chain accountability.

Incorporating social issues into DPPs/DBPs requires a thoughtful and systematic approach, integrating various perspectives. In this case, as a first step, a researcher's perspective can be valuable to give meaningful insights regarding relevant social issues (social datapoint requirements). It is legitimate to carry out a literature review to identify relevant topics, but this can lead to essential aspects being ignored and overlooked, especially if not much literature is available. Drawing only on scientific literature can give a too narrow picture, leading to an information asymmetry. This demands a mixed-methods approach, as used in the present study, in the form of a comprehensive literature review and gathering primary data via expert workshops with researchers.

From a researcher perspective, an information asymmetry between primary and secondary data can be observed. The amount of scientific papers related to social issues in DPPs and DBPs is rather limited, but generally, when screening social issues, previous studies show a “worker” focus, often blending out impacts on other stakeholder groups. The social issues identified via workshops in this study reveal a heterogeneous picture of possible relevant social issues, assigned to six stakeholder groups. Other than the results based on the literature review, the importance of specific topics is emphasized via a collection of 58 different social issues mentioned in total. The importance of these factors seems to vary, as several are rarely mentioned. However, a possible focus is shown by the mention of a total of 27 social issues by more than half of the participants. These 27 social issues concern topics related to “worker” (e.g., health and safety, training and education or child labor), “local community” (e.g., safe and healthy living conditions, local employment or

secure living conditions), “value chain actors” (e.g., supplier relationships, fair competition or promoting social responsibility), “consumer” (e.g., health and safety, transparency or EoL responsibility), ‘society’ (e.g., public commitments to sustainability issues, contribution to economic development or technology development), and “children” (e.g., education provided in the local community or health issues for children as consumers). Social issues relating to children are not mentioned at all in the scientific literature. Still, the primary data research shows that there are indeed relevant topics in this regard from a researcher's perspective. There is also a focus on health-related topics, such as health and safety for different stakeholder groups or in relation to safe living conditions. Overall, there are numerous social issues presented in this study that could be relevant for the conceptual development of a DPP or DBP in particular. The study thus offers a valuable contribution to support the development of DBPs from a holistic sustainability perspective. This study also serves as a call for further studies to explore the social dimension of DPPs/DBPs comprehensively. A mix of different methods and integration of various perspectives could be central to this and is highly demanded.

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Digital vehicle passports for circular value chains: preliminary concept and use cases

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ABSTRACT

This paper presents a preliminary concept for a digital vehicle passport (DVP) of an electric vehicle (EV), abstracting major vehicle components by delineating information requirements needed to support respective circular and sustainable product management. Furthermore, three practical DVP use cases are presented, representing major vehicle life cycle phases. The concept development was driven by a systematic stakeholder mapping, enabling to identify key stakeholders of the EV (component) value chain(s). A systematic literature review enabled the identification of sustainable and circular EV (component) management practices and information requirements for respective support. Those information requirements were synthesized in an abductive approach. This resulted in a DVP concept comprising three main information categories. Furthermore, the developed concept emphasizes a DVP orchestration via subsuming digital product passports (DPPs) of EV components (e.g., digital battery passport, digital e-motor passport, digital tyre passport, etc.), exploiting data synergies. This paper contributes to current DPP literature in a sustainable product management context, as it presents the first conceptualization of a complex multi-component product. Thus, it distinguishes itself from current DPP research, that mainly focuses on energy storage systems or the built environment. The paper further holds practical relevance for regulators and practitioners as it highlights sustainable product management use cases and respective information requirements.

1. INTRODUCTION

Powertrain electrification is considered as one of the major technologies contributing to the decarbonization of the transport sector (Gerlando et al., 2024). Consequently, it is of interest to manage electric vehicles (EVs) with focus on maximising their sustainability and circularity performances, counteracting potentially undesired sustainability impacts (Rusch et al., 2023). EVs are complex multi-component products, complicating respective sustainable product management (SPM) (Gerlando et al., 2024). Each component stems from a different value chain comprising various value chain actors, who are facing different and at times competing SPM strategies and pathways (Hirz & Brunner, 2015). To support the identification of suitable and viable SPM pathways, value chain actors require, among others, high-quality data (Rusch et al., 2023). However, persisting data and information gaps along value chains prove great challenges for SPM (ibid). Digitalization, digital technologies and tools could prove valuable to collect, store, process and analyse product life cycle data, bridging data gaps along the value chain and enabling circular information flows (Rusch et al., 2023). Emerging tools like the digital product passport (DPP) could prove valuable in functioning as data carrier of product life cycle data, bridging data gaps along value chains, and facilitating collaboration among value chain actors (Berger et al., 2022). Sustainability research (Berger et al., 2022; Çetin et al., 2023), initiatives (The Battery Pass, 2024) and regulators (European Commission, 2023) have brought forward different proposals of DPPs for SPM practices in value chains. Major focus is placed on batteries (Berger et al., 2022; European Parliament, 2023; The Battery Pass, 2024) or the built environment (Çetin et al., 2023). However, complex multi-component products such as EVs have received so far limited attention. While from a regulatory side, the notion of a circular vehicle passport (CVP) has been introduced (European Commission, 2023), a DPP comprising a holistic sustainability perspective (i.e., environmental sustainability, social sustainability) for an entire EV has received so far no attention on a regulatory context nor in sustainability research.

This paper sets out to present a preliminary concept of a digital vehicle passport (DVP) in the context of SPM, answering the following research question:

RQ: *How needs a digital vehicle passport to be orchestrated in terms of key information to support the sustainable product management of an electric vehicle?*

Regarding the DVP scope the following major EV components were selected to be represented, based on an initial desk research (Gerlando et al., 2024;

Wen et al., 2021) and consulting policy papers (European Commission, 2023): the e-motor, power converter/inverter, brake system, battery pack, and tires.

The subsequent sections present the theoretical background (section 2), the method description (section 3), followed by the results' presentation (section 4). The paper closes with discussion and conclusion (section 5).

2. THEORETICAL BACKGROUND

2.1 THE ELECTRIC VEHICLE VALUE CHAIN AND SUSTAINABILITY MANAGEMENT

EVs are products that consist of a range of multi-component parts, enabling certain performances (e.g., driving range, charging duration, acceleration times), while fulfilling technical (e.g., weight, size) and safety requirements (Hirz & Brunner, 2015). Major EV components are the e-motor, the EV battery, converters and inverters, brake systems, as well as tires (Wen et al., 2021). Each of those components consist of different parts and materials that require different processes for being produced. For instance, an e-motor contains permanent magnets that require critical rare earth materials (Wen et al., 2021). An EV battery entails different active materials (e.g., lithium, cobalt, iron, manganese, graphite) to produce respective battery cells (ibid). The brake system, on the other hand, requires ceramics, rubber and steel for component production (NRS Brakes, 2023). Consequently, a holistic sustainable EV management constitutes the sustainability-oriented product management of all vehicle components, contributing to the EV's overall sustainability and circularity performance. Such an effort may pose challenging, due to the complexity of SPM decisions that concern not just one component, but multiple components that in turn constitute of different parts (Hirz & Brunner, 2015). Here, various decision-makers along the component value chains may face competing sustainability decision situations, while keeping performance and safety requirements, as well as economic viability into consideration (ibid).

2.2 DIGITAL TECHNOLOGIES AND TOOLS FOR SUSTAINABLE PRODUCT MANAGEMENT: THE CASE OF THE DIGITAL PRODUCT PASSPORT

When maximising a product's (environmental and social) sustainability and circularity performance, a holistic system's perspective is required (Rusch et al., 2023). There are different established concepts and approaches that can support such a fundamental product system transformation, including circular economy, sustainable supply chain management, life cycle assessment, or design for X (e.g., sustainability, circularity) approaches (ibid). Those approaches can be subsumed by the umbrella term SPM, taking into consideration a holistic life cycle approach and the perspective of various value chain actors over (potentially) multiple life cycles (Berger et al., 2022). One of the major challenges of SPM is the lack of high-quality product life cycle data for respective decision support (Rusch et al., 2023). In this context, the sustainability research stream exploring the potential of digitalization and digital technologies to enable SPM actions is continuously growing (ibid).

Recently, the digital tool entitled “digital product passport” has gained increased attention in sustainability research. DPPs are perceived as digital enablers of a sustainable circular economy, as they are envisioned as product life cycle data carrier (Berger et al., 2022). Some studies have already provided DPP conceptualization attempts to enable SPM in the construction sector (Çetin et al., 2023) or the automotive sector (Berger et al., 2022). For instance, Berger et al. (2022) provided a concept of a DPP for EV batteries, comprising four main information categories (cf. Table 1).

DPPs for multi-component products, such as EVs, are currently proposed from a regulatory perspective. Here, the CVP (European Commission, 2023) and environmental vehicle passport (EVP) need to be mentioned (European Commission Council, 2022). While those DPP-variants focus on the entire vehicle, they do not comprise a holistic sustainability perspective, focusing on conveying selective sustainability aspects (i.e., circularity – CVP, legal compliance emission level – EVP). A proposal brought forward by the World Economic Forum to merge the CVP and EVP led to coining the term “digital vehicle passport” (World Economic Forum, 2024). However, it is to be questioned whether a DVP based on DPP-variants that do not take into account a holistic sustainability perspective, can effectively support SPM.

Table 1: DPP information categories in accordance with Berger et al. (2022).

Information category	Description
Battery	Contains information to enable clear product identification, thus contextualization (e.g., technical specifications, performance specifications material compositions, etc.)
Sustainability and circularity	Contains information about the product in terms of sustainability and circularity properties (e.g., indicators relating to sustainability and circularity performances, information regarding disassembly to facilitate R-strategies, etc.)
Diagnostics, performance and maintenance	Contains information about the system status (e.g., state-of-health), maintenance triggers and carried out maintenance measures
Value chain actors	Contains information about value chain actors involved (e.g., value chain actor name, location, identification number, function)

3. METHODS

The DVP concept was developed based on the conceptualization approach proposed by Berger et al. (2022). First, a systematic stakeholder mapping in accordance with the supply chain-oriented process to identify stakeholders (SCOPIS) was conducted (Fritz et al., 2018), identifying value chain actors involved in the following EV component value chains: e-motor, power converter/inverter, brake system tires. The SCOPIS (incl. identification data needs and requirements for SPM) for the EVB has been conducted in a previous study (Berger et al. 2022). SCOPIS was supported by a systematic literature review (Moher et al., 2009). This enabled the identification of value chain actors' potential SPM use cases, and respective data needs and requirements. SCOPIS and the systematic literature review were conducted between December 2024 and March 2025. Literature written in German and English language were eligible for the literature sample. Both, scientific and grey literature were included. Scientific literature (i.e., journal papers, conference

papers) was identified by using the database Scopus. The identification of suitable grey literature (e.g., websites, product specification sheets, white papers, company reports) and respective sources was supported by a knowledge resource nomination worksheet approach (Okoli & Pawlowski, 2004) and the search engine google.

The deployed keywords led to initially 1053 hits. To be considered relevant, the records had to have a clear focus on the automotive sector. Records that focused on other sectors (e.g., energy sectors – wind turbines, aircrafts, electronics – dough makers) were excluded. The records required clear reference to the EV components of interest, enabling to derive information about the product and material structure. Records were also included if they described respective component value chains (upstream, downstream, full value chain) or life cycles (beginning-of-life, middle-of-life, end-of-life). Records that provided superficial information (e.g., "component xy is important") were excluded. Records were considered that discussed the selected components considering sustainability management (incl. circular economy) and respective strategies (e.g., life cycle engineering and management, life cycle assessment). Based on this criteria, 185 records remained after the title screening. Of those records the abstracts were screened. Based on the inclusion and exclusion criteria 31 records remained. Those records were then screened in their entirety, leading to a final sample of $N = 20$ scientific records. The grey literature search led to identifying $N = 32$ records, deemed relevant to support SCOPIS, as well as to identify information requirements for supporting SPM along the EV value chain. Thus, the final literature sample comprised $N = 52$ records. SCOPIS was supported by applying a life cycle perspective, deductively clustering the identified stakeholders, SPM decision pathways, and identified information requirements based on the following life cycle phases: beginning-of-life (BoL), middle-of-life (MoL) and end-of-life (EoL). Based on the SCOPIS findings, the conceptualization of the DVP was carried out following an abductive approach. As the deductive theoretical framework served the information categories proposed by Berger et al. (2022) (cf. Table 1). The identified information requirements were clustered based on those pre-defined information categories. The inductive character is given, as during data point clustering new information categories were developed, which are absent in Berger et al. (2022).

4. RESULTS

3.1 PRELIMINARY DIGITAL VEHICLE PASSPORT CONCEPT

The DVP concept comprises in total three main information categories: “vehicle”, “sustainability and circularity - overall system”, and “diagnostics, maintenance, and performance – overall system”. As the deployment of DPPs will become mandatory for certain products (e.g., battery, tires, steel-based products, aluminum-based products), DVP orchestration should be supported by EV component level DPPs (e.g., battery passport, tire passport, etc.), containing component-based information in the context of SPM. The component-specific DPPs can be considered as independent systems, that function as data sources for the DVP system that enable data synergies. Consequently, the component-specific DPPs comprise of main information categories themselves namely: “product”, “sustainability and circularity”, “diagnostics, maintenance, and performance”, and “value chain actor”. The component-specific DPPs serve to access detailed component-specific information, in particular in terms of sustainability and circularity performances, as well as component health and diagnostics. If component-specific DPPs are unavailable, the required information needs to be included in the DVP system. A visual representation of the DVP concept is depicted in Figure 1. A more detailed concept description is provided in following subsections.

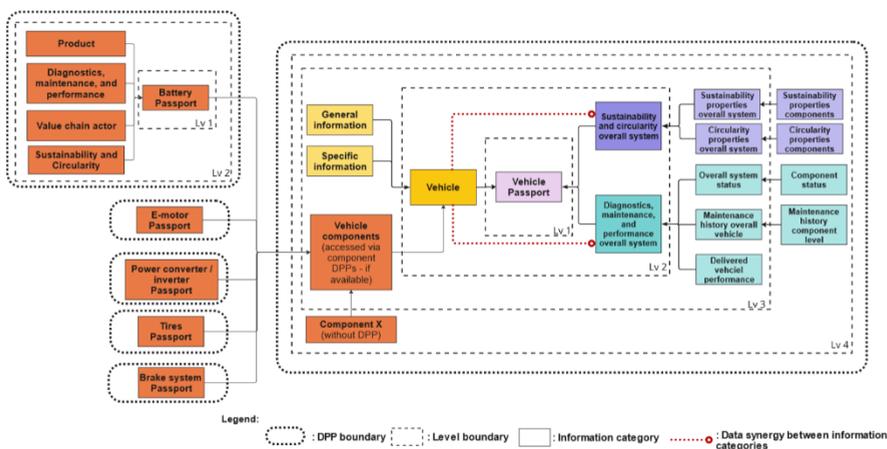


Figure 1: Digital vehicle passport concept. Depiction based on Berger et al. (2022).

3.2 VEHICLE

This main information category comprises two subcategories, namely “general information” and “specific information”. The first subcategory contains data points about general EV features, such as *vehicle class* (e.g., passenger car, heavy duty), *vehicle type* (e.g., battery EV, plug-in-hybrid EV), *vehicle manufacturer*, *location of assembly*. The second subcategory comprises data points related to vehicle performances (e.g., *driving range*, *EV lifespan*, *dis-/charging times*, etc.), technical specifications (e.g., *dimensions*, *weight (curb weight, dry weight)*). Those two subcategories enable a clear product identification, which is a pre-requisite in SPM.

This category also contains the subcategory “vehicle components”, comprising information about major EV components including: the EV battery, e-motor, power converter/inverter, tires and brake system. For each EV component there is a respective information category (e.g., “Battery”, “E-Motor”, etc.) containing the following component specific information categories: “product”, “sustainability and circularity”, “value chain actor”, as well as “diagnostics, maintenance and performance” (cf. Figure 1). Thus, information ranging from component identification, technical specifications, over sustainability and circularity performances on component level, component health, as well as value chain actors involved can be accessed.

3.3 SUSTAINABILITY AND CIRCULARITY – OVERALL SYSTEM

This main information category comprises two subcategories: “sustainability properties – overall system” and “circularity properties – overall system”.

The subcategory dedicated to sustainability distinguishes two sustainability performances; “environmental sustainability performance – overall system” and “social sustainability performance – overall system”. Those information categories enable to derive information in terms of respective sustainability performance, i.e., *indicators and results* (e.g., carbon footprint, water use, land use) of the overall EV. This is complemented by information about applied *standards and impact assessment methods* (e.g., ISO, UNEP). As the EV comprises different components, contributing to the overall sustainability performance, this category enables accessing information about the component-specific sustainability performances. This establishes a link between the information category “sustainability and circularity – overall system” and the component-specific DPPs’ information category “sustainability and

circularity”. Thus, the component-specific DPP serves in particular as data source for the DVP subcategory “sustainability properties – component” (cf. Figure 1). Here, further information can be derived regarding the component-specific sustainability indicator results, as well as the life cycle hotspots. Thus, the DVP enables the identification of (i) critical components, and (ii) their respective critical life cycle processes. This serves to identify areas for potentially enhancing the EV sustainability performance.

The subcategory dedicated to circularity comprises two categories: “circularity performance – overall system” and “circularity support – overall system” (cf. Figure 1). The category “circularity performance – overall system” provides information about the overall EV circularity performance and allowing the identification of components’ contribution to the overall EV circularity via its subcategory “circularity performance-component”. The category “circularity support – overall system” contains information about the EV design, down to the component level. Thus, component-specific data points with respect to *disassembly options and instructions*, as well as *repair options and instructions* can be found in this category. Here, the component-specific DPPs also serve as data source for the DVP subcategory dedicated to circularity properties.

3.4 DIAGNOSTICS, MAINTENANCE, AND PERFORMANCE – OVERALL SYSTEM

This main information category comprises the subcategories “overall system status”, “delivered vehicle performance”, as well as “maintenance history – overall system”. The subcategory “overall system status” provides vehicle diagnostic information, further enabling to derive more detailed component-level diagnostics information due to the linkage of component-specific DPPs (cf. Figure 1). A similar logic applies to the other two subcategories, as the component level of an EV plays a crucial role regarding overall EV system status. The subcategory “maintenance history – overall system” thus enables to derive component-specific data points such as *maintenance triggers*, *carried out maintenance action*, and *responsible party for maintenance action*. The subcategory “delivered vehicle performance” contains data points such as *actual range covered*, or *actual dis-/charging time*, enabling a comparison between the stated EV (component) performance according to the manufacturer and the field performance.

3.5 DIGITAL VEHICLE PASSPORT: USERS, SPM USE CASES AND CONCEPT UTILITY

In the BoL phase, the manufacturers of the EV components (e.g., e-motor, brake system, inverter/converter, tires), as well as the EV manufacturer themselves were identified as key decision makers. As they can opt to include sustainability and circularity requirements in the EV (component) design of next-generation EVs. The manufacturers require information about the environmental and social sustainability performance over the entire vehicle (component) life cycle, enabling the identification of life cycle hot spots. This aids to identify optimization potentials in the own production processes, as well as the overall product (component) design (e.g., material selection, design for X). Furthermore, it enables identifying (potential) life cycle processes, and consequently suppliers, that require supplier development measures (e.g., trainings for sustainability education) to contribute to the product system's overall sustainability and circularity. Here, the manufacturers can derive utility from DVPs of current in-use EVs. Here, the information category "vehicle" for EV identification, and thus contextualization is the first category of importance. Furthermore, the information category "sustainability and circularity – overall system" enabling to derive the sustainability and circularity performance on EV and component level.

In the MoL phase, the EV driver was identified as prospective DVP user. The EV driver may require information about the sustainability performance (e.g., CO₂ footprint of the EV production, estimated energy consumption during the use phase, information about child labour and forced labour involved during production, etc.) and circularity performance (e.g., share of recycled material, share of reused material) to support an EV buying decision. Also, general information about the EV (e.g., technical aspects, performance aspects) may further support the buying decision process. In case of buying a second hand EV, information about the product system's health status is of interest (e.g., maintenance work done, triggers for maintenance work, rest of (estimated) lifetime of the EV or key components, such as the battery). Here, the main information categories "vehicle", "sustainability and circularity - overall system", and "diagnostics, maintenance, and performance – overall system" can provide respective information.

For the EoL phase, in particular recyclers as well as refurbishing and repurposing parties were identified as actors of importance. Refurbishing and repurposing parties (e.g., the EV manufacturer, a third party) can contribute to either restore the EV component for reuse (e.g., tires – retreading) or to

repurpose the component for a second life application (e.g., EV battery – as stationary energy storage system). Here, the main information categories “vehicle”, “diagnostics, maintenance, and performance-overall system”, as well as “diagnostics, maintenance, and performance-component” are useful, enabling to derive health status-related information. Furthermore, the information category “sustainability and circularity – overall system” and its subcategory “circularity support overall vehicle” are beneficial to provide information (e.g., information about dismantling instructions) required for efficient repurpose/refurbishment operations of EV components. The recycler resumes a vital role as they will treat the EV (component), enabling to recover secondary material for primary material substitution in the EV value chain. Recyclers require information about the product composition (e.g., bill of material), as well as information about how to (safely) dismantle the EV component, enabling the design of an efficient recycling process. Here, the information categories “vehicle” and “sustainability and circularity – overall system” and its subcategory “circularity support overall vehicle” are useful.

5. DISCUSSION AND CONCLUSION

The presented DVP concept distinguishes itself from current conceptualization attempts (e.g., Berger et al., 2022) as it focuses on a multi-component product. Compared to the concept proposed by Berger et al. (2022), this DVP concept considers information representing the overall product level (i.e., the entire vehicle), as well as a component-based level. Furthermore, the DVP concept presented differentiates itself from current regulatory proposals (e.g., European Commission, 2023), and NGO recommendations (World Economic Forum, 2024) as it incorporates a holistic sustainability perspective. That said, the proposed DVP concept does not necessarily exclude regulatory use cases (e.g., European Commission, 2023), but goes beyond regulatory required information content, enhancing the SPM support potential of DVP. Furthermore, when conceptualizing a DPP of a multi-component product that consists of different (multi-)components itself, the DPP orchestration needs to be considered. Here, such an orchestration could be supported by integrating (existing) DPPs of those components, that constitute the overall product. Thus, a DVP would be orchestrated by exploiting DPPs of major EV parts, i.e., a digital battery passport, digital e-motor passport, digital tire passport etc. Those component-based DPPs contain component-specific information, providing a comprehensive representation of the entire EV. Thus, the component DPPs are to be seen as the underlying data source of a DVP, enabling the exploitation of data synergies. If no component-specific DPP is available, the DVP

system would require the integration of component-specific information (cf., Figure 2).

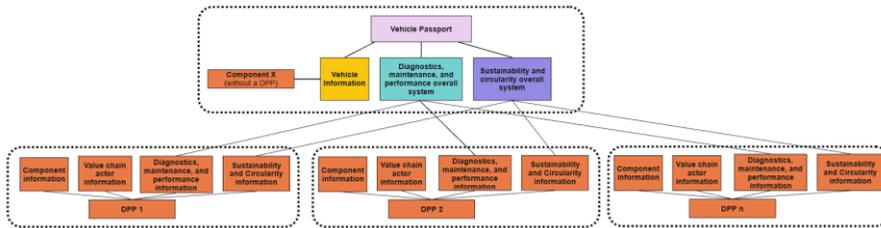


Figure 2: Orchestration of a DPP of a multi-component product via respective component-specific DPPs (own depiction).

This paper holds practical relevancy as it may provide guidance for policy makers and practitioners, when pursuing DPP implementation for SPM due to emphasizing the need of taking a holistic sustainability perspective into consideration. Considering a research perspective, this paper provides the foundation to further develop and refine multi-component DPPs for SPM support.

The major limitations lies in the conceptual nature of this work. Here, empirical validation is required (e.g., by directly involved EV value chain actors) to discuss the concept utility for SPM. Furthermore, further research regarding DPP orchestration and implementation is needed, considering the incorporation of component-specific DPPs. This further includes the design of the DPP and DPP system architecture and respective data security and accessibility issues.

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Digital Battery Passport: Driver for a Sustainable E-Mobility

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EXTENDED ABSTRACT

The automotive industry's shift towards electrification has led to a significant increase in the proportion of a vehicle's lifecycle CO₂ emissions occurring during the production phase. Consequently, vehicle manufacturers and suppliers must now prioritize optimizing the entire product lifecycle rather than focusing solely on the 'in-use phase.' This paradigm shift necessitates a comprehensive approach to product development that encompasses all stages of a vehicle's lifecycle. In this context, the circular economy and sustainable battery solutions have garnered significant attention from global authorities and regulatory bodies. A pivotal development in this area is the EU battery passport regulation, set to come into force in 2027. This regulation mandates new reporting requirements for all electric vehicles and industrial batteries larger than 2kWh, irrespective of the battery's origin. The regulation aims to enhance transparency and accountability in battery lifecycle management, thereby promoting sustainability. Digital battery passports represent a transformative innovation in the rapidly evolving landscape of sustainable energy. These passports are poised to revolutionize battery lifecycle management by providing detailed information on the battery's origin, composition, and performance throughout its lifecycle. However, the implementation and integration of battery passport solutions present several challenges, including data traceability, data integration and quality, and compliance with regulations. These challenges are particularly significant given the nascent stage of the market for battery passport solutions and the scarcity of reference projects. Addressing these challenges requires a holistic approach that combines robust platforms, specialized know-how, and comprehensive consulting and advisory services. This presentation will explore various options for applying the EU battery passport regulation and the legislative boundary conditions for batteries within the EU. It will also showcase best practice examples and

strategies for CO2 reduction in battery production and lifecycle management. The second part of the presentation will delve into a real-life application of battery passport definitions within a battery production environment, highlighting practical insights and lessons learned.

Digital product passport concept for an aluminum bike frame: A case study to enhance circularity and sustainability

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EXTENDED ABSTRACT

Cycling poses an active mobility mode that offers low-cost as well as low to zero emissions compared to other mobility modes (e.g., passenger cars). Bicycles with aluminium frames are associated with increased energy consumption during their life cycle and corresponding environmental impacts. The transition to circular and sustainable value chains requires transparent data access across all lifecycle stages for all stakeholders along this value chain. In this context, Digital Product Passports (DPPs) offer a structured approach to improving sustainability and circularity by facilitating data-driven decision-making. While the implementation of DPPs in the bicycle industry remains at an early stage, their application holds significant potential to advance sustainability and circularity. This study addresses this gap by proposing the first structured DPP framework for aluminium bicycle frames. It also outlines use cases in the context of sustainable product management, demonstrating how the framework enhances sustainability and circularity across the bicycle's life cycle. The development of the DPP framework is based on a structured stakeholder mapping and a systematic literature review. In addition, two expert interviews were conducted to gather further insights and validate and supplement the results. The resulting DPP concept comprises 62 data points organized into four categories: (1) bike frame specifications, (2) diagnostics and maintenance, (3) sustainability and circularity, and (4) value chain actors. These data points provide insights into material traceability, lifecycle

impacts, and product repairability, supporting sustainable product management. The concept also details the specific data requirements of the affected stakeholders, such as engineers, consumers, and recyclers. Furthermore, four use cases illustrating how stakeholders can leverage the DPP to enhance circularity and sustainability in bicycle production and disposal were derived. Hereby, for each lifecycle stage, one stakeholder group was selected. During the early stage, engineers have to opt for the optimal manufacturing process, which includes decisions such as implementing production methods and materials that ensure both performance and sustainability. At the Beginning of Life, raw material suppliers, who can choose between sourcing virgin or recycled materials, are essential stakeholders. Therefore, data regarding the origin of the material and its recyclability have to be provided by the suppliers. In the Middle of Life, consumers can either repair a bicycle or purchase a new one, which leads to a need for modularity and availability of repair options. Lastly, in the End of Life stage, waste management companies are responsible for handling discarded frames. To optimize this process, information such as disassembly guidelines and alloy compositions is required. This study contributes in three ways. First, it introduces a DPP concept for aluminum bicycle frames to enhance value chain circularity and sustainability. Second, it suggests a concept that improves data transparency and facilitates data-driven decision-making, serving as a foundation for future DPP development. Third, the study provides actionable insights for stakeholders to support the adoption of DPPs to accelerate the transition to a circular economy.

Day 1 Session: Innovative Rail Vehicle Design: Lightweight Structures, Efficiency, and Integrated Functions

Impact of normative loads and conventions on car body weight and structure for a rural rail vehicle

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ABSTRACT

Lightweight design in rail vehicles is crucial for enhancing energy efficiency, reducing operational costs, and lowering greenhouse gas emissions. This paper presents an overview of the key structural considerations and design principles involved in the early mechanical design of the car body of a small regional vehicle developed as part of the Horizon Europe Project “FutuRe”. The project aims to create a lightweight, two-axle rail vehicle for rural Europe, with a maximum weight of 32 tons. The design process employs a comprehensive methodical lightweight design approach, including topology optimizations to estimate and minimize the structural mass of the car body and gain insights into its optimal structural design. The results indicate that longitudinal loads for different load categories from EN 12663-1 have minimal impact on the car body’s structural weight. Furthermore, the location of heavy equipment like batteries has a negligible impact on the structural car body mass as well, featuring similar structural results. The findings suggest that normative boards should reevaluate the necessity of distinct longitudinal loads for car body development.

1. INTRODUCTION

Lightweight design in rail vehicles is essential for enhancing energy efficiency, reducing operational costs, and lowering greenhouse gas emissions. It improves performance in terms of acceleration and braking while maintaining safety. Additionally, lighter vehicles can carry more passengers or cargo, increasing the overall capacity and efficiency of the rail network, which is

crucial for sustainable urban mobility. The mechanical design of a train car body plays a crucial role in ensuring the safety, efficiency, and sustainability of rail transportation systems. As one of the most visible and essential components of a train, the car body must withstand various environmental conditions, including high and low temperatures, vibrations, impacts, and provide structural integrity for operational loads, exceptional loads as well as crash while also providing a comfortable and secure ride for passengers. Bringing together these manifold topics is possible with an insight-driven lightweight design approach.

This paper presents an overview of the key structural considerations and design principles involved in the early mechanical design of the car body of a small regional vehicle which is developed as part of the Horizon Europe Project “FutuRe” and has the target of a lightweight optimised vehicle. In this project, a small, lightweight two-axle rail vehicle is developed for rail traffic in rural Europe. The maximum vehicle weight, fully loaded, is limited to 32 tons to reduce strain on the superstructure of the lines (Persson et al., 2024).

A comprehensive methodical lightweight design approach is used to develop and evaluate different arrangements and geometries for the car body. As part of the process, normative conventions for the car body design approach will be challenged. This paper will detail the approach taken to generate car body topology optimizations and interpret the results to generate a structural car body proposal.

2. METHODOLOGY

The design process for the car body entails comprehensive use of topology optimizations (TO) with two objectives: 1) estimate (and minimize) the minimal structural mass of the raw car body; 2) Gain insights into how to best structurally design the car body (conceptual lightweight design approach).

2.1 TOPOLOGY OPTIMIZATIONS FOR CAR BODY DEVELOPMENT

The mechanical architecture of the car body is analysed using topology optimizations. TO is a mathematical and computational method used to determine the optimal material distribution within a given design domain, subject to constraints like structural performance, weight, and functional requirements. The goal is to achieve the best possible design by maximizing desired

properties - such as stiffness and/or strength - while minimizing material usage. The process relies on advanced numerical methods (FEA) to iteratively refine the material layout based on specific optimization criteria.

The key principle behind TO is the reduction of non-load bearing material while maintaining or enhancing the structural performance of a system. For every finite element, it defines the optimal stiffness/strength properties by considering the overall model requirements like defined stiffness and minimal mass of the complete structure.

2.2. RESEARCH OBJECTIVE AND APPROACH

As part of the early development process for the small regional vehicle, two main simulation types will be used to identify properties of the small regional vehicle:

- Structural mass analyses (result = virtual structural mass of car body)
 - Influence of battery configurations on minimum structural mass: Determine a virtual, theoretically achievable minimal structural mass
 - Parameter sensitivity: influence of constraints and loads on structural mass: Determine the influence of important forces and constraints on the mass
- Structural TO analyses (result = material distribution in car body)
 - Influence of load category on structure: Analyse the effect of different load categories from EN 12663-1 on the structure
 - Influence of battery configurations on structure: Analyse the effect of battery mount locations on the optimal material distributions and load paths in the car body structure.

By performing these analyses, it is possible to gain a fundamental understanding of how the normative and assumed loads and boundary conditions influence the car body structure. As an additional secondary objective, the effect of different normative load categories on car body mass will be identified.

2.3 NORMATIVE LOADS ON CAR BODIES

The European normative system provides several norms defining load scenarios and boundary conditions on a car body. Some of these loads were defined in the mid-early 1900s and their origins cannot be verified any more (Malzacher & Mohr, 2019). Studies performed by Schmauder et al. (2022) have also shown that some of the normative longitudinal loads seem to not have a significant impact on the estimated car body mass for a typical main-line rail vehicle, instead identifying the weight force as the major factor to increase stresses (and consequentially the structural weight during a TO). They conclude that EN 12663-1 dictates considering redundant load cases which make the design of railway car bodies inefficient. As part of the car body development in this paper, the effect of normative longitudinal loads on a small rail vehicle will also be researched. The relevant norms used in the topological analyses are listed in Table 1.

While EN 13749 defines loads on bogie frames, some of these loads are introduced to the car body as well and need to be considered in the TOs. For crashworthiness, EN 15227 is not specifically considered as only static loads can be applied in TOs. Furthermore, the longitudinal loads from EN 12663-1 already apply static loads to the crash absorbers.

Table 1 mentions that several norms use vehicle/load categories (use cases) for characterizing the assumed loads on a rail car. These load categories play a major role for the car body development. They are defined as P-I through P-V, starting with the highest loads for coaches (P-I) and continually decreasing the requirements for fixed units and coaches (P-II), underground/rapid transit and light rail (P-III), light duty metro and heavy-duty trams (P-IV) and ending with tram vehicles (P-V).

It is important to note that the nomenclatures overlap for neighbouring categories, meaning that the category used during development is somewhat up to the developer. The small regional rail vehicle which is to be developed in this project is planned to travel autonomously on branch lines throughout Europe. For this application, lower load categories like P-IV could be assumed. However, branch lines could also be connected to main lines or main-line vehicles may also travel on branch lines. This mixed use leads to the fact that the small vehicle might come into contact with larger and stiffer vehicles as well, meaning it would have to withstand the larger forces of higher categories like P-II. For this reason, the mass analyses and structural TOs will be performed for load categories P-II, P-III and P-IV and their impact compared with each other.

Table 1: European norms for mechanical car body design.

Norm	Content
EN 12663-1	<p>“Structural requirements of railway vehicle bodies” Definition of loads and load scenarios for different vehicle categories (use cases). Static load cases that simulate the maximum loads the car body will encounter, such as:</p> <ul style="list-style-type: none"> • Vertical loads due to passenger weight, cargo, or equipment. • Longitudinal loads due to braking, acceleration, or train (de)coupling. • Lateral loads caused by wind pressure, centrifugal forces during curve navigation, or uneven track conditions. • Dynamic loads: equipment accelerations mounted to the car body frame.
EN 13749	<p>“Method of specifying the structural requirements of bogie frames” Definition of loads resulting from the interaction between the bogie and car body</p>
EN 15663	<p>“Vehicle reference masses” Definition of reference masses for passengers/luggage for vehicle categories</p>
EN 16404	<p>“Re-railing and recovery requirements for railway vehicles” Definition of lifting scenarios</p>

2.4 FURTHER MODEL SETUP

The car body is 17 200 mm long with a wheelbase of 12 700 mm, its height is 2 600 mm and its width 2 895 mm. The design space for the TOs is sectioned into modules, indicated by the coloured parts of the car body in Figure 1. The car body is symmetrical along the y-axis and partly symmetrical along the x-axis. There is one door on each side approximately in the centre of the vehicle.

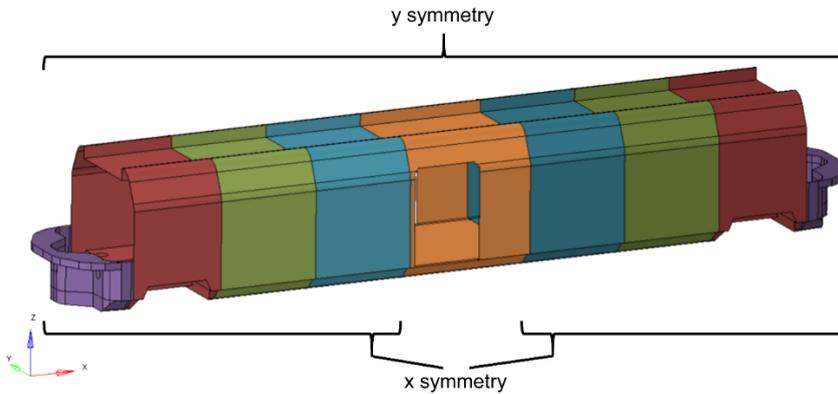


Figure 1: Car body design space with modular sections and symmetries.

The equipment setup can be seen in Figure 2. The configurations will be discussed in more detail in later chapters. The batteries are always attached on their corners to the structural design space with one battery weighing 250 kg. The material for the car body design space is steel.

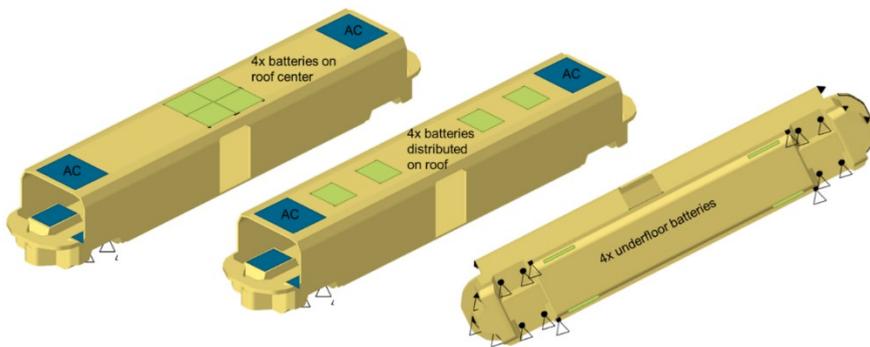


Figure 2: Car body design space with equipment and different battery configurations.

LOADS

The car body is subject to various loads, including passenger weight, track irregularities, and dynamic loads during operation. As mentioned in previous chapters, considered load categories are P-II (fixed units and coaches), P-III (underground/rapid transit and light rail) and P-IV (light duty metro and heavy-duty trams). All applied loads can be seen in Table 2.

OPTIMIZATION CONSTRAINTS / SENSITIVITY ANALYSIS

Topology optimizations need boundary conditions to ensure that the result performs according to the specifications. The boundary conditions used here are of a structural nature, see Table 3. They define maximum deformations on selected key points in the model. Some of these constraints are normatively mandatory, others are chosen based on common engineering experience. During the sensitivity analyses, these constraints will be varied to determine their influence on the car body mass.

Table 2: Loads and load cases of the topology optimizations.

Load / load case	Norm	EN 12663-1 load category		
		P-II	P-III	P-IV
Exceptional load (350kg/m ² standing passengers + seated passengers)	EN 12663-1 EN 15663	11130 kg		
Equipment (batteries, AC, electricals, ...)	-	3233 kg		
Distributed masses (cladding, HVAC, seats, ...)	-	7483 kg		
Lift 1 side at 2 points	EN 12663-1	-	-	-
Lift at all four points	EN 15663	-	-	-

Lift 3 points, 4th free		-	-	-
Lift 4 points, 1 point offset by -10 mm vertical		-	-	-
Lift 4 points with lateral forces		-	-	-
P-category force on window sill	EN 12663-1	300 kN	150 kN	-
P-category force on upper corners	EN 12663-1	300 kN	300 kN	-
P-category force on buffers push/pull	EN 12663-1	1500/ 1000 kN	800/ 600 kN	400/ 300 kN
Lateral accelerations equipment	EN 12663-1	1*g		
Running gear longitudinal/lateral acceleration + max. extraordinary load	EN 12663-1 EN 13749	3*g	3*g	2*g
Emergency towing	-	196 kN		

Table 3: Constraints for the topology optimizations.

Constrained area	Max value [mm]	Axis
Undercarriage deflection	-13 (1‰)	vertical
Lifting point	-100	vertical
Roof deflection	-30	vertical

Interior floor deflection	+/- 20	vertical
Buffer deflection	+/- 50	longitudinal

3. RESULTS

The result presentation is divided into structural mass results and structural topology results.

3.1 STRUCTURAL MASS ANALYSES

The objective of mass analyses is to determine how light the car body structure can become under the specified load conditions. All loads from Table 2 are applied. The objective of the TOs is to find the mass minimum of the design space. For these analyses, all symmetry constraints are removed. The result for each analysis is a mass value in tons. This value represents the virtually possible structural mass (i.e. the net mass of the vehicle structure without any additions, cladding, equipment, seats, etc.). It can be used to compare different configurations with each other, e.g. car body geometries or component arrangements.

INFLUENCE OF BATTERY CONFIGURATIONS ON MINIMUM STRUCTURAL MASS

As shown in Figure 2, three battery locations are considered: underfloor (two batteries in slots in the undercarriage on each side), above door (four batteries on the roof above the doors), and distributed on roof (four batteries distributed over the entire roof). The objective of the analysis is to determine how much the location of heavy equipment like batteries influences the car body structure. Table 4 contains the virtual mass results. They show that the location of the batteries does have an influence on the virtual mass, however, it is not significant.

Table4: Virtual mass results for different battery locations and materials.

Battery location	Load category	Virtual Mass
Underfloor	P-III	2.16 t
Above door		2.19 t
Distributed on roof		2.18 t

PARAMETER SENSITIVITY: INFLUENCE OF CONSTRAINTS AND LOADS ON STRUCTURAL MASS

The parameter sensitivity analyses were performed on the exemplary configuration “batteries distributed on roof” which serves as a baseline for comparison. All constraint values presented in Table 3 were tested for their influence on the car body minimum structural mass. The results and influence can be seen in Table 5.

Table 5: Results of parameter sensitivity analysis for topology optimization constraints.

Constraint	Base value	Modified value	Cat. EN 12663	Virtual mass	Notes/conclusion
-	-	-	P-III	2.18 t	batteries distributed on roof / baseline
undercarriage z	-13mm (1‰)	-26mm (2‰)	P-II	1.79 t	undercarriage deflection has drastic influence on mass
			P-III	1.75 t	
			P-IV	1.74 t	

roof z	-30mm	-50mm	P-II	2.23 t	no observable influence of dcon on mass in given setup
			P-III	2.18 t	
			P-IV	2.17 t	
interior floor z	-20mm	-40mm	P-II	2.23 t	no observable influence of dcon on mass in given setup
			P-III	2.18 t	
			P-IV	2.17 t	
buffer x	+/-50mm	+/-100mm	P-II	2.23 t	no observable influence of dcon on mass in given setup
			P-III	2.18 t	
			P-IV	2.17 t	

It can be noted that, within each variation, the load categories again have a minimal impact on the virtual mass. Further analyses were performed on the impact of the longitudinal forces, see Table 6. Completely removing the buffer force leads to the unexpected result that the mass does not decrease much compared to the baseline model with the usual EN 12663-1 longitudinal loads. Performing another calculation with EN 12663-1 P-category loads but omitting all vertical loads (no passengers or equipment) leads to a decrease in the virtual mass. It can be concluded that the P-category longitudinal loads have minimal impact on the car body structural mass for the considered vehicle.

Table 6: Results of force sensitivity analysis for topology optimization loads.

Force	Base value	Modified value	Cat.	Virtual mass	Notes/conclusion
-	-	-	P-III	2.18 t	batteries distributed on roof / baseline
buffer push force	400 kN	4000 kN	-	3.85 t	drastic force increase has influence -> force application functional
no longitudinal forces	varying	0 kN	-	2.16 t	load categories from EN 12663 contribute little to mass
no vertical loads except structural mass	+/- 50mm	+/-100mm	P-II	1.77 t	no equipment (AC, batteries, seats) or passengers -> vertical loads contribute most to mass
			P-III	1.71 t	
			P-IV	1.67 t	

3.2 STRUCTURAL ANALYSES

Following the minimal structural mass analyses, this chapter will present the approach and results for the structural analyses. Their goal is to get proposals for the optimal material distribution for a structural design of the car body with regard to different load configurations and to provide a baseline for the following mechanical design process.

INFLUENCE OF LOAD CATEGORY ON STRUCTURE

The purpose of these analyses is to study the effect of different load categories from EN 12663-1 on the structure itself. As with the minimum structural mass

analyses, an exemplary battery configuration was chosen (distributed over entire roof). Figure 3 shows the topology results. Blue elements received a low material density during the optimization, meaning they are less important for the structure, whereas red elements received a high material density, meaning they are very important for the structure. It can be noted that all P-categories seem to not necessitate a continuous longitudinal beam along the car body. This further underlines the findings of the previous chapters that the longitudinal loads do not have a significant impact on the car body structure.

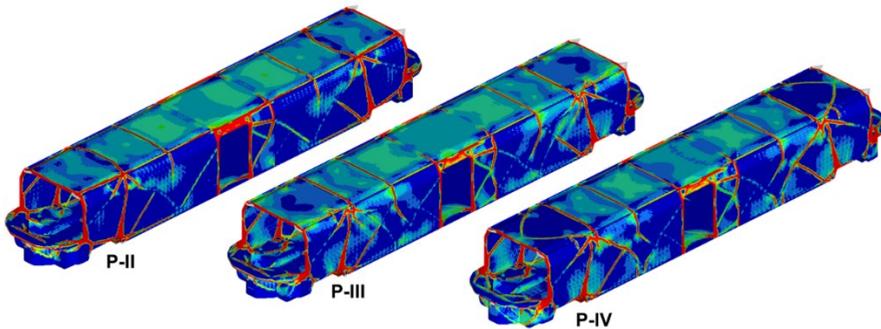


Figure 3: Car body structure for different load categories.

INFLUENCE OF BATTERY CONFIGURATIONS ON STRUCTURE

Concerning the impact of equipment location on the structure, Figure 4 shows a striking similarity between the three configurations. They all feature the same load cases (P-III). Only the battery location was changed. Most noteworthy, the configuration with underfloor batteries does not feature a distinct roof structure. In a failed attempt to prompt a roof structure, the roof deflection constraint was lowered. The air conditioning mounted above the running gears is not enough to prompt the formation of a structure in the roof. Instead, the roof mainly has to withstand torsional loads from the lifting load cases, meaning a semi-stiff shear plane is enough to distribute these loads into the surrounding structure. The other two battery configurations with the batteries mounted on the roof, however, feature a very distinct roof structure with clear X-beams leading through the battery fixation locations. Due to the absence of

continuous longitudinal beams, all models formed pronounced arches above the running gears with vertical spans to the running gear load introduction points.

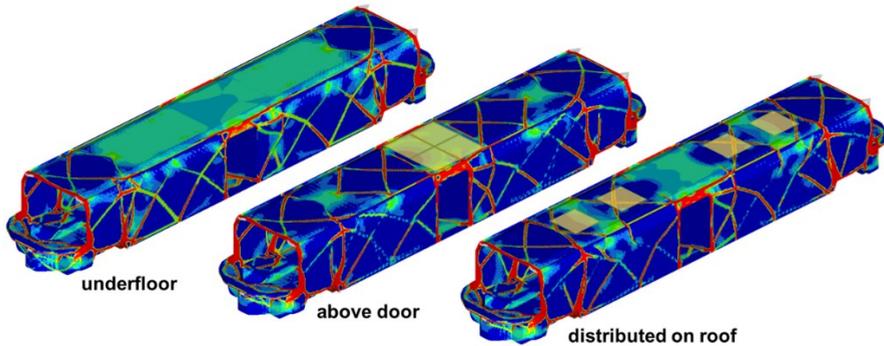


Figure 4: Car body structure for different battery locations (yellow: AC locations).

4. CONCLUSION

As part of the early development process of a small regional rail vehicle, topology optimizations were performed to determine the minimal viable car body mass for different load conditions.

Based on the frame conditions here, the analyses result for the virtual theoretically minimum achievable structural mass show that there is only a negligible mass saving potential for lighter load categories (P-IV over P-II or P-III). The same can be concluded regarding component arrangements. The location (underfloor/above doors/distributed on roof) of heavier components (e.g. four batteries with 250kg mass each) has a negligible impact on the virtual structural mass of the car body.

Based on the considered configurations, there is no significant weight difference between load categories from EN 12663-1. This finding, however, should be confirmed by performing FEM analyses on the future mechanical design of the car body.

The analyses of the structural impact of different load categories come to a similar conclusion that the three investigated P-categories lead to similar structural results with only minor differences in the load application areas themselves. P-III and P-IV are overall very similar regarding their weight and

their structure. This confirms findings from other authors (Schmauder et al., 2022) and should prompt normative boards to reevaluate the necessity for distinct longitudinal loads for car body development.

The analyses comparing different battery arrangements show that the roof is mainly loaded with a shear load if no other significant loads are acting directly upon it. Moving batteries onto the roof will lead to more distinct roof structures.

Overall, the topologies show similar load paths for different load categories and equipment locations. There are repeating major structures over the length of the vehicle with only local variations, see Figure 5 where three different topology results are overlaid. The implications are clear in that different use cases/load categories for a small rail vehicle have only minimal impact on the car body weight or its optimal car body structure.

Seeing as the load paths are similar among load variations, a steel differential design could be used to best follow the force flow of the topology optimization. This could be aided by applying advanced automated design methods to derive suitable cross sections from the optimization result (Gomes Alves et al., 2022), leading to an optimal material usage, reducing the structural weight and, thus, promoting resource efficiency.



Figure 5: Overlapping structural topology results for all three different battery configurations.

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Resource efficient regional train facilitated by single-axle running gears

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ABSTRACT

Regional railway lines with lower usage or part of secondary networks play a vital role in serving regions and as feeders for passenger and freight traffic for the main/core network. These railway lines need to be renewed to make them economically and environmentally sustainable and this is the aim of FutuRe – a project supported by the Europe’s Rail Joint Undertaking. Research is conducted in several areas, like traffic management, train positioning, automatic train control, wayside assets, multi-modal travelling, and the vehicle itself, where the propulsion system and the running gear are key research areas. Low weight and cost are crucial aspects for a resource-efficient regional train. Running gears make up a significant part of the weight of a railway vehicle and use of single axle running gears instead of conventional two-axle bogies would reduce the weight and cost. Single axle running gears have been used for rail vehicles from the beginning. Most of the applications have been for freight service where performance has been less important than the acquisition cost. In FutuRe, it is proposed that single axle gears should be used for a two-axle regional train and that the shortcomings of such a simple design should be mitigated through low force active suspensions. Two types of active suspensions are proposed, an active vertical dynamic suspension to ensure good vibration comfort and an active wheelset steering to ensure good curving performance. The solutions are presented together with early simulation results. The impact on Key Performance Indicators used in FutuRe shows that the proposed vehicle will have lower energy consumption, generate less external noise and require less maintenance compared to the regional train offered by the market today.

1. INTRODUCTION

Regional railways (lines with lower usage or secondary network) play an important role not only in serving European regions, but also as feeders for passenger and freight traffic for the main/core network. Therefore, they have an essential function as an environmentally friendly mode of transport and are an enabler for increasing the transport performance of railways. Unfortunately, many of these routes were abandoned in the past – mainly due to high costs. Therefore, these rail lines need to be revitalized or even renewed to make them economically, socially, environmentally sustainable and meeting current customer needs and challenges. To achieve these ambitious goals, a novel approach is necessary, which is the focus of the FutuRe project (FP6) from the family of the Europe’s Rail Joint Undertaking research and innovation activities. The activities are set up in several areas, but is here limited to the running gear, which is an enabler for weight, cost and energy consumption reduction. FutuRe has created a state-of-art report on present small size regional trains [1].

A selection of key requirements for the regional vehicle is given in Table 1 and a visual impression in Figure 1(right).

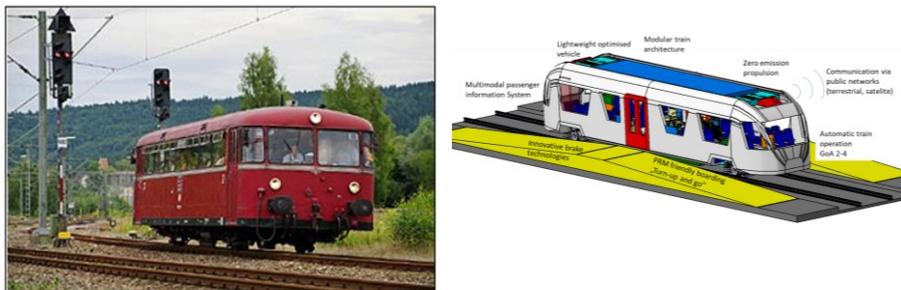


Figure 1: German rail bus from the 1950s (left), The FutuRe vehicle (right) [1]

Table 1: Key requirements for the FutuRe regional vehicle

Requirement	Value	Comment
Loading gauge	G1	European interoperable gauge
Number of passengers	Max. 100 (standees incl.)	Larger vehicles are commercially available
Platform height	550 mm	Level boarding should be offered
Vehicle length	16 m	
Maximum axle load	16 t	Most regional lines allow this axle load
Maximum speed	120 km/h	
Energy source	Battery and hydrogen	Hydrogen for range extension
Service brake	Regenerative	
Emergency brake	Mechanical	
Driving	Remote / automatic	No driver space
TSI compliance ¹⁾	Deviations	Strength, crashworthiness, and interior climate

- 1) Technical Specification for Interoperability (TSI) is a set of requirements that must be fulfilled to ensure that the vehicles are interoperable on the infrastructure complying with the specifications. This is strictly not needed for regional lines, but a noncompliance may impose restrictions when run on mainlines.

Single axle running gears have been used for rail vehicles from the beginning, Figure 1 (left). Most of the applications have been for freight service where performance has been less important than the acquisition cost. In the

Shift2Rail project Run2Rail an innovative metro vehicle with single axle running gear and one suspension step is proposed, (Shift2Rail in [2]). Two types of active suspensions were introduced to overcome the shortcomings with such a simple design, an active dynamic suspension to ensure good vibration comfort and an active wheelset steering to ensure good curving performance. In FutuRe, it is proposed that single axle gears should be used for a two-axle regional train and that the shortcomings of such a simple design should be mitigated through low force active suspensions based on electro-dynamic technology. The further intention is to design a vehicle without a compressed air system, hence the passive suspension is foreseen to be a simple coil spring. The expectations with the proposed design are that both investment and maintenance costs will be reduced, which significantly improves the business case for introduction of active suspension in rail vehicles. The impact is evaluated for a set of key performance indicators (KPIs).

2. CONCEPTS OF ACTIVE SUSPENSIONS

2.1 BASIC CONCEPTS

Railway vehicle suspensions are complicated systems aiming at achieving different functions, active suspension technologies with different functions and configurations have been developed in various forms (Goodall et al. in [3] and Fu et al. in [4]). For a passive suspension, stiffness and damping parameters define the dynamic response of a system. The external excitations of the vehicle suspension system include deterministic (track layout) and stochastic (track irregularity) excitations in different frequency ranges. Therefore, the design of a passive suspension becomes a compromise for different operating conditions. In contrast, an active suspension can provide variable suspension parameters by utilization of sensors, controller, and actuators, Figure 2.

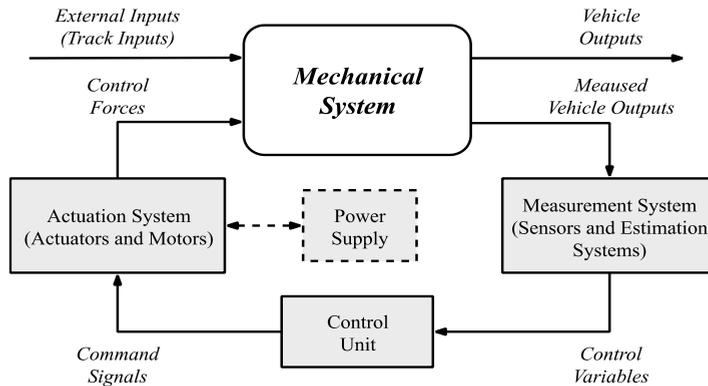


Figure 2: Generic workflow of an active suspension [4]

2.2 ACTIVE SUSPENSION FOR RIDE COMFORT

For FutuRe, active suspension is judged necessary to receive a proper ride comfort. Different approaches are possible to actively improve passenger comfort (Fu et al. in [4]). Among those, a distinction between semi-active and active suspension may be done. Semi-active suspensions could be an option when the initial comfort of the vehicle is sufficiently close to an acceptable limit. However, when the improvement required by the active system is large, fully active systems must be applied. In these cases, the actuators generally replace standard dampers (Pacchioni et al. in [5] and Qazizadeh et al. in [6]). For the two-axle vehicle the latter is to be considered as the comfort with passive suspension is far away from the limit 0.25 m/s^2 for a comfortable ride according to the EN12299 standard [7]. In terms of control strategies, modal sky-hook control, being among one of the most simple and effective strategies, is applied, where the actuator replaces the passive damper and fictive sky-hook is created by integrating body acceleration and using it as force reference to actuator, Figure 3(left).

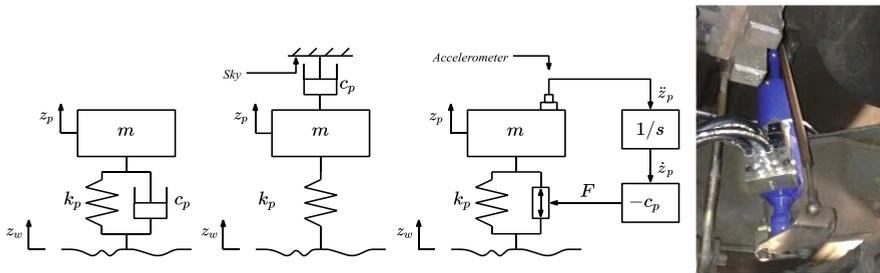


Figure 3: Sky-hook control (left) [4], actuator used in field test (right) [6]

The sky-hook principle has been implemented in field tests, Figure 3 (right) (Qazizadeh et al. in [6] and Sugahara et al. in [8]) as well as on in-service trains. More refined principles may bring benefits, but the sky-hook principle remains the first choice and was used in Run2Rail as well. For FutuRe, the sky-hook will be the starting point together with an electro-dynamic actuator that takes the place of the passive damper.

2.3 WHEELSET STEERING FOR CURVING PERFORMANCE

For FutuRe, active wheelset steering is judged necessary to give proper curving performance. The same judgment was made in Run2Rail and the wheelset steering actuator was set in parallel to the passive wheelset guidance, Figure 4 (left). The main reason was that the safety cases were easier to validate as the passive wheelset guidance ensures safety provided that the maximum actuator force is limited. The actuator was designed to include the passive wheelset guidance to simplify installation. The actuator was tested in the supplier's test bench to validate the performance, Figure 5 (left).

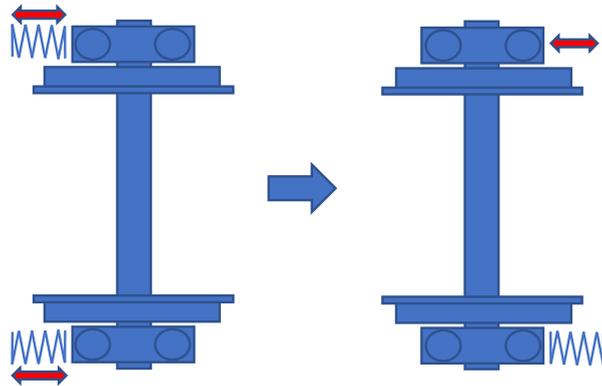


Figure 4: Possible actuator locations in relation to the passive wheelset guidance

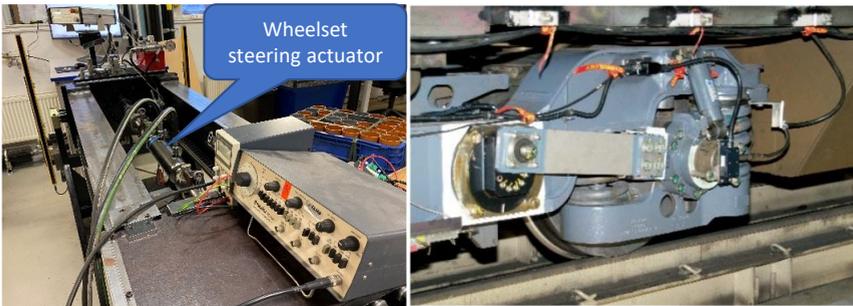


Figure 5: Run2Rail wheelset steering actuator in test bench (left), Bombardier wheelset steering in on-track test (right) [9]

In FutuRe, replacement of passive wheelset guidance with an actuator is studied as it is expected to bring further performance benefits, Figure 4(right). A similar setup was designed and tested on track by Bombardier in the Regina 250 test train (Schneider in [9]). The Regina 250 had bogies with a rotating electro-dynamic actuator replacing the passive wheelset guidance in the primary suspension, Figure 5(right). The vertical coil springs provide passive wheelset guidance, but the horizontal stiffness is not high enough to ensure running stability. With this actuator location, the actuator will be part of insuring vehicle safety. This setup is known as the yaw relaxation principle, where low yaw stiffness allows the wheelset to passively steer due to its conicity and the integrity of wheels and axle. One benefit with this principle

is that the actuator forces are low, allowing use of just one actuator per axle, Figure 6. The actuator is foreseen to be a low force electro-dynamic actuator that is able to work at frequencies relevant for controlling the running behaviour.

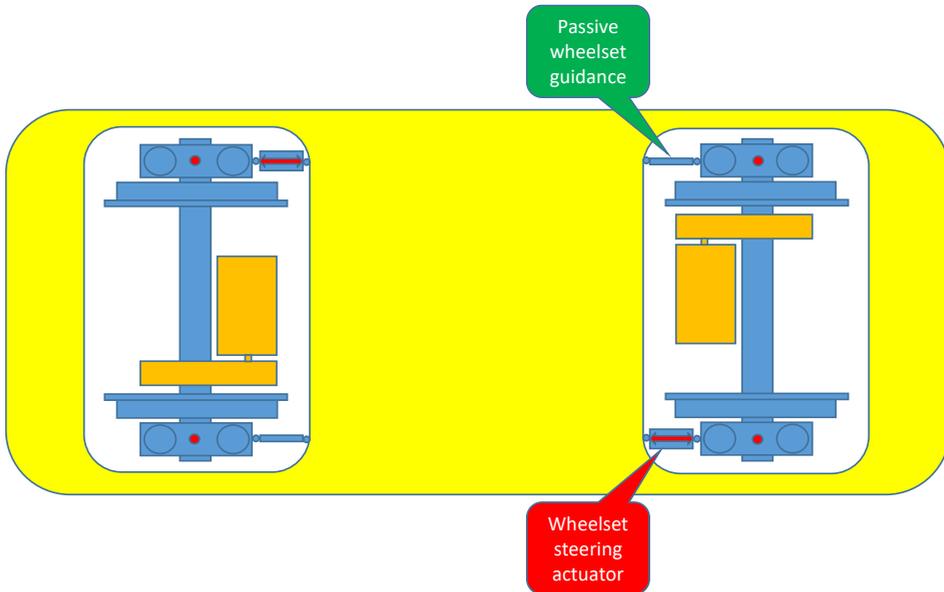


Figure 6: The running gear setup (top view)

3. RESULTS

3.1 FEASIBILITY OF THE VEHICLE

The objective of adding active suspension systems to the vehicle is to allow use of single axle running gears with one suspensions step. Such running gears are simple, low cost, low weight, and takes less space than conventional bogies. Hence, for this vehicle the active systems become an enabler for the entire vehicle concept.

The present calculations on weight and space show that it is possible to design a regional vehicle with zero emissions at the vehicle, level boarding for about 40 seated and 60 standing passengers and still meet the target on axle load.

3.2 ACTIVE SUSPENSION FOR RIDE COMFORT

The comfort evaluation for the vehicle in the Shift2Rail project Run2Rail shows that active vertical suspension significantly improves ride comfort making it possible to introduce a vehicle with single axle running gears and only one suspension step instead of conventional bogies. These simulations were made for a metro vehicle with similar properties as the now foreseen regional vehicle in FutuRe. However, the two vehicles differ in one way. The running gear in Run2Rail had an anti-roll-bar (ARB) built into the running gear frame that allowed the vertical suspension stiffness to be softer than in FutuRe, which does not have an ARB. A harder spring will transfer more vibrations from the wheelset to the body, which must be counteracted by the active suspension system. The enhanced properties for the active system mainly relate to the actuator itself that must be able to produce force at higher frequencies. The active system in Run2Rail relied on hydraulic actuators that gave ride comfort on the target, hence it is unlikely that they would be suitable for the FutuRe. Simulations on ride comfort for FutuRe have not yet been made yet, and the requirements for the actuator will be a result of the simulations.

3.3 WHEELSET STEERING FOR CURVING PERFORMANCE

A vehicle with such a long distance between the wheelset as foreseen here will have a challenge with the curving performance as the wheelset has to turn significantly to avoid the wheels running with flange contact through the curves that will cause both wear and energy losses. In a vehicle with passive wheelset guidance, the wheelset guidance will restrict turning the wheelset, when an active wheelset guidance can support the wheelset to take an approximately radial position in curves. In Run2Rail, the active system was set in parallel to passive wheelset guidance, while in FutuRe a replacement is foreseen, Figure . This setup gives two benefits, firstly the wear can be even lower in curves, and secondly the active force needed is significantly lower as the actuator is not counteracted by the passive wheelset guidance.

The effectiveness of active wheelset steering as wear number on the leading wheelset is shown in Figure 7. Wear numbers higher than about 200 J/m are known to cause significant wear on rails and wheels when low wear numbers risk to cause rolling contact fatigue (RCF). For best wheel life, there should be some wear to limit RCF crack initiation. Hence, optimal wheelset steering depends on several factors, where the curve radii distribution is the most

important one. Regional lines often have curves with smaller curve radii than mainlines and the vehicle must be able to negotiate these without too much wear. The lowest wear numbers are shown for the active wheelset steering with the actuator in series with the passive wheelset guidance, but for most lines, the performance of the active wheelset guidance with the actuators in parallel is good enough. The active wheelset steering can reduce the wear for all radii, but can also be set to give some wear to avoid the risk of causing RCF.

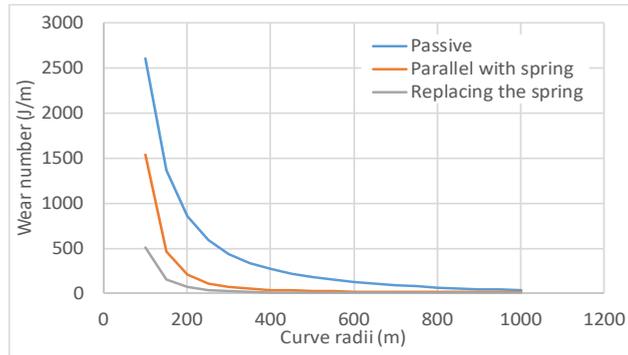


Figure 7: Wear number for leading outer wheel

4. KEY PERFORMANCE INDICATORS

The approach taken is to compare a set of Key Performance Indicators (KPI) relevant to resource efficiency for the proposed small regional vehicle to what the market can offer today. The KPIs used here are the four (4) used in FutuRe. It would be unfair to exclude the larger capacity that today's trains offer. It is therefore assumed that 16 services a day in each direction are needed (one service departing every hour between 6 AM and 9 PM) and that the smaller vehicle must run in multiple operation in two services in the morning peak and two in the afternoon peak. Vehicle properties are shown in Table 2. As an example, the Swedish use case Gårdsjö – Håkantorps, a 121 km non-electrified regional line, is taken. Intermediate stops, gradients and speed profile are considered giving a simulated journey time of about 1 hour and 55 minutes, stopping times included.

Table 2: Vehicle properties

Property	Today's [1]	FutuRe
Number of trains	5 + 1 spare	5 + 2 +1 spare
Number of seats	70	40
Vehicle length	27 m	16 m
Tare weight	58 t	24 t
Weight loaded	72 t	32 t
Maximum speed	120 km/h	120 km/h
Power at wheel	600 kW	390 kW
Starting effort	70 kN	24 kN
Driving	Driver	Remote

4.1 ENERGY CONSUMPTION

The energy consumption is simulated for four (4) cases with details as in Table 3. The benefit of running the smaller vehicles in off peak becomes evident. The running gear is an enabler for the small size and low weight of the vehicles, but are other factors as the high power to weight ratio for the smaller vehicle that allows pure dynamic braking optimizing the energy feedback to the battery. Furthermore, the FutuRe vehicle is designed for remote (automatic) driving, which optimizes the driving compared to what a driver can do, but this difference is not accounted for in the simulations.

Table 3: Simulated energy consumption

Requirement	Today's		FutuRe	
	Off peak	Peak	Off peak	Peak
Service				
Passenger	20	60	20	2 x 30
Number of runs	28	4	28	4
Energy consumption (kWh/km)	2,59	2,68	1,21	2,26

4.2 NOISE EMISSIONS

The wheel-and-rail contact is the main source of external noise for a moving regional train. As the number of wheelsets is 2 on the FutuRe vehicle and 4 on today's vehicle, the sound energy is expected to be halved for the FutuRe vehicle which means a reduction by 3 dB. When the FutuRe vehicle runs in multiple there will be no difference.

4.3 MAINTENANCE

Very simplified, maintenance costs for rail vehicles (and the infrastructure) are derived from the number of wheelsets times their run kilometres, provided that their axle load is about the same. Today's vehicles produce $32 \text{ run} * 121 \text{ km} * 4 \text{ wheelsets} = 15488 \text{ wheelset km}$ a day, while the Future vehicle produces $36 * 121 * 2 = 8712 \text{ wheelset km}$.

4.4 PERSONNEL

The fourth KPI is related to the personnel needed to operate vehicle, but there is no influence by the running gear design on this KPI.

5. CONCLUSION

Single axle running gears are an enabler for the small size vehicle concept. In contrast, conventional bogies occupy a large portion of the underfloor area, making level boarding impossible or significantly limiting the low-floor section. Single axle running gears have two well-known deficiencies, poor curving performance and poor ride comfort. Both these deficiencies can be mitigated with low force active suspensions, which also supports removal of the on-board compressed air system. The single axle running gears positively influence three out of four KPIs used in FutuRe. The most important influence is on energy consumption, where usage of the small size vehicle instead of today's available vehicles with bogies leads to significant energy savings.

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Comparison of integrated functions in a multifunctional sandwich composite rail car body

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EXTENDED ABSTRACT

Sandwich composite panels offer significant weight-saving potential for rail vehicle car bodies (walls, roofs, floors), thereby improving energy efficiency and reducing environmental impact compared to traditional steel and aluminium structures. Conventional car bodies made of metal structures offer high stiffness and strength, but additional materials are needed to fulfil acoustic and thermal requirements. Smart sandwich structure designs can meet these requirements, while also maintaining the fire safety standards. Traditionally, car body materials are evaluated solely based on structural requirements; however, excluding additional materials needed for acoustic and thermal performance can lead to an incomplete or misleading comparison when identifying the most suitable material. For the material selection process Granta Edupack's material database was used. Core materials were evaluated based on yield strength, compressive modulus, compressive strength, shear modulus, shear strength, thermal conductivity, and acoustic velocity, meanwhile face materials were evaluated based on elastic modulus, yield strength, tensile strength, and compressive strength. Due to limited information on flammability in the material data base, that performance indicator was omitted from the current scope, but could be an indicator of interest. The effects of the material properties were also tested on the density and the price per unit volume of the materials. Sensitivity analyses were conducted by systematically varying critical property thresholds and observing their impact on the number of

suitable materials available, as well as on the other performance properties. The base values for the interdependency comparison were chosen based on the rail vehicle standards. These values are good indicators for the eligibility of the materials, but it is important that the structure and the load cases can modify the final requirements. The sensitivity analysis (Figure 1) revealed that thermal conductivity had the most significant impact on core material selection, substantially affecting structural property requirements. Specifically, tightening thermal conductivity criteria dramatically reduced the number of available core materials and restricted feasible structural properties such as yield strength and shear modulus. Conversely, relaxing thermal conductivity constraints significantly broadened material options without negatively impacting other performance criteria. For face materials, the elastic modulus was found to have the strongest influence on tensile strength. Stringent elastic modulus requirements excluded aluminium alloys, narrowing choices to steel and fibre composites. Fibre composites consistently met or exceeded structural requirements while also demonstrating lower densities and potentially lower costs per unit volume compared to steel and aluminium alloys. The results emphasize the critical importance of carefully selecting appropriate performance criteria in sandwich composite material design for rail vehicles. Excessively stringent criteria, particularly related to thermal conductivity and elastic modulus, can severely limit material options without providing proportional performance benefits. Hence, it is essential to critically evaluate which criteria are genuinely necessary and achievable. A multifunctional and integrated design approach, considering interactions and trade-offs between structural, thermal, acoustic, and economic aspects, is crucial for optimizing material and structural selections. This strategy enables designers to identify either suitable materials with the desired properties or to adapt structural designs to compensate effectively for certain material property limitations.

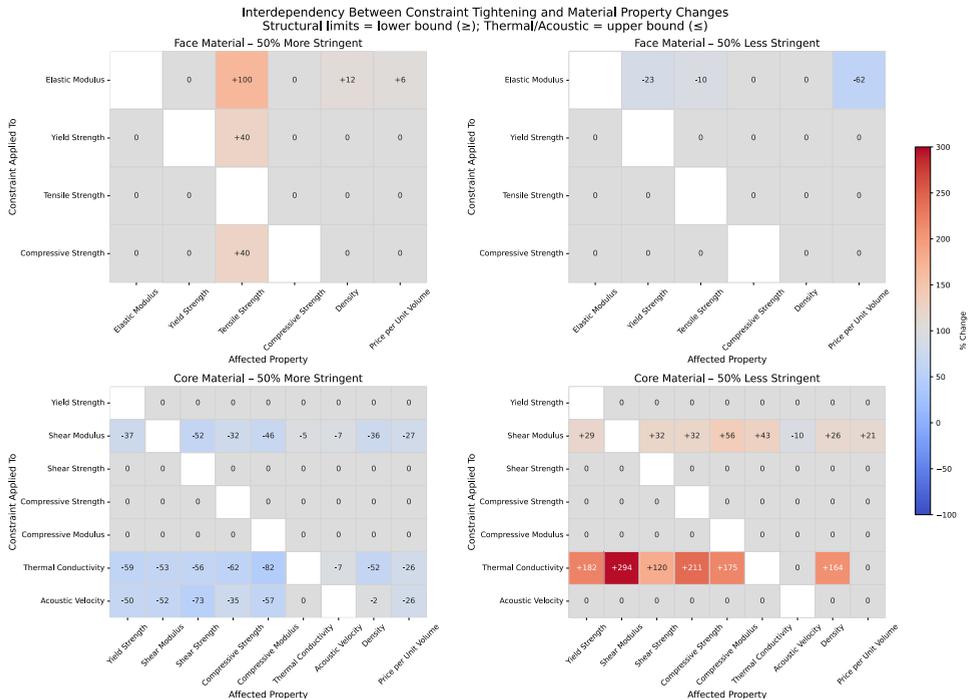


Figure 1: Heatmap visualization of interdependencies between property constraints and resulting material property changes.

ACKNOWLEDGEMENTS

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Analysing the impact of motor design on inverter thermal behaviour using network-based sensitivity analysis

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ABSTRACT

Vehicles are complex systems composed of multiple interdependent subsystems. A design change in one subsystem can lead to either beneficial or detrimental effects on others, making it essential to understand how design choices propagate through the system. This paper focuses on the traction chain in rail vehicles, specifically the interaction between two critical subsystems: the traction motor and the inverter. Since the inverter supplies the current and voltage required by the motor, changes in motor design can affect the inverter's thermal behaviour. We analyse this interaction to understand how motor design influences the temperature evolution of inverter power electronic components. To achieve this, we apply a framework that integrates network theory, structural equation modelling (SEM), and sensitivity analysis. First, analytical models of a three-phase induction motor and an inverter thermal model are developed. A reverse breadth-first search is used to identify all input parameters that influence the inverter temperature. Global sensitivity analysis (GSA) isolates the most influential inputs, enabling the construction of a reduced network graph. Then, SEM and local sensitivity analysis (LSA) are applied to quantify the relationship between motor design parameters and inverter temperature, yielding a coefficient that captures the strength of the dependency. This approach provides an alternative representation of the multidisciplinary interactions between subsystems. It also helps identify key change propagation paths, making it easier for designers to anticipate and manage the consequences of design changes. By reducing analytical

complexity and clarifying subsystem interdependencies, the framework supports more efficient early-stage design, potentially reducing the number of iterations needed to reach a satisfactory solution.

1. INTRODUCTION

The transition from silicon (Si) to silicon carbide (SiC) semiconductors has enabled several benefits such as reduced volume and weight, improved efficiency, and improved thermal performance (Lindahl et al., 2021). This meant that instead of using active cooling using liquid or forced-air cooling using fans, a passive cooling system known as car motion cooling using the airflow surrounding the vehicle in motion can be used. However, the benefits were not limited to the inverter performance but also improved the operation and acoustic noise levels of the motor. This highlights the intricate interdependency between these two subsystems and necessitates a deeper understanding of the interaction.

Moreover, from an operational perspective, this interdependency becomes more relevant under dynamic conditions. The energy dissipation in inverters is high during acceleration, where the demand from the motor is high, while vehicle speed is low, resulting in limited convection cooling. Conversely, at higher speeds, cooling improves due to increased airflow, but the demand from the motor reduces. This imbalance between heating and cooling introduces transient, non-steady state thermal behaviour in the inverter. Consequently, an inadequately designed motor may operate in the inefficient region leading to unfavourable thermal behaviour in the inverter irrespective of the inverter's design. This motivates the need for a more detailed analysis on which aspects of motor design influences the inverter's thermal behaviour and in what way.

However, with such complex systems, it becomes challenging to identify the cause of an observed change and the corresponding change propagation path, especially with the traditional model representations. This may be attributed to the traditional approach's limitations in capturing complex interactions (O'Reilly et al., 2016).

To address this challenge, several tools and methods were developed including machine learning techniques (Charisi et al., 2025), optimisation algorithms for early-stage design exploration (Pillai et al., 2020), multi-layered network-based approaches (Brownlow et al., 2021), and sensitivity analysis-based techniques (Opgenoord et al., 2016). Although these approaches address various limitations of the traditional approach, they focus on isolated

aspects. To overcome this challenge, in the author’s previous work (Abburu, 2023; Abburu et al., 2024), a framework was proposed that integrates network theory and Global Sensitivity Analysis (GSA). The framework provides an alternative representation to complex models and identifies the change propagation path between the input and output. This enables reduction in model complexity while preserving the ability to analyse the cause and effect of design changes on both output and the intermediate variables. Thus, offering the designers a clear insight into the consequences of their design choices.

Utilizing this framework, the present paper investigates the interaction between two subsystems within the traction chain of a rail vehicle. Specifically, the influence of the 3-phase induction motor design on the thermal behaviour of the inverter’s power electronic components is analysed. Subsequently, a function that defines the relationship between the motor design inputs and the temperature behaviour of the inverter components is determined and a coefficient that represents the strength and direction of the influence is calculated.

2. FRAMEWORK

In this section, a brief account on the framework that is utilised to analyse the influence between the two subsystems is provided. There are five major aspects of the framework as shown in Figure 1.

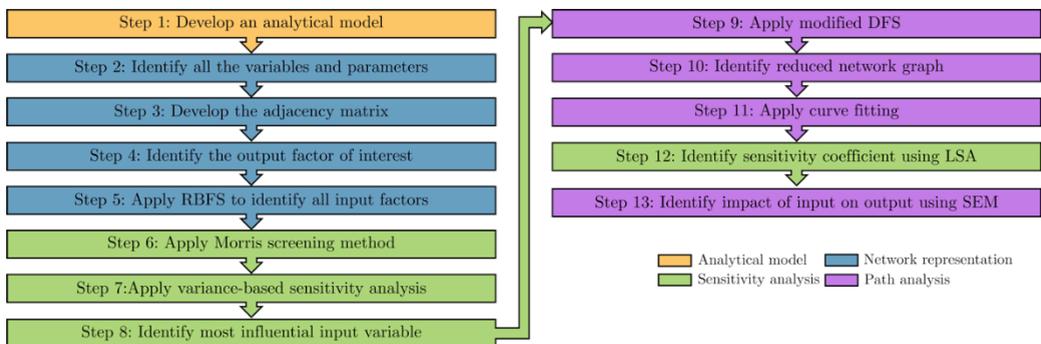


Figure 1: Framework for quantifying impact of an input on an output

In Step 1, an analytical model of the complex multidisciplinary subsystem consisting of multiple subsystems is developed. Subsequently using all the variables, input, and output parameters of the analytical model identified in

step 2, an adjacency matrix is developed in step 3. With the adjacency matrix, network representation of the analytical model is then developed. Subsequently, an output of interest is chosen as the starting point of the analysis in step 4, and a Reverse Breadth First Search (RBFS) algorithm is applied in step 5 to identify all the intermediate variables and inputs that influence the chosen output are determined. This results in a reduced network graph. However, since not all intermediate variables and inputs may not have a significant effect on the output, initially the most influential inputs are identified using Global Sensitivity Analysis methods. Specifically, in step 6, Morris Screening method is applied to filter the insignificant inputs (Morris, 1991), and in step 7, for the filtered inputs, the Sobol indices are identified using the Polynomial Chaos Expansion (PCE) approach (Sudret, 2008). This provides the strength and ranking of influence of the inputs on the output. For the most influential inputs, a modified Depth First Search algorithm is applied in step 9 to identify all the paths that a specific input can take to reach the output. This provides all the intermediate variables that are influenced for a given input and output and hence, an even more reduced network graph in step 10. In step 11, curve fitting techniques are applied to derive a function that defines the relationship between the identified input and the chosen output. Finally, in step 12 and 13, using structural equation modelling and local sensitivity analysis a coefficient that indicates the strength and direction of influence of the input on the output is calculated.

3. SUBSYSTEM INTERACTION ANALYSIS

In this section, the interaction between the traction motor design and thermal behaviour of the inverter is analysed. One of the primary functions of the inverter is to supply the necessary current and voltage for motor operation. Additionally, as indicated in Eq. (1), a major component in calculating the power loss of the inverter includes the voltage (V_{in}) and current (I_{max}) values of the motor along with the inverter dependent variables such as switching frequency (f_s), the latency in time for switching on (t_{on}) and off (t_{off}), and the load resistance of the inverter (R_d). This displays a clear intrinsic connection between the subsystems and the two variables, voltage and current of the motor, will act as the interface edges between the network models of the two subsystems.

$$P_{loss} = 0.5V_{in}I_{max}f_s(t_{on} + t_{off}) + 0.5R_dI_{max}^2 \quad (1)$$

The analysis of the influence of motor design on the thermal behaviour of the inverter is performed by utilizing the framework described. Initially, an analytical model of a 3-phase induction motor and a cooling model of an inverter that captures the temperature evolution of the power electronic components in the inverter are developed. The outline of the combined motor and inverter model is depicted in Figure 2.

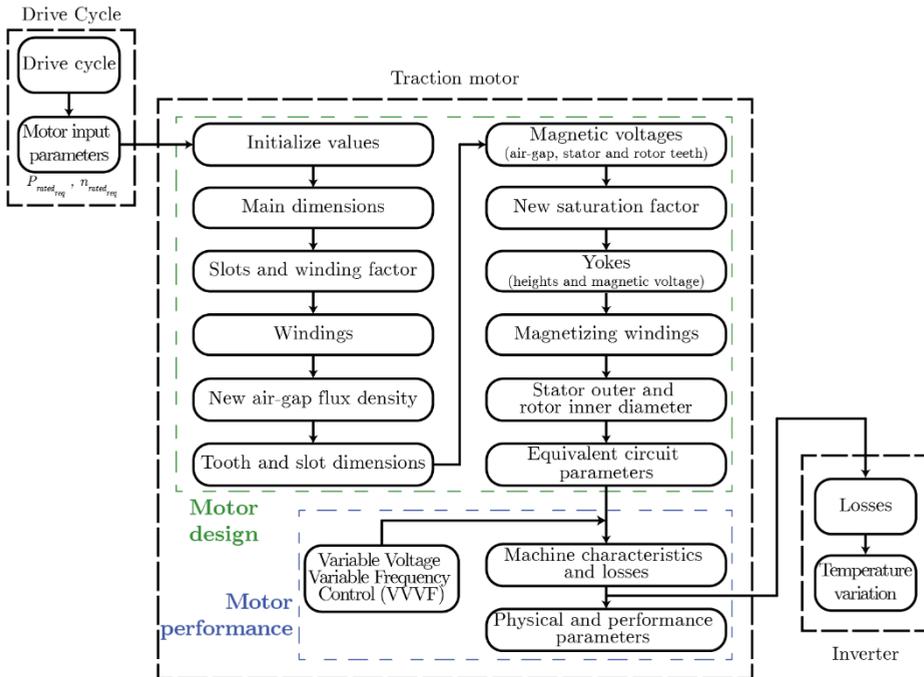


Figure 2: Overall procedure for the combined traction motor and inverter model.

Then, an adjacency matrix is developed using all the variables and parameters in the model. Subsequently, the adjacency matrix is used to develop a network representation of the combined analytical model. There are 238 factors in the developed network model. According to the framework, a variable of interest needs to be chosen as a starting point of the analysis. Since power loss is a main component that influences the thermal behaviour of the inverter and temperature is a more practical metric for evaluating the thermal performance, in this paper, temperature of the power electronic components at the base plate is chosen as the output of interest. Using Reverse Breadth First Search

(RBFS) algorithm, all the intermediate variables, parameters, and inputs that influence the temperature evolution in inverter are determined and a reduced network graph is obtained. The number of factors to consider at this stage has reduced from 238 to 178 i.e. nearly 25% reduction in the complexity of the analysis.

However, there are still several inputs and intermediate variables influencing the output of interest. However, not all the inputs have a significant effect on the output. Therefore, Global Sensitivity Analysis methods are used to identify the most influential inputs, and the strength and direction of these inputs on the output. Specifically, initially Morris screening method is utilized to filter the insignificant inputs and identify the direction of the influential inputs. The results from the Morris screening method are shown in Figure 3. The figure on the left shows the result from the old estimator which calculates the mean and standard deviation of the output while modifying one input at a time. However, in the presence of nonmonotonic functions, this estimator might give incorrect results as the positive and negative values in the function can negate each other. Thus, an absolute estimator is proposed and the results from the new estimator is shown in the right-side figure of Figure 3. It can be observed from Figure 3 (left) that the rated power is on the left axis, indicating an inversely proportional relationship with the base temperature. Thus, using Morris screening method the influential input and its direction of influence is identified.

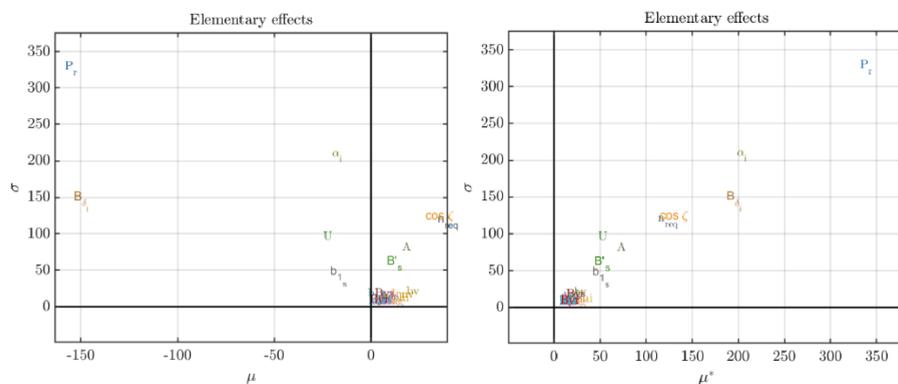


Figure 3: Results of Morris screening method with old estimator (left) and new estimator (right) applied with base temperature as output of interest.

Subsequently, the Sobol indices of the influential inputs are calculated using the PCE approach. The Sobol indices provide a quantitative comparison of the influential inputs providing a metric to measure the strength and ranking of the influence of the inputs. The Sobol indices of the influential inputs are shown in Figure 4.

It can be observed that the rated power is predominantly the most influential input and therefore, in this analysis, the influence of rated power on the temperature of the base plate in inverter is analysed. It must be noted that typically GSA is performed on scalar quantities and temperature is inherently time dependent. Therefore, the maximum temperature observed over the operative drive cycle is used as a representative scalar metric for the sake of simplicity. However, it is worth mentioning that there are cluster-based GSA techniques that can capture temporal or spatial dependencies which shall be considered in future work.

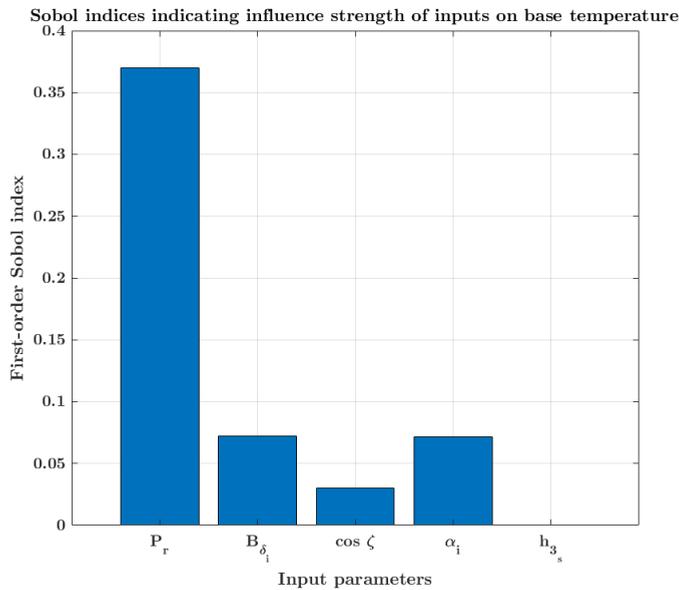


Figure 4: Sobol indices indicating strength of influence of inputs over base temperature

Following this step, a modified Depth-First Search (DFS) algorithm is used to identify the various paths that the input could take to reach the output of interest. This results in a further reduced network graph with just the

intermediate variables that get influenced by changing the rated power and in turn influence the change in the base plate temperature. The reduced network graph from the modified DFS is shown in Figure 5.

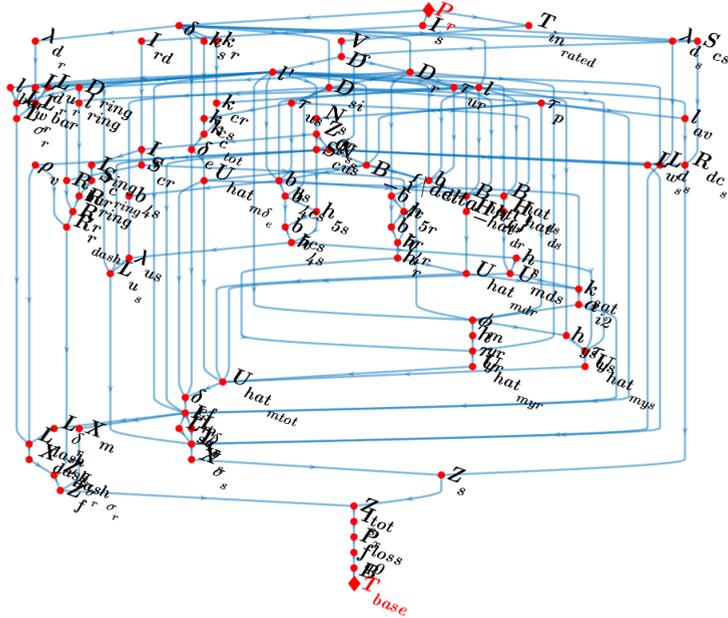


Figure 5: Reduced network graph obtained using modified DFS depicting all paths between rated power (P_r) and base plate temperature T_{base}

At this stage, the number of factors to consider has reduced to 100 from the original 238 factors i.e. reducing the size of the network to consider by nearly 57%. However, the network graph still contains a large number of paths that the input can take to reach the output, specifically, 3568 paths. Therefore, to further reduce complexity and enhance interpretability, the principles of Structural Equation Modelling is applied here. More specifically, the Wright’s multiplication rule which states that the effect of an independent variable on a dependent variable through one or more mediating variables is approximately equal to the sum of the product of path coefficients along all possible causal pathways that connect the independent and dependent variable (Wright, 1934) . Mathematically WMR can be described using Eq. (2).

$$S_{Total} = \sum_{p=1}^n \prod_{i=1}^k w_{i_p} \tag{2}$$

Therefore, in this analysis since the intent is to identify the influence of rated power on the base plate temperature, the intermediate variables are not

analysed. However, if the intent is to analyse the impact of the input on the intermediate variables and how the intermediate variables in turn influence the output of interest, a function representing each edge in the network must be derived. In this paper, for the sake of simplicity, only the input, key interface parameters, and the output are considered.

With the key factors in the network identified, a relationship between the input and output is derived using curve fitting. To perform the curve fitting, first a parametric study is performed by varying the identified influential input, required rated power, and plotted against the maximum base plate temperature as displayed in Figure 6. This essentially means that for a specific operational drive cycle with specific power and speed requirements, the capability of the motor power is increased. With each increment of required rated power of motor, a separate motor configuration is obtained which then produces a different maximum base plate temperature. It can be observed from Figure 6 that there are distinct clusters formed, and this can be attributed to the presence of design margins. The reasoning behind these clusters is discussed further in Section 4. Moreover, it can be observed that there is an overall trend of decrease in the maximum base plate temperature with the increase in required rated power. Using the MATLAB curve fit toolbox, a function that represents this overall trend of rated power and maximum temperature is identified. The resulting curve fit is displayed in Figure 6 and the relationship from the curve fit is identified as Eq. (3).

$$T_{base_{max}} = -0.0013P_r + 1060.3 \quad (3)$$

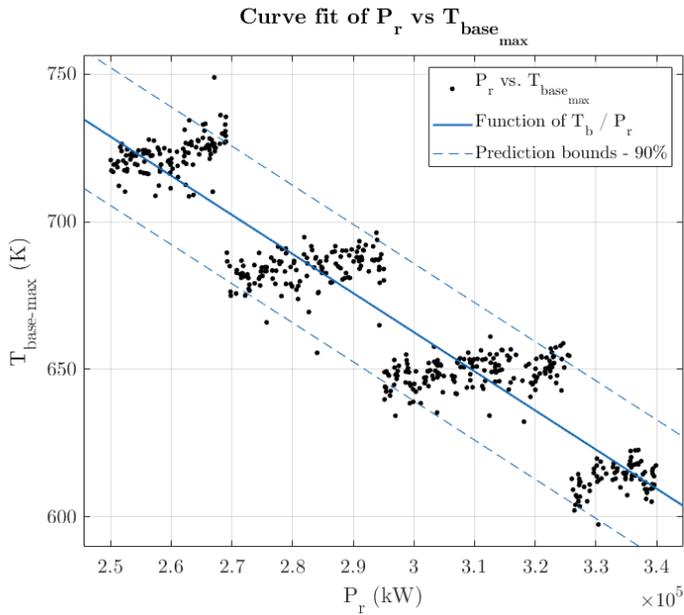


Figure 6: Curve fit depicting the relationship between rated power and base temperature

Subsequently, using the identified function, a sensitivity coefficient that indicates the strength and direction of influence of the input on the output is calculated using Local Sensitivity Analysis techniques as -0.0013 . In fundamental terms, this indicates for every 1 kW increase in rated power, the base temperature value decreases by 0.0013 K. The fitted model includes a 90% prediction interval, indicating that there is a 90% probability that future observations will fall within the prediction bounds.

4. DISCUSSION

The analysis of the influence of motor parameters on the thermal behaviour of the inverter components revealed that the motor input, required rated power had the highest influence on the chosen output of interest, temperature of the base plate in inverter components. For performing curve fitting, the maximum base plate temperature was plotted against different required rated power values and displayed in Figure 6. It can be observed from Figure 6 that there are distinct clusters for a specific range of motor power. This behaviour can be attributed to the presence of design margins of certain components within the

traction motor model. These margins allow for variations in the input up to a certain limit without significantly impacting the component's output. In this design margin, the components act as change absorbers. However, when the inputs are modified beyond these margins, the components begin to either propagate or multiply the incoming changes. This results in the output shifting noticeably, leading to a transition from one cluster to another. Furthermore, by performing curve fitting and calculating a coefficient to indicate the strength and direction of influence showed that the rated power and base plate temperature have an inversely proportional relationship. This means that for a given operational drive cycle with specific power and speed requirements, using a more powerful motor will reduce the maximum temperature. This trend is reasonable, because for the same performance demands, a more powerful motor experiences less operational stress and will operate close to the efficient region. Thereby, leading to reduced operational temperatures. However, there is a trade-off that needs to be considered. A more powerful motor might reduce the operational temperature, but it also results in a larger and heavier motor, which may lead to space and weight constraints. This could further negate the volume and weight reduction achieved by switching from Si to SiC semiconductor. Therefore, this trade-off shall be further explored in future work.

5. CONCLUSION

In this paper, utilizing the integrated framework, the relationship between motor input parameters and thermal behaviour of the inverter components is derived and a coefficient indicating the strength and direction of the influence is calculated. Additionally, by performing this analysis, the various intermediate variables that are influenced and in turn influence the inverter temperature is identified. This information can help the designers understand not only the influence of modifying the input on the output, but also which intermediate variables are being impacted. Furthermore, the approach demonstrated the ability to couple a static model (motor) with a dynamic model (inverter cooling), thereby validating the framework's applicability to multi-scale subsystem interactions. However, a representative scalar value from the dynamic temperature value was used to analyse the influence of the input. To address this limitation, cluster-based GSA shall be explored in future work. Notably, this approach reduced the number of factors to consider by 57%. However, even with the reduced network model, there were large number of factors and paths to consider. A more efficient method to deal with such situation will be explored more in future work.

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Day 1 Session: Advancing Energy Efficiency and Sustainability in Mobility Systems

Optimizing energy consumption of regional trains through speed adjustment: a seasonal and regional perspective

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ABSTRACT

Efficient energy management is a key challenge for regional train services, especially when considering the seasonal variation in auxiliary energy demands such as heating, ventilation, and air conditioning (HVAC). This study explores how adjusting the maximum operational speed of regional trains can optimize energy consumption without exceeding design limits or necessitating larger battery sizes. By achieving a balance between train speed, available travel time, and seasonal auxiliary energy needs, the study proposes an approach to enhance sustainability and reduce operational costs. The research begins by modelling HVAC energy demands under different climatic conditions and train capacities. Using this model, energy consumption for a battery-powered regional train is simulated on two distinct routes: each with unique drive profile and timetables. The simulations are conducted using MATLAB, considering the impact of speed adjustments on both traction energy and auxiliary energy requirements. Results demonstrate the significant potential of speed adjustments to reduce total energy consumption. This approach ensures that battery sizes remain manageable while maintaining performance

standards across different routes and timetables. Furthermore, the findings highlight the broader implications of speed adjustment on battery lifecycle, and CO₂ emissions. This research underscores the importance of precise speed adjustments in achieving optimal performance, cost-effectiveness, and sustainability in regional rail services.

1. INTRODUCTION

The transportation sector remains one of the most significant contributors to global greenhouse gas (GHG) emissions, and although rail transport is among the most efficient modes in terms of energy use per passenger-kilometre, many regional networks still rely on diesel multiple units (DMUs). In light of the European Union's climate goals, such as the European Green Deal target to reduce transport emissions by 90% by 2050, transitioning to cleaner technologies is essential [1].

Battery Electric Multiple Units (BEMUs) are gaining momentum as a sustainable alternative to DMUs on non-electrified or partially electrified rail lines. These trains offer several environmental and operational benefits: zero local emissions, lower noise levels, and compatibility with renewable electricity sources. Notable examples include the Stadler FLIRT Akku, and the Siemens Mireo Plus B, which are optimized for regional and commuter applications [2], [3]. Nevertheless, the widespread adoption of BEMUs is not without challenges. Key concerns include the limited energy capacity of onboard batteries, long recharging times, and high energy demand from auxiliary systems, especially under extreme seasonal conditions.

One of the primary auxiliary energy consumers is the heating, ventilation, and air conditioning (HVAC) system. Depending on climate and passenger occupancy, HVAC loads can represent a substantial portion of total energy consumption. In winter, heating demands spike; in summer, cooling must compensate for solar heat gain and high occupancy levels. Efficient control of HVAC loads is therefore crucial to ensuring energy availability for traction, extending battery life, and maintaining operational reliability. A viable strategy to address these challenges lies in speed optimization.

This study proposes a practical and scalable solution: regulating the train's maximum operational speed in accordance with seasonal HVAC demands and route characteristics. Rather than increasing battery capacity, which adds mass, cost, and environmental burden, adjusting speed can reduce traction energy consumption during periods of high auxiliary load, thus balancing the

total energy budget. This strategy is particularly effective when coordinated with flexible timetables, and it avoids the need for route-specific train designs.

The analysis presented in this paper uses MATLAB-based simulations to investigate two regional train routes with varying drive profiles, stop frequencies, and terrain conditions. The study models HVAC energy demand using standardised operating points, applies a thermal load profile, and battery degradation modelling via Rainflow analysis. The resulting insights include the impact of speed adjustment on total energy consumption, battery cycle life, operational costs, and CO₂ emissions.

The remainder of this paper is structured as follows: Section 2 presents the simulation methodology, including vehicle specifications, route profiles, and modelling assumptions. Section 3 provides the results of the simulations and discusses their implications. Section 4 concludes the paper and offers recommendations. The final sections include acknowledgements and references.

2. METHODOLOGY

This section outlines the simulation methodology used to assess the impact of seasonal speed adjustment on the energy performance of battery-electric regional trains. It includes route selection, train configuration, modelling of traction and auxiliary energy demand, and battery life estimation under dynamic operating conditions.

Two regional routes with contrasting characteristics are selected as case studies. The first route A, between Delmenhorst and Harpstedt in Germany, is 42 km long and includes 8 stops. The second route B connects Borlänge to Malmö in Sweden, spanning 129 km with 12 intermediate stops. Both routes are simulated as round trips, with elevation, velocity, and timing profiles derived from geographic and timetable data. These profiles are illustrated in Figure 1.

The train is powered by a 390 kW electric traction machine, has a gross vehicle mass of 30 tons, 15 meters length, and 10 square meters front area. For energy storage, two battery configurations are considered: a 550 kWh system for the longer Swedish route and a 175 kWh system for the shorter German route. Both configurations are sized to accommodate full daily service without exceeding a critical depth of discharge threshold.

Traction energy demand is calculated using the Davis equation ($R_{\text{Rolling}} = 400 + 2v + 0.2v^2$; v is velocity in km/h), which includes rolling, aerodynamic, and acceleration resistances. The effect of terrain is incorporated through a

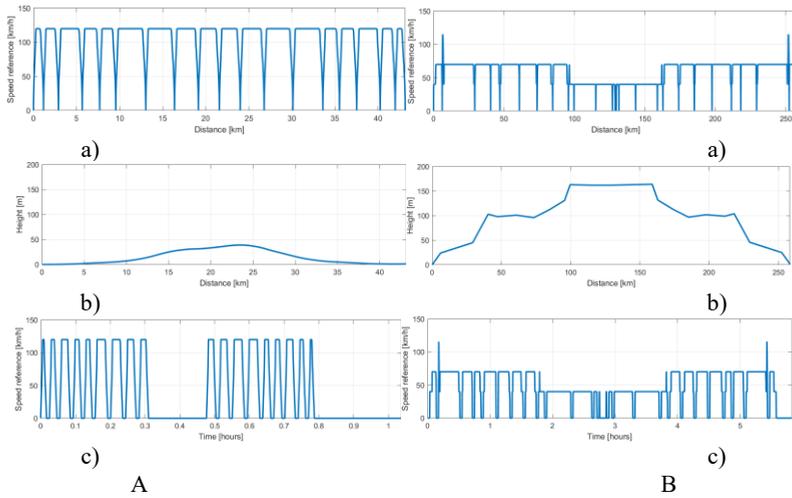


Figure 1: a) Distance-speed, b) distance-elevation, and c) velocity-time profiles for round-trip Route A and Route B.

gradient resistance term $R_{\text{gradient}} = M \cdot g \cdot \sin(\theta)$ (M is the train mass, g gravitational acceleration, and θ is the road gradient derived from the elevation profile.), dynamically computed from the elevation profile for each simulation time step. The total resistance R_{total} is then converted into traction force, and multiplied by velocity (converted to m/s) to compute instantaneous traction power ($P = R_{\text{total}} \cdot v$). This power value is used to determine the required motor torque based on drive train speed and efficiency. The traction system includes a 390 kW permanent magnet synchronous motor (PMSM), with performance evaluated using its torque-speed efficiency map.

To evaluate the potential of speed-based optimization, each route is simulated with varying speed scaling factors. For Route A, the scaling range is 0.6 to 1.0. Dwell time at stations remains constant, and changes in speed affect only cruise segments. This approach enables investigation into the trade-offs between traction energy, auxiliary loads, and journey time. For Route B, maximum speed is scaled between 0.8 and 1.2 (relative to a baseline of maximum speed at each moment).

Auxiliary energy demand, particularly for HVAC systems, is modelled based on a 1D thermal simulation developed within the Flagship Project 6: FutuRe project [4]. This model incorporates temperature and humidity control, solar radiation, and passenger-generated heat and humidity. Simulations are performed under both static ($v = 0$) and dynamic ($v > 0$) conditions. No energy

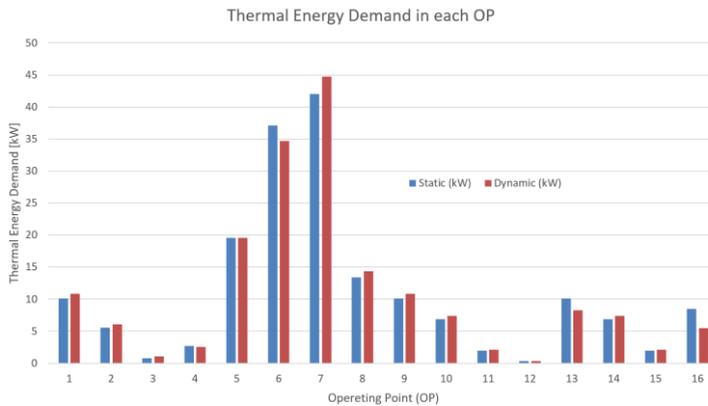


Figure 2: Thermal energy demand in static vs. dynamic conditions across 16 operating points.

contribution from fans or compressors is considered, and the coefficient of performance (COP), defined as the ratio of useful heating or cooling output to the electrical energy input, is fixed at 1 to represent a worst-case scenario with no efficiency gain from HVAC systems.

Sixteen standardized operating points (OPs), developed in alignment with DIN EN 50591 and DIN EN 14750-1 Class A, are used to parameterize external conditions such as ambient temperature, relative humidity, and passenger occupancy (ranging from 0 to 120 passengers), which also affects traction energy demand. These OPs reflect realistic seasonal and occupancy variations. Table 1 summarises the environmental parameters for each OP.

Thermal energy demand for each OP is simulated for both static and dynamic modes. Results indicate that peak demands (up to ~45 kW) occur during summer scenarios with full occupancy (e.g., OP6 and OP7), while winter scenarios with no passengers present minimal HVAC loads. These findings are illustrated in Figure 2.

Thermal energy demand for each OP is simulated under both static and dynamic conditions. For simplification, a fixed coefficient of performance (COP) of 1 is applied for both heating and cooling to represent worst-case scenarios. In practice, cooling systems typically operate with a COP of around 2, while heating remains closer to 1. Based on this, worst-case HVAC demands are assumed for summer cooling with full occupancy, and winter heating. These results are illustrated in Figure 2.

To evaluate battery aging, a Rainflow counting algorithm is applied to the time-series state-of-charge (SOC) profile of the battery under each speed scenario. A cycle-life curve is used to estimate the service life as a function of the depth of discharge [5], [6]. The assumption is based on continuous daily operation (24/7).

Together, this simulation framework provides a comprehensive basis for assessing the trade-offs between maximum speed, total energy consumption, battery degradation, and HVAC performance under seasonally varying conditions.

3. RESULTS

This section presents and analyses the simulation results based on adjusted drive profiles, energy consumption, auxiliary load effects, battery degradation, and the associated economic

and environmental impacts. All results are derived from MATLAB-based simulations that implement drive cycles, elevation data, and HVAC operating points, as described in Section 2.

Speed adjustments were implemented via a scaling factor applied to the original velocity profile. These factors range from 0.6 to 1.0 for Route A and 0.8 to 1.2 for the route B. The simulations confirm that all scaled profiles respect constraints: dwell times at stations remain unchanged, and speed never exceeds the design limit of 120 km/h. The adjusted profiles allow full route completion.

Table 1: Operating points including temperature, humidity, and passenger load conditions.

Operating Point	Temperature (°C)	Humidity (%)	Passengers (%)
OP1	-10	90	0
OP2	0	90	100
OP3	10	90	50
OP4	15	90	50
OP5	22	80	100
OP6	28	70 (I), 70 (II), 45 (III)	100
OP7	40 (I), 35 (III), NA (III)	40 (I), 50 (II), NA (III)	100
OP8	NA (I), -20 (II), -40 (III)	90	0
OP9	-10	90	0
OP10	0	90	0
OP11	15	80	0
OP12	22	80	0
OP13	40 (I), 35 (II), 28 (III)	40 (I), 40 (II), 70 (III)	0
OP14	0	90	0
OP15	15	80	0
OP16	28	50	0

3.1 ENERGY DEMAND AND SPEED ADJUSTMENT UNDER AUXILIARY LOAD SCENARIOS

Figures 3 and 4 illustrate how changes in maximum train speed affect three key variables for each route: total energy consumption, auxiliary energy consumption, and total travel time, under a range of assumed HVAC loads (0 to 45 kW). In this study, HVAC demand is used as a proxy for overall auxiliary consumption, with the understanding that other consumers such

as lighting, door mechanisms, and control systems are present but assumed constant throughout all scenarios. Figure 2 provides the basis for HVAC load variation across operating points.

Figure 3 illustrates the variation in total energy consumption, auxiliary (HVAC) energy use, and travel time under different speed scaling factors for route A. When the maximum speed is reduced by up to 40%, the total travel time increases by approximately 30% (Figure 3c). Despite this time

extension, substantial energy savings are observed, especially in high auxiliary power conditions. As shown in Figure 3a, the total energy demand drops by 30 to 50 kWh, depending on the HVAC power level.

The magnitude of energy savings is strongly influenced by the auxiliary load. Figure 3b shows that at higher HVAC levels, such as 45 kW, the auxiliary energy demand remains high, while the impact of speed change on traction energy becomes more noticeable. This is why the benefit of speed reduction is more significant at higher HVAC loads. Nevertheless, HVAC is not the only influencing factor: when total energy demand is lower, battery charging and discharging losses are also reduced, leading to additional efficiency gains. This effect is embedded in the simulation model through internal power electronics loss modeling.

Assuming an average total energy demand of 100 kWh per round trip, the data show that under this level, all auxiliary power levels from 0 to 45 kW can be accommodated within the same battery capacity. This suggests the following strategy:

- With low HVAC demand, trains can follow original speed profiles within energy limits.
- With high HVAC demand, reduction of the maximum speed helps balance auxiliary energy use.

It should be noted that these results are specific to the train configuration defined in Section 2, including a 390 kW permanent magnet synchronous motor (PMSM). The motor's energy consumption is computed based on an efficiency map depending on operating torque and speed, although the efficiency diagram is not included in this paper. The power electronic motor drive and the mechanical transmission are both modelled with constant efficiencies.

A similar analysis for the longer route B is shown in Figure 4. Although speed changes are more limited in this case ($\pm 20\%$), the trends are consistent. Due to the longer distance, different number of stops per unit, and distinct drive profile and topography, the effect of the maximum speed changes is less pronounced. As shown in Figure 4a, the difference in total energy consumption across the maximum speed range is smaller, yet still present. This is because the longer travel duration amplifies the influence of HVAC runtime on total consumption. In high-load scenarios (e.g., 45 kW), HVAC power can represent more than 50 % of the total energy use.

While energy savings are relatively smaller on this route, the results still support using speed adjustment as a lever for matching HVAC load to battery capacity. For example:

- At low HVAC loads, reducing speed improves energy efficiency by lowering traction demand.
- At high HVAC loads, prolonged HVAC operation may outweigh traction savings, making higher speeds preferable when minimizing travel time is important.

Overall, for this track, the original drive profile appears suitable for average seasonal conditions, but adaptive speed control is recommended under more demanding HVAC scenarios.

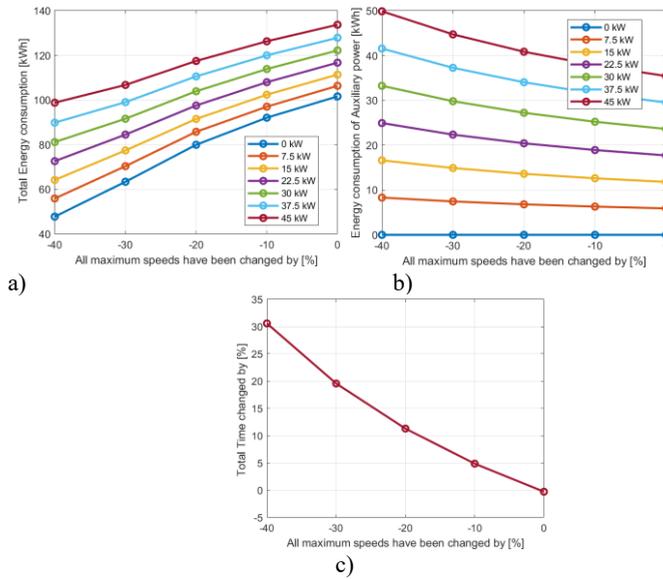


Figure 3. Total energy consumption (a), auxiliary energy consumption (b), and travel time variation (c) for route A under various speed scaling factors and HVAC power levels.

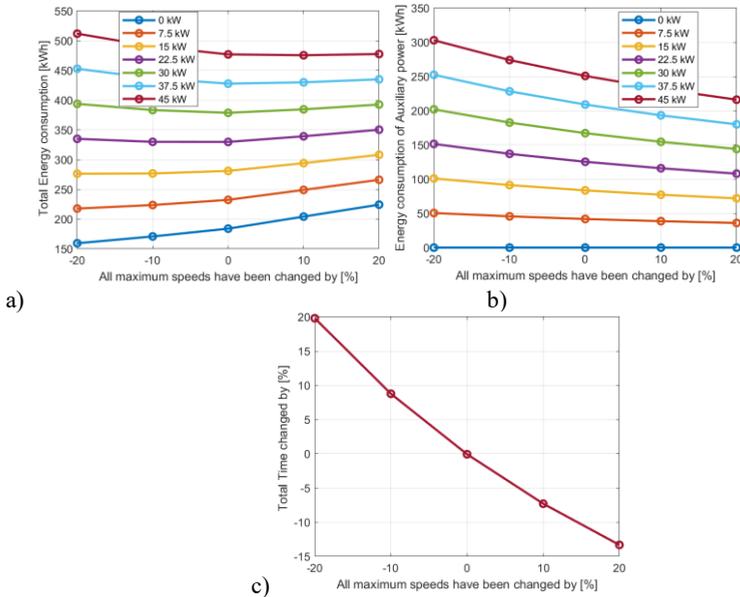


Figure 4. Total energy consumption (a), auxiliary energy consumption (b), and travel time variation (c) for route B under various speed scaling factors and HVAC power levels.

3.2 BATTERY DEPTH OF DISCHARGE AND SERVICE LIFE

Figure 5 illustrates the relationship between speed adjustment, depth of discharge (DoD), and battery lifetime for route A. As shown in Figure 5a, it is observed that reducing the maximum speed by up to 40 % results in a significant decrease in DoD, ranging from 20 % to 30 % across different levels of auxiliary power. The depth of discharge increases consistently with higher auxiliary loads and higher speeds.

The impact of this variation on battery lifetime is shown in Figure 5b. A degradation model based on Rainflow counting and DoD-dependent cycle life is applied, assuming continuous operation (24 hours a day, 365 days a year). Although real-world trains often experience fewer daily cycles and longer calendar life, a conservative maximum battery service life of 20 years is considered here [7].

Under scenarios with the lowest auxiliary power, adjusting the maximum speed can increase the battery life from approximately 3 years to over 14 years. Even at 45 kW auxiliary load, which represents a worst-case HVAC scenario, lifetime still improves from about 2 to 5 years by applying speed reduction. These results indicate that maximum speed adjustment can significantly extend the time before battery replacement is needed, even under demanding conditions. Based on an average battery cost of €100 per kWh [8], increasing battery longevity directly reduces replacement costs and lowers the total cost of ownership. Moreover, longer lifetime reduces the frequency of battery production and disposal, contributing to sustainability goals. These results support the integration of speed planning not only for energy management but also as a strategy for battery aging mitigation and cost control.

For the longer route B, similar analyses are presented in Figure 6. Figure 6a shows that changes in DoD are generally smaller across the speed range (–20 % to +20 %), due to the higher initial energy demand and larger installed battery capacity. Nevertheless, a noticeable trend remains. The corresponding impact on lifetime is shown in Figure 6b. For example, at 25 kW auxiliary power, battery service life ranges from approximately 15 to 20 years, depending on the maximum speed. However, at low auxiliary loads, the battery already reaches its calendar life limit of 20 years, and further reductions in speed no longer yield lifetime benefits. At very high auxiliary loads (e.g.,

45 kW), the influence of speed becomes marginal due to the dominant effect of HVAC energy demand.

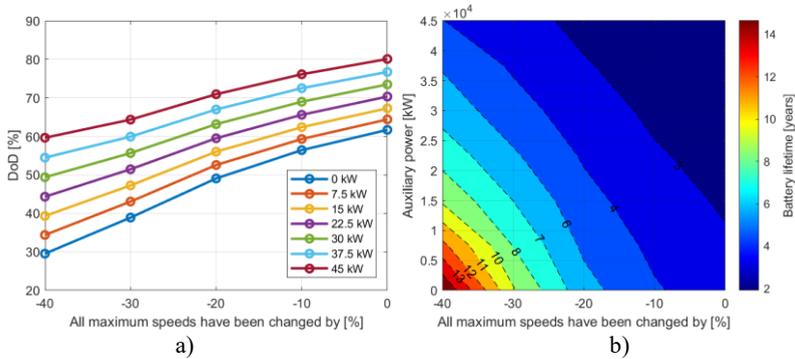


Figure 5. (a) DoD for the route A under different maximum speed levels and auxiliary power conditions (0 to 45 kW). (b) Estimated battery lifetime under the same conditions.

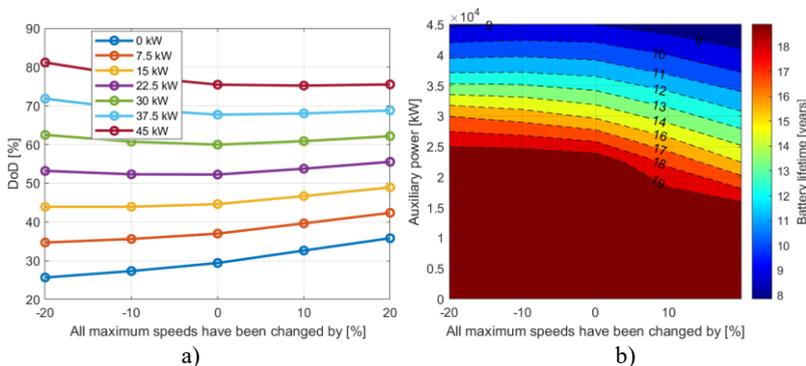


Figure 6. (a) DoD for the route B across varying auxiliary power levels and speed scaling (-20 % to +20 %). (b) Estimated battery lifetime under the same conditions.

3.3 ECONOMIC AND ENVIRONMENTAL IMPACT

The economic and environmental implications of speed adjustment strategies are evaluated in Figures 7 and 8, based on variations in auxiliary power levels and grid emissions. Using an average electricity price of €0.28 per kilowatt-hour for Sweden and Europe in 2023[9], [10], the electricity cost per kilometre was calculated for both simulated routes. For route A, Figure 7a shows

that this cost varies significantly depending on speed and auxiliary demand. Similarly, for the route B, Figure 8a demonstrates that costs range.

The associated environmental impacts are presented in terms of CO₂ emissions per kilometre, calculated for two grid contexts. For Sweden, one of Europe's cleanest electricity producers, the emission intensity is 26.5 gCO₂eq/kWh on average (2019–2023)[11]. In contrast, the European grid average is significantly higher, at 244 gCO₂eq/kWh (2019–2022)[12]. In Figure 7b, emissions for the shorter route A range under the European average. Similarly, Figure 8b indicate emissions for Sweden along the route B.

These results emphasize that energy-efficient operation, achieved through the maximum speed adjustment, has not only a measurable impact on electricity cost but also a considerable influence on transport-related carbon emissions, particularly in regions with fossil-heavy electricity production. Furthermore, these benefits extend beyond operation. As discussed in Section 3.3, reducing energy consumption and extending battery life decreases the need for frequent battery replacement, which also reduces upstream CO₂ emissions from battery manufacturing. Given that the carbon footprint of lithium iron phosphate (LFP) battery production is approximately 55 kg CO₂eq per kilowatt-hour[13], any operational strategy that reduces battery usage or size contributes to lifecycle sustainability.

In summary, seasonal speed adjustment strategies offer a promising approach for reducing both operational costs and environmental impact in battery-electric train services. While the effectiveness of this method is particularly pronounced under high auxiliary loads, elevated electricity prices, or carbon-intensive energy grids, the authors acknowledge that any real-world implementation must be accompanied by comprehensive safety assessments, revised operational protocols, and route-specific feasibility analyses. These considerations do not diminish the value of the findings; rather, they emphasize the importance of further research and coordination with regulatory frameworks to ensure that the substantial potential benefits identified in this study can be safely and practically realized.

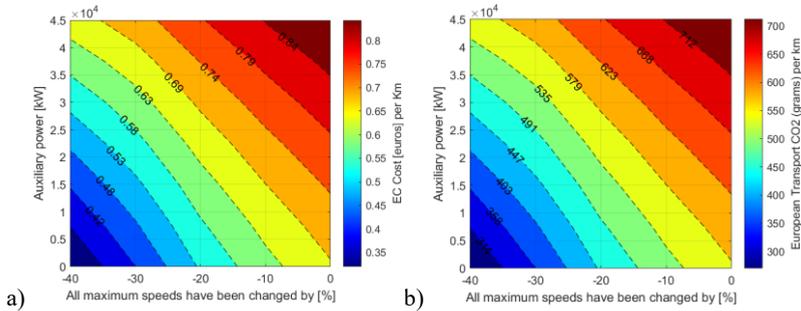


Figure 7. (a) Electricity cost per kilometre for route A across speed and auxiliary power levels. (b) CO₂ emissions per km assuming the European grid average

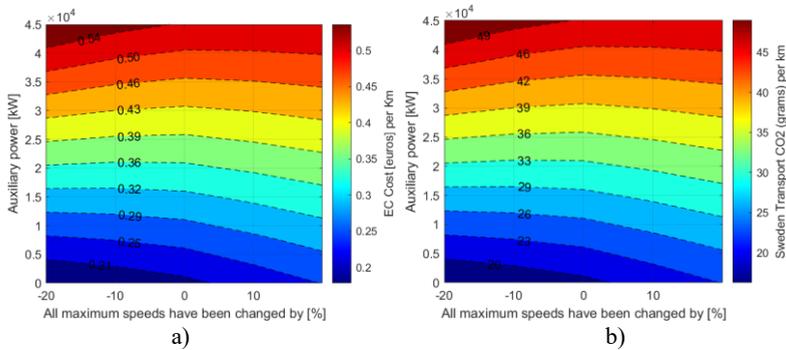


Figure 8. (a) Electricity cost per kilometre for route B across speed and auxiliary power levels. (b) Transport-related CO₂ emissions for Sweden

4. CONCLUSION

This study demonstrates that seasonal adjustment of the maximum speed provides a practical and efficient approach to improve the energy performance, battery lifetime, and environmental footprint of battery-electric regional trains. By aligning operational speed with auxiliary energy demands, minimize battery degradation, and lower CO₂ emissions without altering hardware or battery capacity.

Importantly, the results showed that the effectiveness of seasonal adjustment of maximum speed varies between cases, depending on route characteristics,

train specifications, and auxiliary load profiles. Therefore, any implementation must be evaluated case-by-case, considering local topology, service frequency, and vehicle configuration. Although practical deployment requires alignment with safety protocols, timetable constraints, and regulatory frameworks, the demonstrated benefits justify further investigation and application.

ACKNOWLEDGEMENTS

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Assessing climate neutrality and circularity potentials - A LCA case study on city buses

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EXTENDED ABSTRACT

Reaching climate neutrality by GHG reduction and circularity by closed material cycles is a societal challenge. Climate neutrality and circularity are addressed by the methodology of dynamic Life Cycle Assessment (LCA), where GHG emissions with its radiative forcing potential and material flows with its (non-)circular flows are calculated over the entire lifetime. In the Technology Collaboration Program (TCP) of the International Energy Agency (IEA) on Electric Vehicles (EV) experts from 20 countries cooperate on LCA of electric vehicles since 2010, where Task 46 performed a case study for 100% climate neutral buses with a newly developed methodological framework, to compare buses with different propulsion & fuel combinations, e.g. battery & hydrogen electric city buses, diesel and e-diesel using wind energy. To reach 100% climate neutrality these systems are combined with a Carbon Capture & Storage (CCS) system. So far, there was no common framework to assess climate neutrality and circularity scientifically. Now in this international cooperation of researchers an initial methodology was developed and tested in various applications. In this methodology Climate Neutrality and Circularity can be assessed in LCA based on the GHG emissions and the mass flows over the lifetime. Therefore, a LCA based definition of Climate Neutrality and Circularity is necessary. To keep the wording

appropriate to LCA nomenclature, in the Impact Assessment two new impact categories - “Climate Neutrality Potential (CNP)” and a “Circularity Potential (CPO)” - are developed and applied. These definitions were developed in IEA EV Task 46 (<https://ieahev.org/tasks/46/>) and applied for the first time in this LCA Case study on city buses. The definition is: A product or service is “climate neutral” and “circular”, if its whole life cycle - production, operation and end-of-life - uses only reused components, recycled material, renewable energy and makes no waste and no GHG emissions. The indicator for the assessment of circularity is the CPO calculated in the dynamic LCA. The CPO is based on data of the Inventory Analysis using the material flows in and out of the considered systems in its total lifetime including non-renewable energy inputs. The material flows are used to calculate the Material Circularity Index (MCI). The MCI is 100%, when the system is completely circular, whereas an MCI of 0% means a total linear material use. The MCI is calculated using the Linear Flow Index of materials (LFI_{material}) and the Utility Factor of a product (UF_{product}) covering the lifetime and the intensity of the use. The Climate Neutrality Potential (CNP) is based on the cumulated GHG emissions in the Impact Assessment of dynamic LCA. The total top-of-atmosphere radiative forcing potential based on the GHG emissions over lifetime is calculated in W per m^2 . A 100% Climate Neutrality is reached if W/m^2 is 0. The key findings are 1) Climate Neutrality Potential & Circularity Potential are additional environmental impacts in dynamic LCA not yet covered in the existing Impact Categories. 2) Only systems using renewable energy have the potential towards Climate Neutrality and Circularity. 3) Only in combination with CCS all buses might have zero GHG emissions and can be “100% climate neutral”. 4) The Circularity Potential of electric (57 – 58%), hydrogen (55%) and e-diesel buses (48%) are quite similar due to renewable electricity use, for diesel it is very low (3%) due to diesel use. 5) The diesel bus has the highest environmental impacts, except primary energy demand lower than for e-diesel. 6) For 100% Climate Neutrality the electric bus with CCS needs the same amount of additional renewable energy than the diesel bus with CCS; and it needs 5 times less additional renewable electricity to use fossil diesel with CCS than making e-diesel with CCS.

A techno-economic assessment of battery-electric and fuel cell electric powertrain systems for the transformation of the heavy-duty transport

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EXTENDED ABSTRACT

The transformation of the energy system also provides the transport sector with the opportunity to reduce primary energy use, increase overall efficiency, and reduce greenhouse gas emissions. While the light-duty vehicle fleet is increasingly being electrified by battery-electric powertrains, reaching almost 19% of new registrations in May 2025 (Germany) [1], the challenges of road-based freight and passenger transportation in moving large masses over long distances remain due to high weights and costs of batteries. In this regard, hydrogen from green electricity or e-fuels can provide gravimetric and economic advantages under certain operating conditions. This requires an individual, thorough decision-making process for determining the most economically optimal technology. A comparative assessment of the techno-economic performance of respective powertrains is necessary to identify preferable combinations of powertrain technology and vehicle application, exhibited in the context of the provision of renewable electricity and hydrogen by the energy system.

This investigation presents the results of a bottom-up, simulation-based analysis of zero emission vehicle powertrains, integrating detailed technical and user cost analyses methods incorporated in an overall energy system scenario. Zero emission powertrains under consideration include battery-electric vehicles (BEVs) and hybrid fuel cell electric vehicles (FCEVs) incorporating a hydrogen fuel cell and a battery. Among alternative powertrains, both systems offer the greatest potential for reducing end-user related emissions, noise and

efficiency. Furthermore, there is an opportunity to complement the energy supply in the future energy system by building on the two forms of energy within hydrogen and electricity [2].

This study considers a variety of on-board storage technologies for hydrogen storage and different cell chemistries for the batteries in the specified powertrains. The former is considered using high pressure vessels or liquid phase storage tanks. The electrical storage characteristics of batteries vary within several available cell chemistries. In order to ensure application-oriented comparability, vehicle application combinations are analyzed that represent typical German national transport operations. For this purpose, vehicle classes are predefined for the simulation based on the respective transport operation, using vehicle type and body, axle configuration, and specific application profile. The required transport data are obtained from the European and national transport registers of Eurostat, Destatis and the 'Kraftfahrt-Bundesamt'. Application-oriented driving profiles are derived from the European Automobile Manufacturers' Association. Due to the specific simulation of vehicle powertrain configurations, the energy consumption and the technical constraints required for the evaluation can be compared for different powertrain configurations. This approach is suitable for a wide range of vehicle segments and application scenarios beyond the configurations considered in this investigation. To perform energy demand calculations, a longitudinal dynamic vehicle model was developed that incorporates case-specific velocity and topography information. The investment costs of the components required for the powertrain configuration are calculated in an integrated bottom-up cost model based on component cost analyses. It integrates the learning curve approach based on cumulative production volumes and dimensioning as a result of an optimization. The cost model is extended to include fixed and variable operating costs to calculate the total cost of ownership (TCO) of a vehicle for the operating period under consideration. In order to incorporate the infrastructure costs, a spatially resolved modeling approach is applied, which takes into account the hydrogen provision costs related to production, transport, distribution and refueling [3].

The results provide an application-specific evaluation of BEV and FCEV powertrain systems for heavy-duty vehicles in terms of expected TCO. Thus, a comparative analysis is performed for different vehicle classes and specific scenarios based on energy demand, TCO as well as infrastructure requirements. Finally, the results of this study are used to identify appropriate vehicle powertrain and application combinations. The economic efficiency is found to be highly dependent on the vehicle energy costs as a great share of the vehicle TCO as well as the associated availability of the required energy

demand. Among the application-specific strengths, it is evident that FCEVs currently possess a purchase price that is almost three times the cost of diesel vehicles. FCEVs achieve cost competitiveness when there is a reduction in both investment and fuel costs. While BEVs require a substantial initial investment as well, the price trend of -20% in 2024 for traction batteries, a crucial cost-intensive component, indicates greater potential for cost reduction. This suggests that price parity between BEVs and diesel trucks can be expected before 2030. The findings provide valuable insights for policymakers and industry stakeholders, supporting strategic decisions for sustainable road transport.

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For the purpose of improving the linguistic clarity and consistency of the English text, the AI-based translation tool DeepL was used for initial language polishing. All content was subsequently reviewed and revised by the author to ensure accuracy and adherence to scientific standards.

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Environmental and socio-economic potentials of automated cars on the European passenger car fleet

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ABSTRACT

Automated vehicles (AVs) are considered as one of the most significant disruptive technologies in mobility systems in the coming years. AVs have the potential to create impacts at different levels, from single-vehicle level (i.e., added weight and energy demand from sensing and computing components) to the entire fleet (e.g., reductions of traffic congestion, fewer traffic accidents, and shorter delays). Understanding how AVs will affect mobility systems and user behavior from both environmental and socio-economic perspectives is an important topic for AV development and their penetration into the fleet. Focusing on passenger cars, this paper aims to investigate a wide range of potential impacts, i.e., technical, socio-economic, and environmental, caused by automated cars on the European passenger car fleet. First, potential environmental impacts will be discussed in view of reduction of emissions due to improved traffic, but also in view of increased energy consumption and changed user behaviors. Second, AV impacts on vehicle costs, including fixed, variable, social, and environmental costs, will be assessed. Next, fleet characteristics, such as the number of vehicles-in-use and penetration rate, will be combined with AV-related vehicle impacts to quantify AV impacts on the fleet. Potential impacts of AVs are analyzed across several scenarios that differ in terms of penetration rates, as well as in additional fuel and energy consumption resulting from AV operation (labeled Average, High saving, and No saving). The results indicate that fleet scenarios with lower total fleet emissions tend to have lower total fleet costs. In addition, supportive policies and business models that enable AVs to achieve their maximum emission saving potential are key to a sustainable fleet.

1. INTRODUCTION

There are 6 levels of automation for on-road vehicles according to SAE International, ranging from no automation (0), driver assistance (1), partial automation (2), to conditional automation (3), high automation (4), and full automation (5) (SAE, 2018). While automation levels 2 and 3 are already integrated into most new passenger car models, automated vehicles (AVs) at SAE level 4 and 5 are currently being tested worldwide, with some widely commercialization plans in place. For example, Waymo – the AV unit of Alphabet – already provides a fully autonomous ride hailing service called Waymo One in cities like San Francisco, Phoenix, Los Angeles, and Austin, providing over 200,000 paid trips weekly (Shepardson, 2025).

Potential impacts of AVs can be assessed according to three impact levels: subsystem, vehicle, and fleet. Considering an AV being a sensing and computing subsystem added to a vehicle platform (Gawron, Keoleian, Kleine, Wallington, & Kim, 2018; Kemp, 2020), the AV subsystem adds extra weight, requires added energy, respectively, fuel consumption, and increases drag force. At vehicle level, AV subsystems alter the driving experience of the vehicle platform via several direct effects, i.e., eco-driving or platooning. Furthermore, at fleet or mobility system level, AVs have a wide range of indirect effects, which can either reduce fleet emissions (for example via reduction of congestion and vehicle right-sizing), or increase emissions, especially regarding empty miles or increased travel demand by cars and competing with public transport (Wadud & Mattioli, 2021; Shapiro & Yoder, 2023). In addition, AVs can change vehicle and mobility system costs in numerous ways, for example, increasing capital costs, reducing insurance premiums, potentially altering vehicle operation costs, causing job losses in various sectors, as well as enhancing safety, mitigating traffic congestion, and relieving drivers of the task of driving (Klaver, 2020; Wadud, 2017).

Integration of AVs into the fleet requires a holistic view on how AVs will contribute to the total fleet emissions from a life cycle perspective as well as how they will create changes in vehicle and mobility systems' costs, especially with regards to the European context. This paper investigates total fleet emissions and total fleet costs in various considerations of technical (AVs powered by internal combustion engines (ICEV) and battery electric (BEV) platforms in different penetration levels), environmental (emission saving scenarios), social-economic (via fixed, operation and maintenance – O&M, social, and environmental costs) aspects. Even though the term AVs is utilized, in this paper we solely focus on passenger cars.

2. METHODOLOGY

This paper follows a methodology framework described in Fig. 1. At first, based on literature review and previous life cycle analysis of AVs, vehicle emissions are identified and defined as emission units, meaning life cycle gCO₂-equivalent (gCO₂-eq) per vehicle per km. Similarly, AV impacts on vehicle costs are computed in a comprehensive assessment including fixed, variable, social, and environmental cost items and according to available data on notable sources. This results in cost units of AVs – which are EUR per vehicle. These emission units and cost units are then combined with fleet data, such as number of vehicles-in-use, shares of ICEVs and BEVs in the fleet, vehicle life span and age, under several scenarios, i.e., different AV penetration rates, fleet characteristics in 2022 and assumed fleet in 2050, and three emission saving scenarios.

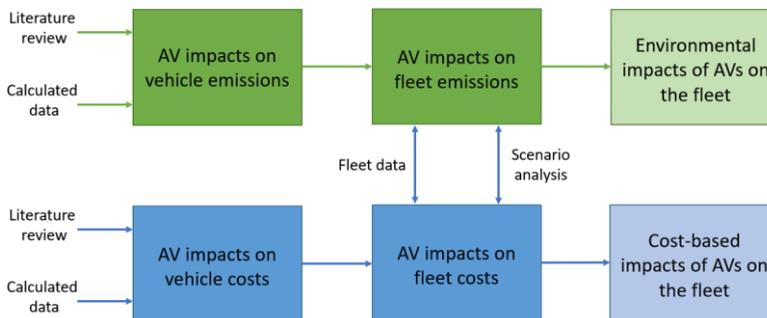


Figure 1: Methodology framework.

2.1 EMISSION SAVING SCENARIOS

Three emission saving situations are considered, in which the total AV effects bring out High saving (HS), Average (AVE), and No saving (NS) in terms of fleet CO₂-eq emissions. Table 2 presents a number of AV effects analysed in this paper, their value ranges obtained from literature review, and how they are defined in saving scenarios.

Table 1: Definition of three saving scenarios

AV effect	Value range*	Defining saving scenarios
Eco-driving	-4% to -20%	<p>HS: AVs achieve maximum emission savings through optimized eco-driving, widespread platooning, and full deployment of V2V/V2I systems. Traffic flows smoothly with minimal congestion or crashes. Shared mobility is dominant with carpooling and car sharing being widely adopted, and ride hailing is efficient and pooled, minimizing empty miles. Vehicle right-sizing and low-energy trip patterns further enhance system efficiency, supported by strong infrastructure and policies.</p> <p>AVE: This scenario reflects moderate AV adoption and mixed impacts. Efficiency gains from AV features are partially realized, with limited platooning and incomplete connectivity. Traffic improves modestly, but increased demand, especially from non-pooled ride hailing, reduces net savings. Car sharing and carpooling grow but compete with private AV use. Overall, emissions decline slightly, but benefits are diluted by behavioral and system-level trade-offs.</p> <p>NS: AVs increase energy use due to higher speeds, limited efficiency features, and significant growth in ride hailing with low occupancy and high empty miles. Shared modes remain marginal, while private AVs dominate. AVs also compete with public transport. Induced travel and poor system integration outweigh technical gains, leading to higher emissions and a more resource-intensive transport system.</p>
Platooning	-3% to -25%	
Routing efficiency	0% to -13%	
Intersection connectivity (V2V/V2I)	-2% to -4%	
Higher high-way speed	2% to 40%	
Traffic congestion	0% to -60%	
Crash avoidance	-6% to -23%	
Reduced acceleration	-5% to -23%	
Vehicle right-sizing	0% to -50%	
Increased travel demands due to cost reduction	4% to 60%	
Increased travel demands due to new user groups	2% to 10%	
Empty miles	11% to 167%	
**Car sharing	-12% to -50%	
***Carpooling	-16% to -23%	
****Ride hailing	3% to 47%	

*Potential increase or decrease of fuel/energy consumption due to the effects (data extracted from (Nguyen & Hirz, 2025))

**Car sharing and/or car rental: the cars owned by a company, users pay a fee to use the cars.

***Carpooling: several different passengers share the same ride when they have the same starting point and destination. The cars are owned by individuals, often the drivers. The passengers pay a fee to the drivers, as well as a possible fee to the digital platform where they are connected.

****Ride hailing: cars are owned by individuals or a company. The passengers don't drive the cars themselves, but pay a fee to be transported from A to B.

2.2 FLEET EMISSIONS

The passenger car fleet is considered to include four vehicle technologies, namely ICEVs, AVs powered by ICEV platforms (AV_ICEV), BEVs, and AVs powered by BEV platforms (AV_BEV). Fleet emissions are calculated for each fleet (E_F) under different penetration rates (j) and time spots (k) consisting of different vehicle technologies (i) having emission units (E_i):

$$E_F = \sum E_i * VKT_{i,j,k} \quad (1)$$

$$VKT_{i,j,k} = N_{i,j,k} * Annual\ VKT_{i,j,k} \quad (2)$$

$$N_{i,j,k} = Fleetshare_i * N_k \quad (3)$$

$$Fleetshare_i = Penetrationrate_j * Fleetshare_k \quad (4)$$

$$Fleetshare_i = (1 - Penetrationrate_j) * Fleetshare_k \quad (5)$$

Emission units (E_i) refers to life cycle emissions in terms of gCO₂-eq/km for each vehicle technology in the fleet. The emission units are taken from

previous studies published by the same authors (Nguyen & Hirz, 2025; Nguyen & Hirz, 2024). In which, the 2050 scenarios are considered to be powered by 100%-renewable-based electricity mix and fossil fuels are replaced by e-fuels. Emission factor of the electricity mix is considered 20 gCO₂-eq/kWh in 2050 versus the current 310 gCO₂-eq/kWh (Scarlat, Prussi, & Padella, 2022). Vehicle kilometre travelled (VKT) is defined and calculated for each vehicle technology (ICEV, AV_ICEV, BEV, AV_BEV) by multiplying number of vehicles-in-use ($N_{(i,j,k)}$) of that vehicle technology in the fleet with an average annual kilometre travelled (Eq. (2)) of the vehicles. We assume a life span of 200,000km spanning over 15 years in this paper (Nguyen, Rust, Brunner, Bachler, & Hirz, 2021). Number of vehicles-in-use of a vehicle technology depends on share of that technology in the fleet and the total fleet vehicles-in-use. Fleet share of a technology (i) is divided into two groups: AVs (AV_ICEV and AV_BEV) and non-AVs (ICEV and BEV). For the first group, $[Fleetshare]_i$ is equal to penetration rate multiplied by fleet share of the vehicle platform technology in the 2022 or 2050 fleet (Eq. (4)). On the other hand, Eq. (5) is used to calculate fleet share of ICEVs and BEVs in the fleets.

Total passenger cars on road in the EU-27 are about 246.5 million in 2020 and 252.2 million in 2022 (ACEA, 2024). Considering a projection of car activity in 2050 in comparison with 2020 (Transport & Environment, 2018), we assume a 2050 fleet consisting of 322 million passenger cars. Roughly 5.3% of cars are powered by electric powertrains (including hybrid and plug-in hybrid) in 2022 (ACEA, 2024), and we assume that ICEVs are responsible for the rest. Using the approach in (Nguyen & Hirz, 2025), which considered average values from expert consultations for 2050 European road projection (Krause, et al., 2020), we assume that the 2050 fleet is covered by 20.5% ICEVs and 79.5% BEVs. As pointed out in literature, AV adoption scenarios for 2050 can vary from 5% to 70%, or even the whole fleet (Shapiro & Yoder, 2023). Therefore, in this paper, penetration rates are considered to be 25%, 50%, and 75% for analysis, as utilized by Shapiro & Yoder (Shapiro & Yoder, 2023) and Klaver (Klaver, 2020). Furthermore, fleet emissions are investigated for three saving scenarios, based on potential impacts of AVs in the fleet as mentioned above.

Table 2: Emission units per vehicle technology in different saving scenarios

gCO ₂ - eq/km	2022			2050		
	HS	AVE	NS	HS	AVE	NS
ICEV	207	207	207	86	86	86
AV_ICEV	125	201	276	71	94	117
BEV	126	126	126	40	40	40
AV_BEV	95	123	151	40	42	43

2.3 FLEET COSTS

In terms of total costs, Nguyen & Hirz (Nguyen & Hirz, 2025) investigated a comprehensive cost structure of ICEVs and BEVs as vehicle platforms, as well as AVs powered by these propulsion technologies, covering not only fixed and variable (O&M) costs, but also social and environmental cost items. These serve as cost units (C_i) in this paper. A large number of potential social effects of AVs caused to the mobility systems are analysed in monetary term by conducting a literature review. Data reflecting several European member states and the EU-27 is taken from various data sources, including scientific studies, reports conducted by or for the European Commission (EC), data from Statista, Eurostat, and extensive market research (Nguyen & Hirz, 2025). Conversion is made to EUR from other currencies when necessary and the year 2022 is the basis for calculation and inflation indexing using the average EU-27 inflation rates (Statista, 2024). Depreciation is considered for 4 years of ownership, similar to Total Cost of Ownership structure of cars in Europe (Statista, 2024).

AVs are expected to alter vehicle costs in both directions. Vehicle costs can rise by the added AV subsystem, added energy consumptions for connectivity services, map data transmission, additional interest, maintenance and repair services, and more mileages. On the other hand, cost reductions can be achieved by enhanced safety capacity and thus, fewer safety equipment and devices are required for the vehicle, making it lighter, as well as decreasing

insurance cost. Operation of the vehicle is supposed to be more efficient and it consumes less energy and fuel.

Regarding socio-economic aspects, AVs are reported to have similar impacts on system costs. They are expected to reduce traffic accidents and deaths, saving billions of EUR for the society (Klaver, 2020; Shapiro & Yoder, 2023). The time saved from driving also has a monetary value, which is computed by combining shares of trip purposes and hourly travel costs by car in the EU members states (Wadud, 2017; Eurostat, 2021; Wardman, Chintakayala, & de Jong, 2016), resulting in 9.5, 19.5, and 8.8 EUR/h for commute, business, and other purposes, respectively. However, AVs can bring economic losses to the society due to loss of driving jobs, jobs in insurance industry and repair services (Klaver, 2020). In addition, AVs may require advanced digital infrastructure, for example Cooperative Intelligent Transport Systems (C-ITS) and 5G infrastructure. Using a report from the EC on costs of C-ITS till 2030 (European Commission, 2016) and estimating cost of 5G infrastructure based on total 5G costs worldwide and market share of transportation and logistics in the global market segment (Research and Markets, 2024), we calculated added infrastructure costs for AVs.

Environmental costs include resource requirements from car production, maintenance, distribution, and disposal, with data taken from Gössling et al. (Gössling, Kees, & Litman, 2022), and climate change avoidance cost calculated based on the EC handbook on external costs in transportation (European Commission, 2019) and fleet emissions computed in the previous steps.

Total fleet costs C_F (including fixed, variable, social, and environmental costs) are formulated in Eq. (6). Estimation of AV costs in 2050 is challenging due to a large number of fluctuating and uncertain factors in view of future markets and regulations. However, AVs are supposed to become significantly cheaper due to mass production and economies of scale, established C-ITS systems, technological advancements to bring down AV hardware costs, software maturity, and a broad shift towards shared mobility. Litman (Litman, 2024) predicted that shared AVs could reduce per-mile costs by 60-80% in 2050. In the meantime, Waymo's AV unit cost has dropped 55% by 2021. C-ITS infrastructure costs are also expected to be about 20% cheaper between 2022 and 2030 already (European Commission, 2016). However, considering an annual inflation of about 2% that most central banks target (European Central Bank, 2025), vehicle prices will increase by roughly 175% in 2050 in comparison to 2022. In this paper, we make a compromising assumption, in which cost units of AVs will stay the same in both studied time spots.

$$C_F = \sum C_i * N_{i,j,k} \tag{6}$$

Table 3: Cost units per vehicle technology in different saving scenarios

EUR/vehicle	2022/2050		
	HS	AVE	NS
ICEV	14427	14427	14427
AV_ICEV	12865	16151	19438
BEV	12790	12790	12790
AV_BEV	12701	14442	16183

3. RESULTS AND DISCUSSION

Figure 2 indicates fleet emissions according to three saving scenarios under different penetration levels (25%, 50%, 75%) in 2022 and 2050. The only fleets with total negative emissions are the 2022 fleets where AVs claiming 50% and 75% of the total vehicles-in-use and AVs are supported to reach their highest saving potentials. This is due to the fact that the 2022 fleet consists of nearly 95% ICEVs and it is reported that AV impacts are significantly more noticeable on ICEV platforms than on BEV platforms as their emissions are largely reduced by direct and indirect effects, as well as sharing models (Nguyen & Hirz, 2025). It is interesting to see that in 2050, AVs with average or no saving potentials will increase total fleet emissions when penetration rate increases while in 2022, AVs with average effects can already reduce fleet emissions when AVs are penetrated further into the fleet from 25% to 75%. The chart also shows that higher integration of AVs will lower total fleet emissions only in a HS scenario, with 44% less emissions in case of 75% penetration rate in comparison with 25% penetration rate in 2050. This highlights the importance of supportive policies and business models to facilitate AVs to reach their maximum saving potentials.

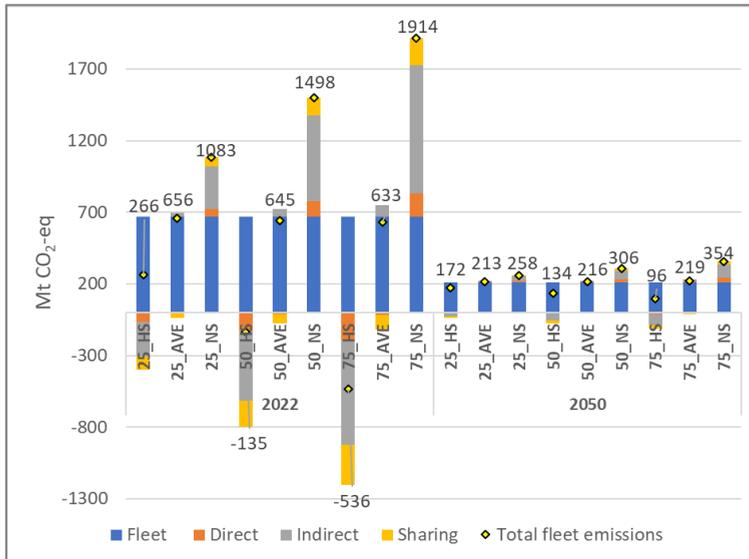


Figure 2: Total fleet emissions in the studied scenarios

Across all penetration levels, total fleet costs increase from 2022 to 2050, from about 17% in 25_NS scenarios (2050 vs 2022) to about 27% in 75_HS scenarios (2050 vs 2022), see Fig. 3. Fixed and O&M costs account for the majority of total fleet costs, ranging from 88% in the 2022 fleet with 25% penetration rate to 95% of the 2050 fleet with a 75% penetration. Fixed costs rise consistently across all penetration levels, suggesting that AV deployment is capital intensive. O&M costs increase in NS scenarios, stay almost constant in AVE scenarios, and decrease in HS scenarios, suggesting that optimized fleet operation and efficient use of AV sharing models are critical to sustainable mobility systems. Shares of social costs are generally reduced when AVs penetrate further into the fleet, from a maximum 10% of total fleet costs (25_AVE and 25_NS) to 4% (75_NS) in 2022 and from 8% (25_HS) to a minimum of 3% (75_NS) in 2050. On the other hand, environmental costs only change among saving scenarios while penetration rates do not appear to have an effect: in 2022 they are responsible for 1%, 2%, and 3 % of total fleet emissions in HS, AVE, and NS scenario, respectively; in 2050 they stay constantly at 1% as BEV platforms dominate the fleet. Thus, environmental impacts of AVs are minor in their cost structure.

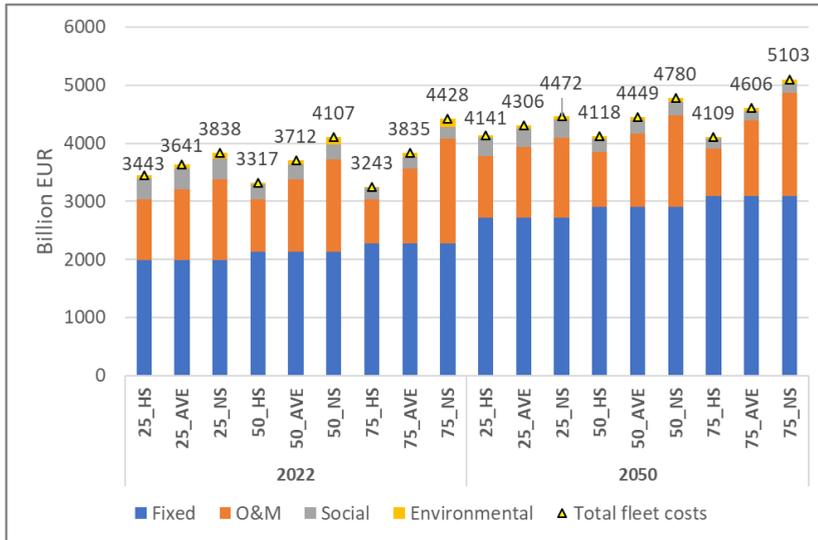


Figure 3: Total fleet costs in the studied scenarios

Combined together, Fig. 4 presents a comparison of total fleet emissions and costs across various scenarios for the years 2022 (blue) and 2050 (green). There is a clear relation between total fleet emissions and total fleet costs: in both time spots, scenarios with lower emissions tend to have lower costs. This suggests that more efficient AV deployment with highest saving potentials results in economic and environmental benefits. In general, 2050 scenarios have lower emissions, mostly below 400 Mt CO₂-eq, but they come at a higher cost range, between 4100 – 5100 Billion EUR compared to the range of 3200 – 4400 Billion EUR of 2022. This implies that a BEV-dominant fleet as assumed for 2050 is cleaner but more expensive than the ICEV-dominant 2022 fleet. The differences across HS, AVE, NS scenarios are substantial, especially at 75% penetration rate – for both years the 75_HS fleet has lowest emissions and costs while the 75_NS has the highest emissions and costs. Furthermore, HS scenarios, especially at 50% and 75% in both years, lie in the lower-left quadrant, indicating lower emissions and costs, and therefore, being more favourable.

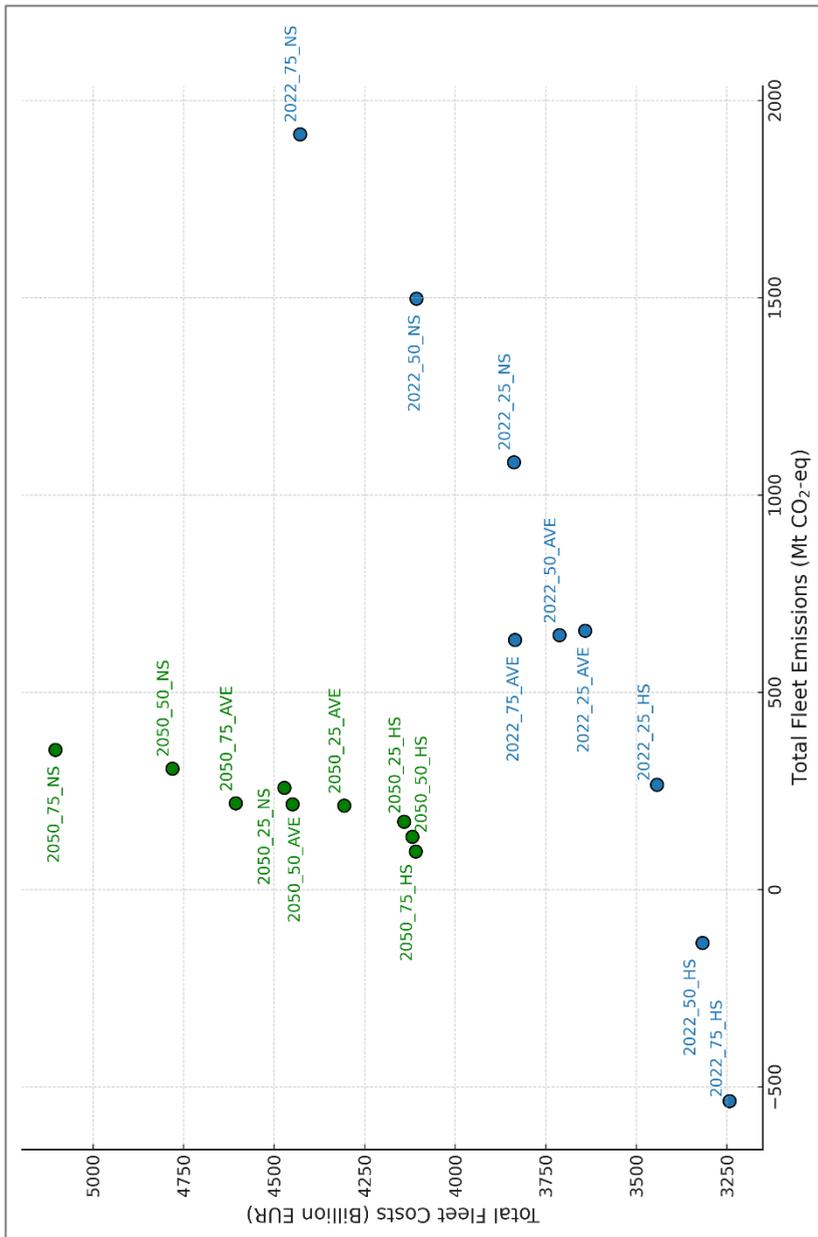


Figure 4: Comparison of total fleet emissions and costs across various scenarios

4. CONCLUSION

The paper assessed the total fleet costs and total fleet emissions of integrating AVs into the European passenger car fleet under various scenarios. To lower total fleet emissions, increasing number of AVs in the fleet needs to be coupled with supporting the AVs to achieve maximum emission saving potentials. Optimum fleet operation as well as positive AV sharing business models (pooling and sharing) are vital to move forwards sustainable fleets. Moreover, efficient AV deployment as reflected in HS scenarios is not only better for the environment, but also economically favourable. In contrast, deploying AVs without proper management and efficiency, i.e., higher speeds, significant growth in ride-hailing, increased empty miles or AVs competing with public transport, may result in a costly and more carbon-intensive transportation system.

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Day 2 Session: Data-driven Circular and Sustainable Vehicle Management

Hybrid Modelling for Second-Life Battery Optimization in Light Electric Vehicles

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ABSTRACT

The repurposing of second-life lithium-ion batteries (LIBs) offers a sustainable solution for less demanding applications, such as light electric vehicles (LEVs) or stationary storage. However, limited information on their usage history and internal condition hinders their effective reuse. This paper presents a hybrid modelling (HM) approach that combines a data-driven model (DDM) with a physics-based model (PBM) to assess battery health and predict future performance. The DDM estimates, from a simple charge test, three key parameters: state of health, full equivalent cycles, and active material volume fractions. These are then used to initialize the PBM, which simulates degradation and estimates remaining useful life under LEV application profiles. Trained on experimental data from NMC811 cells, the HM demonstrates strong potential as a practical tool for second-life battery evaluation for different types of cells, integrating adaptability and physical accuracy in a single framework.

1. INTRODUCTION

The growing integration of renewable energy sources and the electrification of transport have significantly increased the demand for reliable and efficient energy storage systems (ESS). Among the various available technologies, lithium-ion batteries (LIBs) have emerged as the dominant solution due to their high energy density, long cycle life, and lower production costs (Nitta et al., 2015). One of the main advantages of LIBs is their versatility across a wide range of applications. They can be used in both stationary systems, such as grid-scale energy storage, and mobile applications, including consumer electronics and electric vehicles (EV).

In demanding applications such as EVs, LIB packs are generally considered unsuitable when their available capacity falls below 80% of the nominal. This threshold typically marks the end of first-use life, although most cells within the pack still retain sufficient capacity and functionality for less demanding applications such as light electric vehicles (LEVs) or off-grid ESS. Reusing these cells in second-life batteries (SLBs) offers significant environmental and economic benefits by reducing resource consumption, even though it is a time-consuming and complex process.

Despite the promising idea of giving used batteries a second life, the process is not yet optimized, and the deployment SLBs is hindered by several challenges. First, a major barrier is the lack of data provided by the manufacturers, such as cell characteristics and pack specifications. Additionally, first-life usage information, like operating conditions and degradation patterns, are often unavailable and critical for selecting an appropriate second-life usage. This lack of transparency complicates accurate assessment of battery state and forecasting, increasing uncertainty and risk (Von Bülow et al., 2024).

To bridge this gap, battery modelling and data analysis have become essential tools for inferring the internal state of LIBs from measurable data, enabling both diagnostics and prognostics. Physics-based models (PBMs) and data-driven models (DDMs) have gained significant attention and have emerged as powerful approaches for evaluating and forecasting the behaviour of SLBs.

PBMs are grounded in electrochemical and physical laws, with various model typologies depending on the underlying assumptions. However, these models are typically computationally intensive, require extensive parameterization, and lack adaptability when applied to batteries already degraded or with unknown composition (Jokar et al., 2016). In contrast, DDMs rely on statistical or machine learning techniques to learn patterns from measured data. They

can model complex energy system dynamics; however, they often struggle to generalize beyond their training data.

To leverage the strengths of both approaches, hybrid models (HMs) and physics-informed machine learning (PIML) have emerged as a promising strategy. These models integrate physical laws and machine learning in a unified framework, enabling both accurate internal state estimation and generalizable prediction of battery performance. By embedding physics-based constraints or using machine learning to estimate hard-to-measure physical parameters, PIML provide a balanced trade-off between accuracy, generalizability, and interpretability (Navidi et al., 2024).

Recent advances in hybrid modelling include the use of DDMs to estimate parameters for PBMs and using these last ones to generate synthetic data (Wang et al., 2024). However, a major research gap still exists in the application of HM approaches for SLBs, particularly in cases where no prior usage history is available. Most existing studies either focus exclusively on new cells under controlled conditions or rely on assumptions that are not valid for cells with unknown degradation pathways.

In this context, the present work proposes a HM, comprised of a DDM and a PBM, designed to address the uncertainties associated with SLBs. Firstly, the DDM based on XGBoost, estimates health indicators, such as state of health (SOH), full equivalent cycles (FEC), and active material volume fractions ($\epsilon_{act,k}$), from a single laboratory charge test. Then a PBM, based on the pseudo-two-dimensional model (P2D) and incorporating degradation mechanisms, simulates future battery performance, predicting SOH evolution and remaining useful life (RUL) based on DDM outputs. By integrating both modelling approaches, the HM enables informed decision-making for SLBs deployment, even in the absence of historical data. The model provides valuable insights into the battery's current condition and estimates its suitability for specific applications such as LEVs.

The rest of this paper is structured as follows: Section 2 details the development and integration of the DDM and PBM components. Section 3 describes the experimental calibration and validation of the models using NMC811 cells. Section 4 outlines the methodology for performance estimation under realistic use cases. Section 5 presents the results, and Section 6 concludes with insights and future directions for SLBs modelling.

2. HYBRID INFORMED MODEL FORMULATION

As previously noted, limited information on LIB characteristics and usage history during their first life represents a major barrier to the optimal deployment of SLBs. The absence of such data and knowledge about the battery's state increase the risks associated with operation and pose significant challenges in determining its most suitable application. To address this issue, the article proposes a HM capable of providing a clearer assessment of actual LIB condition and estimating the future performance under a certain application, with just a full charge test.

The designed HM consist of two complementary components: a DDM responsible of assessing the current battery condition and a PBM that estimates future performance under second-life applications. To achieve that objective, the DDM provides three key indicators: SOH, which quantifies the loss of battery capacity relative to the nominal value; the FEC, which reflects battery usage expressed on cycles; and the $\varepsilon_{act,k}$, a parameter representing the amount of active material available in the electrodes per unit volume. This latter parameter determines cell capacity in PBMs and provides valuable insights into the internal states of the LIB (Chen et al., 2020).

Based on the current state analysis provided by the DDM, the PBM estimates battery performance in second-life applications. Specifically, the model predicts SOH evolution and generates additional diagnostic indicators such as the RUL, expressed in years, which quantifies the time left before the battery reaches its end of life or becomes unsuitable for the studied second-life application (O'Kane et al., 2022).

HM is designed to operate with cell-level data, focusing exclusively on NMC811 cells, one of the most widely used LIB chemistries currently available (Huotari et al., 2021). The model does not, however, assess risk or account for mechanical deformation from stresses or vibrations during the first life, which may cause discontinuous operation and deviations in results.

2.1 DATA DRIVEN MODEL (DDM)

DDMs are widely used across different types of applications and there are multiple options in terms of model types, such as random forest, neural networks (NN), etc. The selection of the model type depends on the intrinsic characteristics of the system aimed to be represented and the characteristics

of available data. For example, time series data are often modelled using recurrent NNs, while tree-based models perform superior for tabular data.

In this study, the objective is to build a DDM capable of estimating SOH, FEC, and $\varepsilon_{act,k}$, from a charge test executed at the laboratory, going from the minimum to the maximum voltage specified by the manufacturer.

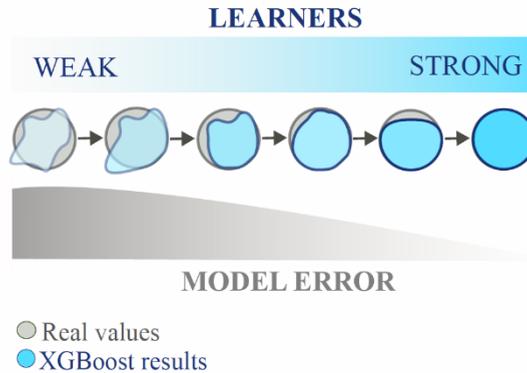


Figure 1: Fundamental operation of a XGBoost algorithm.

For this study scenario, the XGBoost algorithm has been selected, because it works well with tabular data and has been successfully used for predicting battery behaviour with time-dependent variables (Huotari et al., 2021). Moreover, since not all inputs of the developed DDM will be normalized, XGBoost offers a particularly interesting choice.

Like other tree-based models, XGBoost generates outputs from the combined response of multiple individual models but enhances this approach with a boosting method that executes models sequentially. As shown in Figure 1, the initial models, or weak learners, have higher error, while subsequent models learn from previous ones, gradually improving accuracy until forming a precise strong learner. Detailed functions and parameters governing its operation are omitted here but can be found at O’Kane et al. (2022).

2.2 PHYSICS-BASED MODEL (PBM)

PBMs are based on physics and chemical principles, including Fick’s laws of diffusion, electrochemical kinetics like the Butler-Volmer equation, and electrical transport laws such as Ohm’s law. This foundation makes them robust and typically involve solving multiple partial differential equations (PDEs).

Their main advantage lies in accurately representing the internal states of LIBs, such as current distribution and lithium concentration within electrodes and electrolyte.

Among the existing PBMs, the P2D is one of the most used. It considers two dimensions: the particle radius (r) and the overall location on the battery dimension (x), as shown in Figure 2.

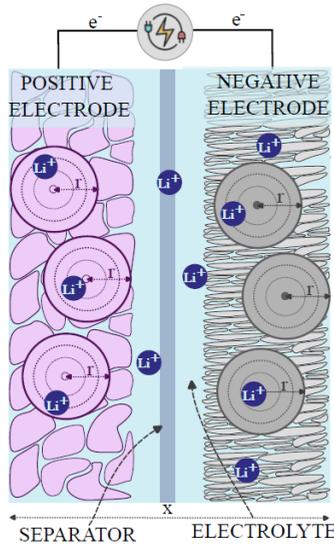


Figure 2: LIB from the perspective of a P2D model

It uses five PDEs and requires 35 parameters to accurately represent the cell performance. Further information of the fundamentals and mathematical background of this model can be found at Chen et al. (2020).

As mentioned before, $\varepsilon_{act,k}$, $k \in \{n, p\}$ is one of the parameters that determines the cell capacity in the P2D. Positive and negative electrodes have different active material volume fractions, denoted as $\varepsilon_{act,p}$ and $\varepsilon_{act,n}$, respectively.

Degradation mechanisms, associated with capacity fade, can also be incorporated into PBMs. In this study, the equations proposed by O’Kane et al. (2022) have been implemented, which model phenomena such as solid electrolyte interface growth, lithium plating, particle cracking and loss of active material.

2.3 INTERACTION BETWEEN MODELS

After outlining in a general manner the models comprising the solution, the operation of the HM is described at Figure 3. The second-life cell is subjected to a charge profile test, during which it is charged from its minimum to maximum voltage, thereby going from 0% to 100% state of charge (SOC). This data generated at the laboratory, is then processed by the DDM which estimates the SOH, FEC, $\epsilon_{act,p}$ and $\epsilon_{act,n}$. These last two parameters, that represent the available active lithium within the positive and negative electrodes, are then introduced to the PBM. With this information, the PBM estimates the cell degradation under a specific future usage pattern anticipated in the second-life application.

By repeating the usage pattern several times through simulation, the PBM estimates the expected operational lifespan, by providing the SOH evolution and RUL. In this way the HM enables an informed assessment of the suitability of the cell for a continued use in a new application, reducing the risk and the resources required.

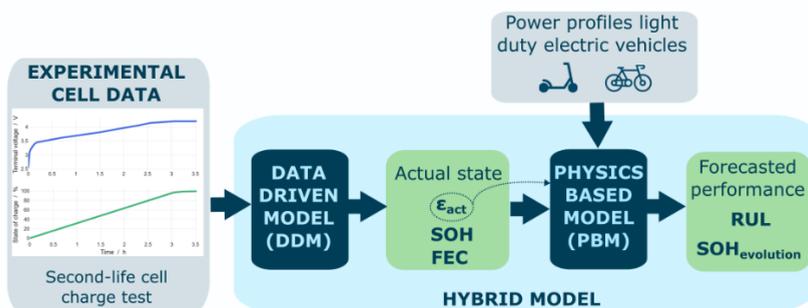


Figure 3: HM structure and principal interactions between DDM and PBM.

3. CALIBRATION AND TRAINING

To properly calibrate the models, experimental tests have been carried out with cylindrical Li-ion cells. The cells modelled are INR21700 M50 (LG-M50), with their main specifications listed in Table 1.

Table 1: INR21700 M50 (LG-M50) principal manufacturer specifications

Item	Manufacturer specifications
Chemistry	NMC811
Nominal capacity	5 Ah
Geometry	Cylindrical
Voltage limits	2.5-4.2V

In total six cells have been considered with different usage patterns: two of them were subjected to driving conditions and the remaining four were charged and discharged according to manufacturer maximum constant current rates, two between 0 to 100% SOC and two between 20 to 80% SOC, respectively. Temperature was held constant at 35°C.

The six LG-M50 underwent a Reference Performance Test (RPT) at 25°C after every 25 cycles. This RPT consisted of fully charging and discharging the battery two times at a c-rate of C/3, to track the degradation in the same conditions.

3.1 DDM

The DDM was trained on charge profiles obtained during the RPT using the XGBoost package (Chen & Guestrin, 2016) implemented in Python. The objective is to enable the assessment of the SOH for any NMC811 cell, regardless of its characteristics, geometry or nominal capacity. To ensure that the DDM is compatible across different cell formats and types, all input features provided to the XGBoost algorithm have been normalized. It is assumed that manufacturing differences between cells do not substantially influence battery performance, hence the model inputs are chosen as listed in Table 2.

Table 2: Inputs necessary for the DDM

Variable	Description
Terminal Voltage (V)	Measured voltage
Temperature (°C)	Measured cell temperature
C-rate (A/Ah)	Measured current divided by the nominal capacity of the cell
dQdV (Ah/V)	Differential capacity with respect differential voltage
dVdt (V/s)	Differential voltage with respect differential time
Cnormalised (Ah/Ah)	Tracked capacity divided by the nominal capacity of the cell

For the training process SOH, FEC, and $\varepsilon_{act,k}$, have also been provided to the DDM. The experimental SOH was calculated after each RPT, by dividing the maximum capacity at 100% SOC by the nominal capacity specified by the manufacturer. The FEC were computed as the sum of the total discharged and charged energy, divided by twice the nominal capacity of the battery.

The $\varepsilon_{act,k}$ were correlated with the SOH based on PBM simulations. Chen et al. (2020) determined initial values for a new LG-M50 cell, as $\varepsilon_{act,p} = 66.5\%$ and $\varepsilon_{act,n} = 75\%$, respectively. By reducing both active $\varepsilon_{act,p}$ and $\varepsilon_{act,n}$ according to the SOH, a relation between active material volume fractions and capacity decay was found as shown in **Figure 4**.

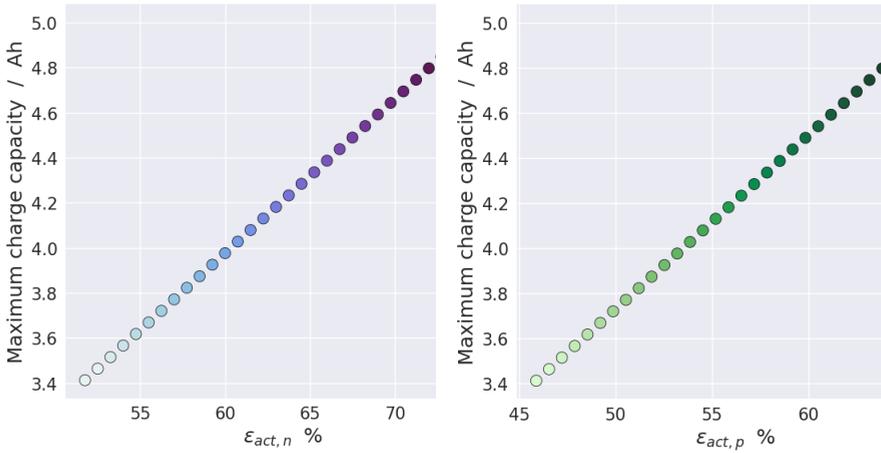


Figure 4: Relation between $\epsilon_{act,k}$, SOH and maximum charge capacity, according to PBM results. **Left**) Negative electrode ($\epsilon_{act,n}$) **Right**) Positive electrode ($\epsilon_{act,p}$).

Using these inputs and targets, the XGBoost model was trained to minimize the squared error between each true target values and the model estimate. Parameters such as the sub-sampling rate (0.8), the fraction of features to evaluate (0.8), and the random seed (42) have been taken from Huotari et al. (2021). A detailed description of the XGBoost model parameters and configuration will be provided in a forthcoming publication and is not included here due to space limitations.

3.2 PBM

The P2D relies on 35 parameters to properly represent the behaviour of LIBs. Therefore, an exhaustive study of the different components comprising the battery is necessary. The values provided by Chen et al. (2020), validated in multiple studies and adequate for the NMC811 chemistry, have been considered in this work. In addition, the degradation equations considered in the P2D, developed by O’Kane et al. (2022), also apply to the same cell. The PBM was developed with the Python library PyBaMM (Sulzer et al., 2021).

The LIBs tested at the laboratory are the same as the ones investigated by both studies, with the same chemistry NMC811 and components. The only parameter modified in this case study was the active material volume fraction,

provided by the DDM, effectively adjusting the battery's maximum capacity according to the state of degradation.

4. METHODOLOGY

After calibrating and training both models, it is possible to test the whole operation of the HM. For validation purposes, a LIB has been tested in the laboratory, for which cycle life, SOH and FEC are known and experimentally determined. This cell, functioning as SLB, is of the same type as those employed during the training phase (LG-M50), however its cycle life data was excluded from training to prevent overfitting the DDM. The cell exhibits a degradation pattern distinct from the training cells, enabling a more realistic evaluation.

To assess the impact of using the SLB in a new application, an electric scooter usage profile was analysed. The LEV was monitored over 24 h in a commuting scenario in the city of Barcelona (Spain), recording battery voltage, current, SOC, and temperature. **Figure 5** presents the voltage of one cell in the pack. After executing the DDM, this profile was applied to the PBM and repeated multiple times to estimate future battery's performance under specified SLB conditions.

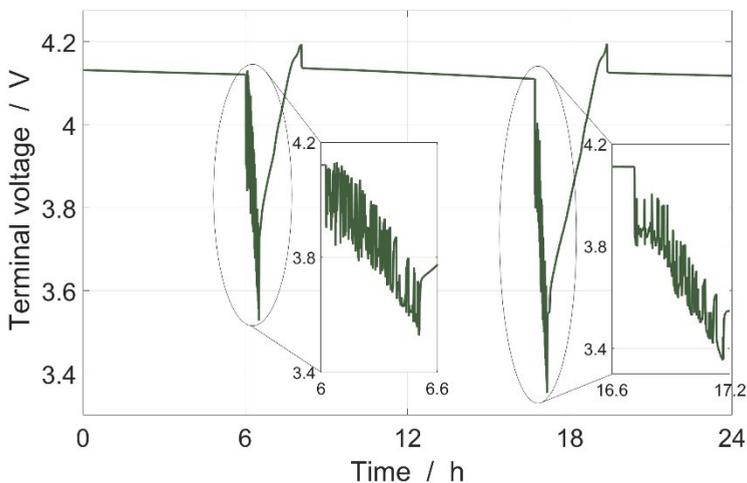


Figure 5: Cell voltage during 24 h of electric scooter operation. The LEV was charged to 100% SOC immediately after use and remained at rest when not in operation.

5. RESULTS

In the first phase, the HM processes the variables listed in Table 2, derived from a charge profile, and uses the DDM to assess the current battery state. Since the data was obtained from a laboratory-tested battery, the SOH and FEC were available for different degradation levels, allowing direct comparison between measured performance and model predictions.

Figure 6 a) and b) compare the DDM estimation of SOH and FEC values, with the relative error against the measured data. For both variables, the XGBoost model shows lower accuracy when the battery is at the beginning of its cycle life (94–92% SOH) and improved precision after approximately 200 cycles. SOH estimation remains accurate, as it is directly related with battery capacity, with relative errors between 1.1% and 0.3%. In contrast, FEC predictions deviate substantially from actual values, particularly at low FEC. Indeed, this parameter is harder to forecast because it is influenced by multiple variables such as usage patterns, operating conditions, manufacturing variability, or other factors.

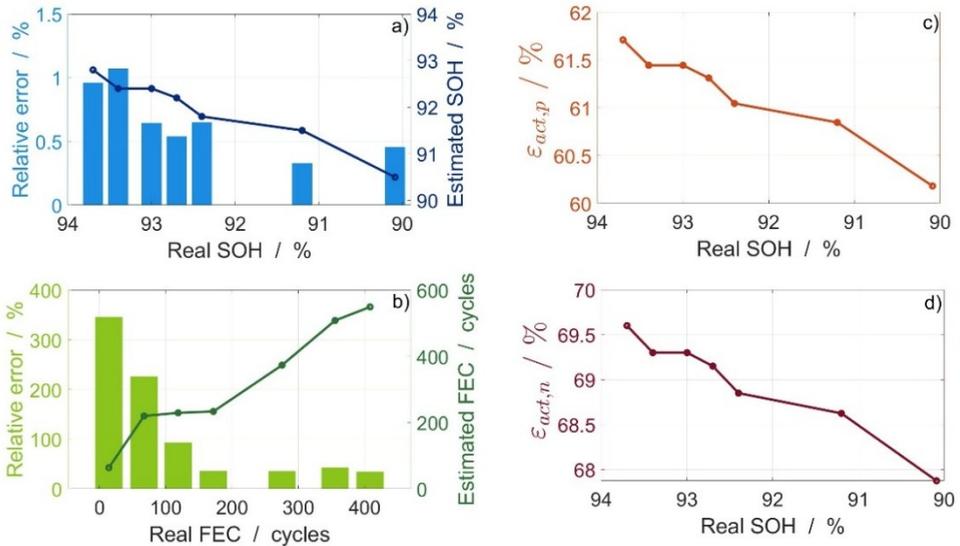


Figure 6: DDM results: a) and b) show the SOC and FEC estimates vs laboratory measurements, respectively, showing relative error (left y-axis) and estimated values (right y-axis). c) and d) show the active material volume fractions for the positive and negative electrodes, respectively.

The DDM also estimates $\varepsilon_{act,p}$ and $\varepsilon_{act,n}$, shown in **Figure 6 c)** and **d)**, both of which decrease uniformly with SOH.

Once this information is obtained, the HM proceeds to the second phase, estimating the future performance of the SLB under a LEV scenario.

The PBM forecasts performance by repeating the desired usage pattern, illustrated in Figure 5, which reaches its maximum depth of discharge between hours 16 and 17, corresponding to a total discharge of 3.9 Ah. Assuming the scooter is fully recharged after each use, the LG-M50, with a nominal capacity of 5 Ah, remains suitable for this second-life application until reaching 78% SOH. Based on this assumption, the PBM estimates the RUL at different SOH levels by modelling the SOH evolution for the case study. **Table 3** summarizes the HM results, indicating that the SLB would remain operational for 5.3 to 4.4 years, depending on the initial SOH of the LIB.

Table 3: RUL estimated by the PBM at different SOH initial states

SOH measured / %	RUL / years
93.7	5.3
93.4	5.2
93	5.2
92.7	5
92.4	4.8
91.2	4.7
90.1	4.4

6. CONCLUSIONS

This study demonstrates the potential of HMs that combine DDMs with PBMs to evaluate and forecast the performance of SLBs. A 24-hour scooter usage profile, measured under real-world operating conditions, was used to validate the model. The DDM achieved high SOH estimation accuracy, with deviations of 0.3–1.1% from experimental data. In contrast, FEC predictions showed larger errors, likely due to their higher sensitivity to prior usage, operating conditions, manufacturing variability, and the limited training dataset of only six cells. Differences in degradation patterns between the tested SLB cell and the training cells may also have contributed to the substantial deviation in FEC estimation.

The study also highlights the value of active material volume fraction as a key parameter for linking DDMs and PBMs. This parameter enhances degradation modelling, provides insight into electrode-level changes, and improves the adaptability of PBMs for already degraded batteries. PBMs proved useful for predicting future performance, including SOH evolution and RUL, relevant for LEV applications.

The reduced number of cells considered in this study may not capture the full range of degradation patterns or effects such as manufacturing variability, limiting the generalizability of the results. Future work will expand the dataset to include more LIBs with different usage histories, test the HM in more conditions and study how certain degradation mechanisms affect the $\varepsilon_{act,k}$ of each electrode. Overall, the proposed HM effectively integrates the strengths of DDMs and PBMs, offering a promising tool for promoting SLB use in sustainable energy storage systems while reducing testing time. Although demonstrated on NMC811 cells, the methodology is adaptable to other chemistries and applications, with practical value for research, industry, and areas like warranty design.

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Social life cycle assessment of battery electric vehicle following ISO 14075 standard

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EXTENDED ABSTRACT

Beginning with a meticulous examination of the social ramifications inherent in Battery Electric Vehicle (BEV) lifecycles, this study delves into the complexities of sustainable mobility from a social sustainability perspective. As global momentum shifts towards the decarbonisation of the transport sector, BEVs have emerged as a cornerstone of clean mobility strategies. However, while environmental and economic dimensions of BEVs are widely studied, the social impacts spanning labour rights, community well-being, and ethical governance remain less explored. This research seeks to bridge that gap through a comprehensive Social Life Cycle Assessment (S-LCA), following the ISO 14075 standard, offering a structured and systematic methodology to assess social performance across a vehicle's entire life cycle. The assessment is centred on a detailed case study of a German-manufactured Battery Electric Sport Utility Vehicle (SUV), chosen for its relevance to both European and global automotive markets. In addition to the case-specific investigation, the study incorporates an extensive literature review to contextualise findings within existing research and to identify persistent knowledge gaps. The S-LCA framework used is grounded in the UNEP-SETAC guidelines and enhanced through the use of OpenLCA software in combination with the Product Social Impact Life Cycle Assessment (PSILCA) database, a widely accepted tool and database for quantifying social risks across global supply chains. This integration facilitates both the modelling of life cycle stages and the identification of regional and sector-specific risk indicators, providing a robust basis for empirical evaluation.

The research systematically categorises social impacts across key stakeholder groups, namely Workers, Local Communities, Consumers, and Society at large. These categories align with internationally recognised standards and enable a holistic understanding of how various social dimensions interact with technical and supply chain processes. The scope of the assessment spans all phases of the product life cycle—from raw material extraction, material processing, and manufacturing, through distribution and vehicle use, to eventual disposal and recycling. This full-spectrum approach ensures that no phase is overlooked and that cumulative social burdens are appropriately accounted for. One of the primary contributions of this study is the development of a clear, reproducible procedure for conducting an S-LCA. The procedure includes goal and scope definition, inventory analysis, impact assessment, and result interpretation—each phase being tailored to capture social criteria specific to the BEV context. The inventory analysis stage identifies the material composition of the vehicle, supplier origins, and transportation logistics, while the impact assessment quantifies potential risks using PSILCA indicators such as child labour, gender wage gap, occupational hazards, and corruption indices. The interpretation phase consolidates these findings, contextualising them within the broader implications for sustainability policy and industry practice. Key findings from the assessment reveal significant social sustainability challenges in the upstream phases of the BEV supply chain, particularly during raw material extraction and manufacturing. Elements such as cobalt, lithium, and nickel critical for battery manufacturing are frequently sourced from regions marked by severe socio-political instability and weak regulatory frameworks. The study identifies high-risk zones, where forced and child labour are prevalent in mining and manufacturing operations. Similarly, other regions, where hazardous working conditions and gender-based wage disparities are commonly reported within resource-extractive sectors are also identified. These issues underscore the ethically problematic origins of many materials that underpin the clean mobility revolution. The analysis also reveals social risks during the operational phase of the BEV, particularly related to the electricity generation sector. In the German context, despite progressive energy policies, a significant share of electricity still originates from fossil-intensive sources imported or traded through countries with questionable governance records, including Poland, the Czech Republic, and Russia. The study highlights governance-related risks such as corruption, bribery, and anti-competitive behaviour within energy and utility sectors, which in turn influence the overall social footprint of BEV usage. Although the end-of-life and distribution stages of the BEV life cycle exhibit relatively lower overall social impacts, they are not devoid of concern. The interpretation phase of the S-LCA provides nuanced insights into risk variability under different

scenarios. For instance, increased medium-risk hours are observed in scenarios where the vehicle's material inputs originate from multiple countries with inconsistent social performance ratings. High-intensity usage patterns, such as frequent rapid charging and high-speed driving, were also associated with higher energy demands and thus greater exposure to the social risks embedded in electricity supply chains. These findings emphasise the dynamic nature of social impacts, which can vary significantly based on consumer behaviour, sourcing strategies, and geopolitical developments. Key recommendations include the implementation of supplier auditing systems, increased traceability through blockchain-based tracking technologies, and strengthened enforcement of social compliance through international trade agreements. The study also advocates for consumer-oriented policies such as social labelling schemes to promote ethical purchasing decisions. In conclusion, this research offers a critical contribution to the field of sustainable mobility by foregrounding the social dimensions of BEV production and usage. It presents a replicable S-LCA framework, validates it through a real-world case study, and draws attention to both high-risk zones and overlooked lifecycle phases. By doing so, it supports policymakers, manufacturers, and researchers in identifying priority areas for intervention. The findings reinforce the urgent need for coordinated global action to enhance labour protections, bolster governance mechanisms, and promote equity and justice in clean technology transitions. As the automotive industry pivots towards electrification, ensuring that this transition is not only environmentally sustainable but also socially responsible is imperative for long-term success.

Optimizing energy use in electric vehicles: A comparative study of optimization methods

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ABSTRACT

Electric and hybrid passenger vehicles offer the ability to recover braking energy and optimize power distribution, enabling significant improvements in efficiency compared to conventional vehicles. In this study, we quantify and compare the energy-saving potential of three optimization methods—mixed-integer linear programming (MILP), nonlinear programming (NLP), and dynamic programming (DP)—for a battery-electric vehicle following the Urban Dynamometer Driving Schedule (UDDS). A simplified longitudinal EV model with aerodynamic, rolling, and gravitational resistances is used to simulate vehicle dynamics, battery charging/discharging, and regenerative braking. The reference case enforces exact tracking of the UDDS speed profile, including late, hard braking at stops. Over a receding horizon of five seconds, MILP linearizes resistive forces and solves a linear program (≈ 16 ms per step), while NLP retains full nonlinear dynamics with a quadratic speed-deviation penalty (≈ 1.7 ms per step). DP serves as an offline global benchmark across a discretized state-of-charge and velocity grid. Results show that, relative to the baseline, NLP achieves the largest net-energy reduction (31.1 %), followed by DP (23.5 %) and MILP (18.2 %). NLP's ability to model exact aerodynamic drag and smoothly coast into stops yields the highest savings but requires more computational effort. MILP offers a compromise between efficiency and real-time feasibility on automotive ECUs, although its hard speed bounds induce oscillatory speed errors. DP, while globally optimal under exact speed tracking, is best suited as an offline reference. These findings suggest that hybrid approaches—such as DP-trained lookup tables or variable-efficiency NLP surrogates—could approach global optimality while meeting real-time constraints. Future work will validate these methods on

additional driving cycles and incorporate variable motor/regenerative efficiency maps to better align with real-world performance.

1. INTRODUCTION

Electric and hybrid passenger vehicles have spurred extensive research into strategies for minimizing energy consumption, motivated by environmental goals and the need to extend electric driving range (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). Unlike conventional vehicles, EVs and HEVs offer new degrees of freedom such as regenerative braking and power split between engine and motor that can be optimized to improve efficiency. Researchers have explored various control and optimization approaches to reduce energy usage by adjusting driving speed, power distribution between power sources, regenerative braking intensity, and even gear selection in multi-gear transmissions. Recent studies range from global optimization methods that assume complete knowledge of the driving cycle, to real-time strategies embedded in vehicle controllers.

1.1 RECENT DEVELOPMENTS IN VEHICLE ENERGY OPTIMIZATION

In the past decade, energy management strategies for EVs and HEVs have rapidly advanced, moving beyond simple rule-based heuristics to more sophisticated optimization-based and learningbased techniques (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). A broad trend is the pursuit of global optimality in energy use: many researchers formulate the problem as an optimal control or optimization task over a driving cycle or route. For example, dynamic programming (DP) has been used to compute the theoretical minimum energy or fuel consumption requirement for a predetermined trip. Such globally optimal solutions, while computationally intensive, serve as benchmarks to evaluate other strategies (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). Other recent works employ mathematical programming formulations, including linear and nonlinear programming, to handle the HEV power split problem or EV speed profile optimization with high fidelity models (Braghin, Robuschi, Sager, Cheli, & Zeile, 2019) (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). There is also growing interest in predictive and connected vehicle strategies: using lookahead information (from GPS or V2X communication) about road grade, traffic, and route to improve efficiency. Studies show that incorporating upcoming road slope data into

energy management can yield measurable fuel or energy savings. For instance, (Zhang, Pisu, Li, Tennant, & Vahidi, 2010) demonstrated that pre-viewing terrain elevations enables a hybrid vehicle to save additional fuel, with the benefit depending on speed and road profile. Overall, recent developments emphasize integration of vehicle data and advanced algorithms to push energy efficiency closer to its theoretical optimum under real driving conditions (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). However, each approach comes with practical trade-offs, leading researchers to investigate a spectrum of methods.

1.2 SIGNIFICANCE OF BENCHMARKING MULTIPLE METHODS

Given the variety of optimization approaches, systematic benchmarking under consistent conditions is crucial. Direct comparisons of MIP, NLP and DP can illuminate trade-offs between optimality, computational cost, and robustness, helping practitioners select the most suitable methods. Benchmarking across varied driving scenarios; urban, highway and hilly would provide deeper insights into method-specific strengths and weaknesses (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). Furthermore, combining methods within hybrid control architectures could unlock near-optimal real-time strategies by balancing global planning and fast local decision-making. A study that unifies and evaluates these approaches would address a major research gap and offer practical guidance for next-generation energy management systems.

1.3 OPEN CHALLENGES AND RESEARCH GAPS

Despite substantial progress, several open challenges remain in the quest for optimal vehicle energy management. Dynamic programming and fully non-linear MPC remain too slow for production ECUs; customised solvers must deliver sub-second runtimes in all conditions for real-time feasibility. Strategies tuned to specific cycles degrade when driver behaviour, weather, or component ageing diverge from assumptions; stochastic and RL-based schemes help but still lack reliable on-road calibration. Hybrids such as DP-trained neural policies or metaheuristic-tuned ECMS are promising yet largely unexplored. Furthermore, multi-objective considerations such as battery longevity, emissions, and thermal limits increasingly matter, but few energy-management systems handle such trade-offs online. Finally, most studies remain

simulation-only; systematic hardware-in-the-loop and public road campaigns are still scarce.

This study aims to quantify and compare the energy-saving potential of three optimization approaches - mixed-integer linear programming (MILP), non-linear programming (NLP) and dynamic programming (DP) - when applied to a standard passenger vehicle driven over the Urban Dynamometer Driving Schedule (UDDS).

2. CONTROL OPTIMIZATION METHODS

To minimize energy consumption, a variety of optimization techniques have been applied in prior studies. These include Mixed-Integer Programming, Nonlinear Programming, Dynamic Programming, and metaheuristic algorithms. In this section the focus is on how each method has been used and its suitability for real-time embedded implementation.

Mixed-Integer Programming (MIP) formulates discrete choices as integer variables and linearises the remaining drivetrain dynamics. The resulting Mixed Integer Linear Program (MILP) can be solved fast enough for short-horizon supervisory Model Predictive Control (MPC) on modern embedded CPUs (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). According to that review, Yamanaka et al. (2022) demonstrated an online MILP power-split controller for connected HEVs, and Robuschi et al. (2020) reported fuel savings using iterative linear programming. The strengths of MIP in this context are exact treatment of discrete decisions and guaranteed convergence to the MILP optimum. Limitations include linearisation errors and rapidly increasing solve time as the time grid or integer count is refined (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025).

Nonlinear Programming (NLP) keeps the full non-linear problem, capturing aerodynamic drag, battery losses and engine maps without requiring linearisation. The well-known Pontryagin-based ECMS converts electric energy to an equivalent fuel cost and reaches $\approx 95\%$ of the DP optimum when its equivalence factor is adapted online (Zhu, Wu, & Xu, 2020). Direct transcription NLP is typically run offline; when real-time is required researchers pre-compute speed and torque trajectories or convexify the model for rapid MPC (Burtchen, Maurer, & Pickenhain, 2016). The strengths of NLP lie in its high model fidelity and transparent inclusion of complex constraints. It is limited by heavy computational load where full real-time NLP remains difficult on production ECUs (GómezBarroso, Vicente Makazaga, & Zulueta, 2025).

Dynamic Programming (DP) provides the global minimum energy for a fully known drive cycle and is therefore the gold-standard benchmark (Gómez-Barroso, Vicente Makazaga, & Zulueta, 2025). Its weaknesses are the curse of dimensionality and the need for full-cycle preview. Practical spin-offs include stochastic DP policies, DP-derived lookup tables and neural or reinforcement-learning surrogates trained on DP data that deliver millisecond decisions (Fan, o.a., 2024).

3. MATHEMATICAL FORMULATIONS

Section 3.1 describes our discrete-time longitudinal EV model, which captures aerodynamic, rolling and gravitational forces along with battery charge/discharge and regenerative braking. Sections 3.2–3.4 then present the optimisation formulations -receding-horizon MILP, direct-shooting NLP, and global-benchmark DP (with SoC and speed discretisation) used to compute energy-efficient speed trajectories.

3.1 DYNAMICS AND ENERGY MODEL

The energy model is based on the state and control variables presented in Table 1, together with the vehicles’ physical parameters given in Table 2. Values used in the simulation are also given in the tables.

Table 1: State and control variables.

Symbol	Definition
v_k	Vehicle speed at time step k [m/s]
θ_k	Road slope angle at step k [rad]
SoC_k	Battery state of charge at step k [0-1]
	Regenerative braking efficiency [-]
	Motor efficiency 0.9 [-]
F_k	Applied traction force during $[k, k + 1]$ [N]
$F_{res}(v_k, \theta_k)$	Total resistive force [N]
P_{wheel}	Mechanical power at the wheels [W]

Table 2: Physical parameters.

Symbol	Description	Value
m	Vehicle mass [kg]	1610 kg
g	Gravitational acceleration [m/s ²]	9.81 [m/s ²]
ρ	Air density [kg/m ³]	1.225 [kg/m ³]
A	Frontal area [m ²]	2.22 [m ²]
C _d	Aerodynamic drag coefficient	0.23
C _r	Rolling resistance coefficient	0.012
Q	Battery capacity [kWh]	60 [kWh]
Δ	Regenerative deadband threshold	300 [W]

The driving force is modeled as the sum of the forces to overcome aerodynamic drag, rolling resistance and climbing resistance

$$F_{res}(v_k, \theta_k) = \frac{1}{2} \rho A C_d v_k^2 + mg C_r \cos(\theta_k) + mg \sin(\theta_k) \quad (1)$$

The battery power at step k is computed as

$$P_{bat,k} = \begin{cases} \frac{P_{wheel,k}}{\eta_{mot}} & P_{wheel,k} \geq 0 \\ 0 & P_{wheel,k} < 0, |P_{wheel,k}| \leq \Delta P_{db} \\ P_{wheel,k} \eta_{regen}(v_k) & P_{wheel,k} < -\Delta P_{db} \end{cases} \quad (2)$$

Where η_{regen} depends on speed. With discrete time steps $\Delta t = 1s$ the vehicle dynamics and battery State-of-Charge are modeled as:

$$v_{k+1} = v_k + \Delta t \frac{F_k - F_{res}(v_k)}{m_{eff}}, \quad SoC_{k+1} = SoC_k - \frac{P_{bat,k} \Delta t}{Q} \quad (3)$$

The rotational inertia of wheels and drivetrain is modeled as an equivalent mass applied only m_{eff} in the inertial term, ensuring correct accounting of acceleration/deceleration energies.

3.2 BASELINE PROBLEM

The reference solution is given by accurately following reference speed $v_k^* \Rightarrow F_k$ given by (2).

Net energy is

$$E_{ctrl} = \sum_{k=0}^{N-1} \max(P_{bat,k}, 0) \Delta t \quad (4)$$

3.3 MILP

For a rolling window $H = 5$ steps the resistance forces are linearised around v_{k+1}^* and the following Mixed-Integer Linear Program is solved:

$$\begin{aligned} \min_{F_{0:H-1}} \quad & \sum_{i=0}^{H-1} (\hat{\alpha}_i F_i + \hat{\beta}_i) \Delta t \\ \text{s. t.} \quad & v_{i+1} = v_i + \frac{\Delta t}{m_{eff}} (F_i - \hat{F}_{res,i}) \\ & |v_{i+1} - v_{k+i+1}^*| \leq 0.5 \\ & -F_{max} \leq F_i \leq F_{max} \end{aligned} \quad (5)$$

Where $\hat{\alpha}_i, \hat{\beta}_i$ are linearisation coefficients, integer variables enforce a three-way disjunction (motoring/deadband/regeneration), and regenerative efficiency η_{regen} is represented by an SOS2 piecewise-linear approximation.

3.4 NLP

By a single shooting method, the following non-linear program is solved explicitly:

$$\min_{F_0:H-1} \sum_{i=0}^{H-1} \left[\max(P_{bat,i}, 0) \frac{\Delta t}{3600} + w_v (v_{i+1} - v_{k+i+1}^*)^2 \right] \quad (6)$$

With box-bounds $|F_i| \leq F_{max}$. The weight parameter d_e is chosen to achieve an acceptable speed error compared to reference.

3.5 DP

The State of Charge is discretized in M grid points s_j . Transform from SoC index j to \hat{j} at step k is given by (1):

$$\hat{j} = \text{round} \left(j - \frac{P_{bat,k} \Delta t}{Q \Delta s} \right) \quad (7)$$

And at each timestep k we discretize the vehicle speed in L evenly spaced values with $\pm \Delta v$ around the reference speed. The cost is:

$$\ell_k(j, \hat{j}) = \max(P_{bat,k}, 0) \frac{\Delta t}{3600} + w_v (v_j - v_{ref}[k+1])^2 \quad (8)$$

Where $J_k(j)$ the minimal cumulative cost to reach SoC state j at time k forming a sequence. Bellman-recursion is then used to optimize this sequence:

$$J_{k+1}(j) = \min_{\hat{j}} (J_k(j) + \ell_k(j, \hat{j})) \quad (9)$$

Backtracking gives global minimal positive battery energy $E_{DP} = J_n(j_N)$ as well as optimal $SoC^*(k)$.

4. RESULT

This section presents a comparison between the baseline (reference) scenario and the three optimization methods: MILP, NLP, and DP. Table 3 summarizes key energy metrics such as traction energy, recovered regenerative energy, net battery usage, and average energy consumption.

Table 4 shows the absolute and percentage-based energy savings compared to the reference. The NLP method demonstrates the greatest reduction in both net energy consumption and average consumption per kilometer, followed by MILP and DP.

Figure 1 provides a visual comparison of speed and battery state-of-charge (SoC) profiles over time.

Table 3: Energy and consumption results.

	Reference	MILP	NLP	DP
Traction energy [Wh]	2142.8	1713.5	1955.2	1799.0
Regen recovered [Wh]	362.3	254.2	730.7	439.8
Net battery energy [Wh]	1780.5	1459.3	1224.5	1359.3
Average consumption [Wh/km]	148.5	121.5	102.3	113.7

Table 4: Energy savings compared to reference

	Δ Net energy [Wh]	Δ Consumption [Wh/km]	Savings [%]
MILP	-321.2	-27.0	18.2
NLP	-556.0	-46.2	31.1
DP	-421.2	-34.8	23.5

5. DISCUSSION

NLP delivers the largest percentage savings because it retains the full nonlinear physics (aerodynamic drag, battery losses, motor efficiency maps) without linearisation. This allows it to exploit every opportunity for energy recuperation and efficient acceleration more fully than the MILP approach.

The residual velocity plot in figure (1) highlights a characteristic behaviour of the MILP method, where the optimal solution frequently oscillates within the acceptable speed deviation. This is a direct consequence of how the MILP problem is constructed where the deviation constraint $|v_k - v_k^*| \leq 0.5$ m/s is implemented as a hard bound. As long as the solution remains within this constraint all speeds are equally “free” from a cost perspective. The MILP solver exploits this flexibility, allowing the speeds to alternate between upper and lower bound to achieve a lower net energy. A proposed possible solution to this is implementing a cost in the objective function.

Although DP is globally optimal by design, in our implementation it is limited by the grid size and only small speed deviations allowed. The speed tracking penalty imposed on the cost function is a function of w_v , which was chosen to 4. This specific value was chosen arbitrarily to allow slight deviation from the reference speed. This parameter depends on the driving cycle and cannot be arbitrarily chosen to fit all cycles. The DP algorithm was also limited by a hard speed constraint of 1 m/s, this was done partly to speed up computation and to limit the solvers’ ability to stray too far away from the reference speed. This limits its real-world energy benefits compared to NLP and the receding-horizon MILP. In practice, relaxing the hard speed constraint or increasing the SoC and velocity grid size could recapture some of DP’s “lost” potential.

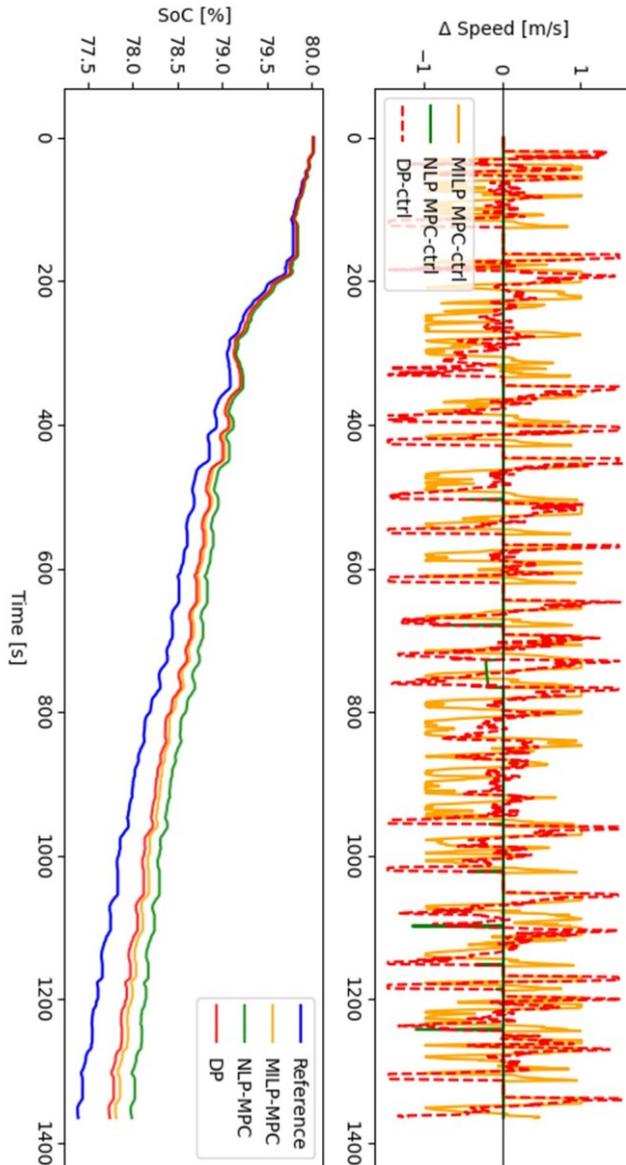


Figure 1: Time series comparing the reference case with each optimization method

Nonlinear programming (NLP) delivered the largest percentage savings (31.1 %) by retaining the full nonlinear physics (aerodynamic drag, battery losses, etc.) and yet each receding-horizon solve took only around 1.7 ms. Mixed-

integer linear programming (MILP) achieved 18.2 % savings but required roughly 16 ms, per 1 s window placing it on the upper edge of a typical automotive ECU budget (10-20 ms for a 1 Hz loop). Dynamic programming (DP), at 2788 seconds total, remains strictly an offline benchmark in line with the NLP and MILP results.

The simpler MILP scheme requires less maintenance and validation, whereas full NLP demands high-fidelity models and very stable solvers, which can be harder to certify in automotive applications where parameters can change quickly.

The Battery model is limited by the assumption that the parameters are constant, in reality these vary with battery age and temperature. If this is proven to be a substantial source of error the NLP method could be built upon with a non-linear function of, while MILP would require further linearisation of these parameters. η_{regen} was expanded into a small efficiency map dependent on vehicle speed which improved performance but was limited in scale.

Other studies such as (Hamednia, Sharma, Murgovski, & Fredriksson, 2022) have reported savings of 15.7% for a mixed route when an SQP-NLP based method is applied on an electric vehicle. Efficiencies of regenerative braking and engine were modeled using nonlinear functions of motor speed and torque. The difference in savings is likely due to the reference simulation exactly following the UDDS speed profile exactly. This results in braking as late and as hard as possible at every stop, which maximizes regenerative torque. In contrast the optimized strategies tend to coast more, regenerating less peak energy. As a result, the percentage reduction of the optimized methods artificially inflate.

Results are tied to the UDDS drive cycle. Savings might shift in stop-and-go city traffic, highway cruising, or hilly terrain. It is therefore recommended that the models are validated and compared on different cycles.

Future work should include validation of these methods on stop-and-go urban cycles such as the WLTC city segment, High-speed freeway cycles such as LA-92 and hilly terrain where grade preview is critical. Incorporation of variable efficiency maps for η_{regen}, η_{mot} could better position savings results against published literature. Finally exploring hybrid strategies such as DP-trained lookup tables and machine-learning surrogates could reveal whether a mixed-method approach can capture most of the offline optimality while still running in real time.

6. CONCLUSION

This study set out to compare three optimisation approaches: MILP, NLP, and DP on the UDDS cycle. We found that NLP achieved the greatest net energy savings (31.1 %), MILP delivered near-real-time performance with 18.2 % savings, and DP at 23.5 %.

For applications demanding strict real-time operation, MILP-based MPC is already feasible on modern ECUs. However, systems seeking maximum efficiency should consider hybrid or full NLP strategies as computational power grows.

Future work should integrate predictive data (e.g. V2X information) and broader set of driving conditions. As well as developing hybrid control schemes that combine each method's strengths which could yield both real-time capability and near-optimal efficiency. Balancing optimization accuracy against real-time feasibility is critical for the sustainable deployment of future electric and hybrid vehicles.

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Data-driven prediction of the viability of remanufacturing for heavy-duty vehicle components

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ABSTRACT

The production of a heavy-duty road vehicle is a major contributor to the overall financial cost and environmental impact of the vehicle. In recent times, closing the material loops using circular practices has emerged as a promising approach to reduce the environmental impact of the vehicle production. The most common circular practice is material recycling, however, it is a low-value process, as any embodied value in the product apart from the material refinement is lost. In addition the recycling process might be cumbersome if the product is composed of multiple materials that cannot be easily separated. A promising approach to circularity is remanufacturing where a product is disassembled and the constituent components are cleaned and inspected. The components which pass the inspection are then reused in new products, while maintaining quality and warranty equal to new products. This preserves the value in the reused products and not only reduces the consumption of raw materials, but also manufacturing effort. In order for the remanufacturing process to be worthwhile, some conditions need to be satisfied. Firstly, the product needs to be valuable enough for the remanufacturing effort to make economic sense. Secondly, the state of a product that is returned from a customer must be able to be ascertained with a certain degree of confidence in a quick manner. One way to evaluate the state of a returned product

is by using the historical usage data of the vehicle it comes from. The goal of the work presented here is to study the feasibility of remanufacturing for different heavy-duty road vehicle components based on the economic benefits as well as the availability of data for the component in question, as well as identifying the relevant data for evaluating its remanufacturability. The economic feasibility is evaluated by considering the purchase price of the component compared to the costs and cost savings associated with the remanufacturing process. Criteria for the available data, meanwhile, are formulated based on four publicly available datasets that are used in the prognostics literature.

1. INTRODUCTION

As issues of sustainability become ever more prevalent in the contemporary political debate, so does the need for resource efficient manufacturing practices. While this could mean manufacturing practices similar to the traditional ones but simply more efficient, there is another, completely different way of viewing manufacturing and resource consumption, that being the circular economy.

In a traditional, linear manufacturing scheme, virgin material is extracted, processed and converted to finished goods in the manufacturing process. After a product has reached its End Of Life (EOL), the product is discarded and thrown away (Potting, Hekkert, Worell, & Hanemaaijer, 2016).

In a circular economy, a product that has reached its EOL is instead fed back into the economy, preserving not only the materials used to manufacture the product, but also some of the value embodied in the product through the manufacturing process. There are a number of possible strategies that can be implemented in order to achieve a more circular resource flow, these are referred to as circular strategies. Out of these strategies, recycling is arguably the most famous and most widely adopted. However, it is very low in the hierarchy of circular strategies, as only the value of the processed materials is recovered, and the recycled material has to be put through a new manufacturing process to be turned into new products (Potting, Hekkert, Worell, & Hanemaaijer, 2016). In (Potting, Hekkert, Worell, & Hanemaaijer, 2016), ten different strategies are identified. These are known as R-strategies and consist of, in order of decreasing circularity: Refuse, Rethink, Reduce, Re-use, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. The focus of the work presented in this paper is on the strategy remanufacturing. Before proceeding, however, it would be prudent to more precisely define what is

actually meant by remanufacturing, as multiple definitions appear in the literature.

In (Potting, Hekkert, Worell, & Hanemaaijer, 2016), remanufacturing is defined as the use of components from a discarded product in a new product with the same function. However, the use of the word *remanufacturing* is used in a variety of contexts in the literature.

A common definition of remanufacturing is that the remanufactured product should be returned to a “as good as new” condition and be covered by the same warranties as a new product (Du, Cao, Liu, Li, & Chen, 2012), (Zhang, et al., 2022) and (Jensen, Prendeville, Bocken, & Peck, 2019). In (Kerin, Hartono, & Pham, 2023) remanufacturing is used to describe the entire process that follows the decision to actually recover an EOL product. This includes a number of possible decisions regarding what happens to the product. One of these options is called *reincarnation*, and means that components that are of good quality in the EOL product are salvaged after disassembly and combined with new, purchased components in new products. This is basically the same as remanufacturing as defined in (Potting, Hekkert, Worell, & Hanemaaijer, 2016). Other possible strategies are *reuse* (direct resell of components to the second-hand component market) and recycling.

It might be assumed “remanufacturing” involves some type of more advanced repair techniques. This is also present in parts of the literature, where remanufacturing is used to describe the process where a EOL product with actual damage is repaired and can be put back into service. This is described using the term *value added treatment*. Examples of this are found in (Qin, Yang, Huang, Xu, & Liu, 2015), where scratched hydraulic cylinder bores are repaired using honing, in (Lei, Huajun, Hailong, & Yubo, 2017) where laser cladding is used to return material to damaged impeller blades, and (Wilson, Piya, Shin, Zhao, & Ramani, 2014), where laser deposition is used to repair damaged turbine blades. This type of treatment is considered out of scope for the presented work.

The work in this paper focuses on remanufacturing in the sense that components from EOL products that are of satisfactory quality are salvaged and can be used in conjunction with new components in new products.

The process of remanufacturing then consists of returned EOL products, also known as *cores*, being disassembled, the components cleaned and inspected, and the components that pass the inspection being returned to the manufacturing pipeline and the other components being recycled (Kroner, Luo, & Bertsche, 2020).

One large problem with the current remanufacturing practice is that the quality of the returned cores can vary significantly, and it is only at the final inspection step that the actual quality of the components can be ascertained. This means that products of low quality will go through the cumbersome and costly disassembly and cleaning phases, despite providing little to no value at the end of the process (Kroner, Luo, & Bertsche, 2020).

A possible way to reduce the uncertainty is to pre-screen the returned components and evaluate their condition before making the decision whether they should be put through the remanufacturing process, with the intention of sorting out the cores that are likely to be of low quality (Kroner, Luo, & Bertsche, 2020). This pre-screening could be done based on the recorded diagnostic and usage data of the product. Developing such a decision-making tool is not a trivial problem, though, and would have to be done for every type of product individually. This means that in order for the industry to embrace such a decision-making tool, the economic gain from the remanufacturing process has to be great and the pre-screening has to be technically feasible and practical to perform. Here, technical feasibility means that there exist sufficient data on the core in order to evaluate its state when it is returned.

This is the main focus of the presented work. The goal is to establish the foundations of a framework for evaluating the economic benefits and data availability in order to decide what whether to develop a remanufacturing decision-making tool for a certain product. The economic benefits are evaluated by comparing the cost of a new product with the remanufacturing cost, whereafter the remanufacturing cost is broken down into its different components. The data availability is treated by going through four publicly available product datasets that are featured in the prognostics literature and comparing their similarities to establish common features.

The paper is structured as follows: Section 2 first deals with the economic evaluation criteria, followed by what data needs to be available for a successful product state evaluation. Section 3 then discusses the results and concludes the paper.

2. PRODUCT EVALUATION

2.1 ECONOMIC FEASIBILITY

In order for the remanufacturing of a product to be economically feasible, there has to be sufficient cost savings to warrant the remanufacturing process.

Approaching the problem from a component perspective, the net gain of replacing a new component with a recovered one can be formulated as

$$P_i = C_{p,i} - C_{r,i}, \tag{1}$$

where P_i is the profit associated with replacing component i (an index) and $C_{p,i}$ and $C_{r,i}$ are the costs associated with purchasing a new component (or manufacturing a new one) and recovering an old component from a core, respectively. The recovery cost can be further broken down into the costs of the different steps of the manufacturing process. In (Jiang, Wang, Zhang, Mendis, & Sutherland, 2019) the recovery cost is broken down into cost for disassembly, value recovery (cleaning and inspection in this case) and reassembly. The contribution from reassembly can be ignored, as the new product is assumed to have the same assembly procedure, and therefore cost, independently of the amount of recovered components present. The recovery cost can then be formulated as,

$$C_{r,i} = C_{D,i} + C_{C,i} + C_{I,i}, \tag{2}$$

where $C_{D,i}$, $C_{C,i}$ and $C_{I,i}$ are the disassembly, cleaning and inspection costs, respectively.

Since the goal is to evaluate the profitability on a product basis, the profit is calculated on a product basis by summing the contributions from each component in the product,

$$P = \sum_{i \in I}^N C_{p,i} - \sum_{i=1} C_{r,i}, \tag{3}$$

Where N is the total number of components in the product and I is an index set of the components that pass the inspection. The reason that the purchasing price is not summed over all components is that only the components that pass the inspection can replace new components in the new product.

Sometimes the remanufacturing company incentivizes customers to return cores through buyback schemes, thus a third term can be added to Eq. (3), the core buy-back price C_B ,

$$P = \sum_{i \in I} C_{p,i} - \sum_{i=1} C_{r,i} - C_B. \quad (4)$$

In Eq. (4) it is already seen how the quality of the returned core affects the profit from the remanufacturing process. The second sum and the third term are constant, as all components go through the remanufacturing steps up to and including inspection and the buy-back price is constant. In contrast, only the components that pass the inspection contribute to the first term. Inserting Eq. (2) into Eq. (4) yields,

$$P = \sum_{i \in I} \sum_{i=1}^N C_{p,i} - \sum_{i=1} (C_{D,i} + C_{C,i} + C_{I,i}) - C_B. \quad (4)$$

Although simple, Eq. (4) gives some indication of the desired properties of the product. Ignoring questions regarding the core quality, the first sum is maximized when the individual component purchasing prices are as large as possible.

The second sum is minimized when the product disassembly cost and component cleaning and inspection costs are low. This means that the product should be easy to disassemble and the individual components should be easy to clean and inspect.

Finally, in order to keep the buy-back price low, the core itself should have a low value on the second-hand market in order to incentivize the customer to sell it back to the OEM instead of selling it on the second-hand market.

There are other possible costs associated with, for example, recycling the discarded components. Modelling these costs are outside of the scope of the presented would have to be done in a more comprehensive study that takes into account multiple different R-strategies. The same holds for the assessment of the environmental impacts and the circularity performance of the remanufacturing process. While such assessments would complement economic feasibility with a measure for environmental and resource efficiency, they would require more detailed, process-specific data and would, in most cases, be conducted at a later stage of the decision-making framework.

2.2 TECHNICAL FEASIBILITY

PROGNOSTICS

As is mentioned in the introduction, the ultimate goal of the research is to create a decision-making model that can make the decision about whether or not to recover a core based on the quality of the core, as estimated using data about the vehicle and its usage history. While there are many possible metrics for evaluating the quality, in the literature on remanufacturing it is common to use the residual useful life (RUL) or the reliability of the product as a measure of the overall quality (Psarommatis & May, 2025). It is common to define some type of condition on the RUL or reliability and the product is declared fit for remanufacturing if the condition is satisfied. In (Hu, Liu, Lu, & Zhang, 2014) and (Zhang, et al., 2022), the reliability is used as a measure of when to remanufacture roller bearings. Similarly, in (Chen, Wang, Zhang, Zhang, & Dan, 2019) the reliability is used to determine the optimal remanufacturing point of engine blades. In (Hu, Liu, & Zhang, Remanufacturing decision based on RUL assessment, 2015), the reliability of a fictional product with a crack is used to determine when the product should be remanufactured.

The estimation of RUL of a product is a field known as prognostics and has two main branches, model/physics based and data-driven (Kim, An, & Choi, Introduction, 2017). In model-based prognostics, the degradation process modelled using a mathematical model, and the prognostic process then becomes about fitting the model parameters based on the data recorded from the product during usage, usually through a Bayesian filter, such as a particle filter. An example of such a model is the Paris-Erdogan law for crack propagation (Kim, An, & Choi, Tutorials for Prognostics, 2017).

In data-driven prognostics, there is no model for the degradation, instead a large amount of recorded data from the product is used to find patterns relating to the state of the product (Kim, An, & Choi, Introduction, 2017). Tools from the field of machine learning can be used to unearth patterns between the data and the degradation state (Kim, An, & Choi, Introduction, 2017).

The work presented here will exclusively focus on data-driven prognostics. The reason for this is that developing a model of the degradation is too difficult for an assembled product with multiple possible failure modes and very complex behaviour. Data-driven methods, on the other hand, only requires large amounts of sensor and usage data from the product, which is often collected by vehicle OEMs.

Given that the goal of the presented work is to evaluate what data is needed in order to successfully construct prognostic tools, the focus of this section will be on the datasets that are used in the literature, rather than the methods used.

Four publicly available datasets have been chosen to illustrate the required properties of recorded data. These four are the NASA battery dataset (Saha & Goebel, 2007), the FEMTO bearing dataset (FEMTO Bearing Data Set, 2012), the Scania Component X dataset (Kharazian, Lindgren, Mangússon, Steinert, & Andersson Reyna, 2025) and the SCADA wind turbine dataset (Wind turbine scada signals 2016, n.d.).

The NASA battery dataset is a dataset developed by subjecting lithium-ion batteries to accelerated aging experiments. The batteries were repeatedly charged and discharged under different conditions and the current, voltage and temperature was measured during each cycle and the battery capacity was measured after each cycle. Similarly, the FEMTO dataset is developed by subjecting ball bearings to accelerated aging in a laboratory environment. An experimental setup was built and the bearing housings were equipped with vertical and horizontal accelerometers and a temperature sensor. The bearings were then spun with a certain angular velocity and under a certain load until the acceleration magnitude reached 20 g (g being the gravitational acceleration).

Other datasets come from recorded industry data. The Scania Component X dataset is based on recorded operational data and repair records for a number of Scania heavy-duty road vehicles. The component itself is an unknown engine component and all of the data has been normalized and the data types have been erased to protect proprietary information.

Another industrial dataset is the SCADA dataset for wind turbines. SCADA is short for Supervisory Control and Data Acquisition and is a system for monitoring industrial processes, but this particular dataset is one recorded from offshore wind turbines (Zhang, Vatn, & Rasheed, 2025). It contains about 80 recorded features, ranging from temperatures of different components, rpm of different components and ambient environmental conditions.

In the NASA dataset, the degradation is defined as the decrease in capacity of the batteries, and failure is often defined as the time when the capacity decreases below a threshold value, usually between 70-80% of the original capacity. Examples of prognostics on this dataset in the literature are (Ma, et al., 2019), (Zhang, Li, & Li, 2020) and (Zhang, et al., 2019). In (Ma, et al., 2019) and (Zhang, Li, & Li, 2020), neural networks (NN) are used to predict the

future degradation based on past degradation. The process is illustrated in Figure 1, which shows the degradation of one of the batteries in the dataset. The dots show the measured data and the crosses show the results of a convolutional neural network (CNN) trained to predict the degradation in capacity. The process will be explained in slightly more detail for clarity.

The green dots in Figure 1 show the training data that is used to train the CNN, this data forms a vector $x = (x(1), x(2), \dots, x(n))$, where $x(i)$ is the capacity measured after load cycle i and n is the number of training data points. Now an embedding dimension $d \in \mathbb{N}$ is chosen and the data is arranged in the following way:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \dots \\ X_{n-d} \end{bmatrix}, X_i = (x(i), x(i+1), \dots, x(i+d-1)) \quad (5)$$

$$Y = \begin{bmatrix} x(d+1) \\ x(d+2) \\ \dots \\ x(n) \end{bmatrix}. \quad (6)$$

Each row in the matrix X is a window sequence of length d from x and the corresponding element in Y is the element from x that immediately follows the sequence. The CNN is trained to predict the elements of Y using the rows of X as input. The results can be seen in Figure 1 as the blue crosses.

Once the model is trained the future capacity is predicted by inputting the last d elements of x into the CNN, thus predicting the capacity one cycle into the future from known data. The prediction can then be fed back into the CNN by including it in the input sequence, thus predicting the capacity 2 cycles into the future. This process is repeated until the predicted capacity reached the threshold. The predicted future capacity can be seen as the black crosses in Figure 1, while the red dots show the actual capacity. For this particular model, d was selected to be equal to 11.

This method is known as 1-step ahead prediction and is what is done in (Ma, et al., 2019), although with a different NN architecture. In (Zhang, Li, & Li, 2020) a similar approach was used, but one that allowed for prediction multiple cycles ahead.

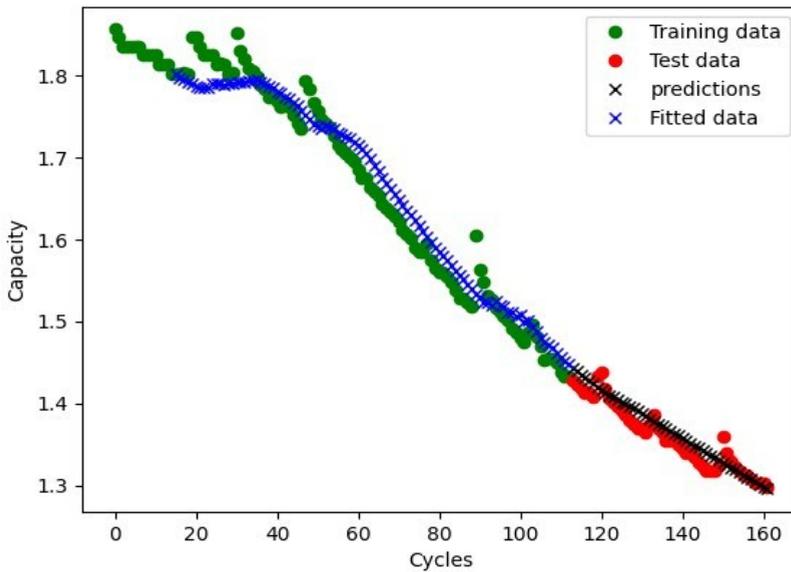


Figure 1. Predicted degradation of battery capacity.

These methods assume that the degradation can be directly and easily measured and that failure can be simply defined using the degradation. This is not always the case and sometime the degradation has to be estimated from other data. Staying with the NASA dataset, in (Zhang, et al., 2019), features extracted from the voltage and current measured during discharging are used to estimate the capacity and RUL indirectly using a neural network.

For the bearing dataset, failure was defined as the point when the acceleration reached 20 g. The research that uses this dataset focuses on extracting features from the vibration data that show clear increasing or decreasing behaviour with regards to RUL. In (Kim, An, & Choi, Applications of prognostics, 2017), the entropy for certain frequencies in the acceleration spectrum was used to estimate the RUL. The frequencies were selected so that the entropy decreased with increasing number of load cycles, as this behaviour was similar for all bearings, despite wildly varying RUL.

In (Zhang, et al., 2022), different features from the vibration signal, both time and frequency features, were used to estimate the reliability of the bearings, with focus being put on determining the best time to remanufacture the machine containing the bearings.

In contrast, the wind turbine dataset contains the operational data of four different wind turbines, as well as the logs when certain events occurred. This also means that failure is not defined by any of the recorded features and the relationship between the signals and the failure has to be learnt by the model. In (Zhang, Vatn, & Rasheed, 2025), a normal behaviour modelling (NBM) approach is used. NBM is based on the concept of defining a normal state when the product is healthy and then using the deviation from this normal state to define how close the system is to failure. A regression model was trained to estimate the temperature at different parts of the wind turbine based on other recorded features, such as rpm. The model was trained on data recorded a long time before failure occurred. This means the model will accurately estimate the temperature when the system is far from failure. As the wind turbine degrades, the relationship between the temperature and other parameters changes, which means that the regression model performs worse. The difference between the result of the regression model and the actual temperature could then be used to estimate the level of degradation.

Finally, the Scania Component X dataset contains operational readouts for 14 different features in time as well as the time that the unknown was replaced (if it was). In (Zhong & Wang, 2024), (Parton, Fois, Veglió, Metta, & Gregnanin, 2024) and (Carpentier, De Temmerman, & Verbeke, 2024), different machine learning algorithms were used to predict the RUL of the component as part of a challenge. For this dataset, the degradation is not directly known, in fact, due to the anonymization of data, not even the types of data collected are known, so the problem of identifying features that relate to failure have to be learnt purely from data, as knowledge about the product and data is non-existent.

3. DISCUSSION AND CONCLUSIONS

Based on the four datasets presented and the literature examples using them, some preliminary conclusions can be drawn regarding the necessary data for prognostics to be successfully implemented. One thing that all datasets have in common is that they contain data recorded during a large part of the product use phase, both when the product is healthy, degraded, and when the product fails. For the battery and bearing datasets, the failure is defined in terms of thresholds of the measured data, meaning that, theoretically, no other data is required for a prognostics model, one can simply use time series analysis to predict the future degradation based on past measured degradation. However, as is seen in the bearing dataset, the acceleration remains fairly stable during

a large part of the lifetime and only changes significantly very close to failure, making prognosis difficult. While feature extraction and signal processing can help mitigate these issues, having data on more features could help the prognosis model, as these might be more stable in their change over time.

From the two industrial datasets, the failure of the component is its own category, completely unrelated to any of the recorded data. In both datasets a large number of different data are recorded continuously during operation of the product in question, from a healthy condition all the way to failure.

As the purpose of the presented work is to develop evaluation criteria for if a product has sufficient data recorded during operation to facilitate the development of a prognostics model, the two industrial datasets are deemed most important. This is because the failure of a product in an automotive context usually is discovered during an inspection or due to the performance suddenly worsening, which is unrelated to the recorded data. While a direct measurement of the degradation of health state is useful, the two most important features of a product dataset are that data is recorded from when the product is healthy and all the way until failure and that a large amount of unrelated features are recorded, as the relevant features are unknown a priori and are determined during development of the prognostics model.

Because the proposed criteria are defined independently of any specific product and manufacturing method, they can easily be applied to a large amount of different types of products.

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From customer usage to a sustainable product offering through digitalization

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ABSTRACT

To develop sustainable vehicles understanding their intended usage is crucial. This knowledge allows us to translate usage patterns into specific requirements, enabling the design of optimal transport solutions. To gain a holistic understanding of the real usage of our trucks, it is essential to provide insights into both vehicle performance and the environment in which they are operated. Logged vehicle data provides a valuable source for understanding customer usage patterns. This data can be clustered into groups with similar usage profiles, and these patterns can then be translated into the requirements. To apply clustering, real-time tracking and data collection from vehicles are necessary. In this work, telematics technology has been utilized as a digitalization tool, enabling seamless transmission, storage, and reception of daily logged vehicle data. The data flow serves as the foundation for conducting a variety of analytics using advanced AI techniques. Amongst the collected data, a set of about fifteen parameters related to the vehicle usage and operating environment have been selected as the input to this study. In the data preparation phase, several preprocessing methods such as data cleaning, data transformation, feature creation and feature selection are applied. Clustering, which is one of the popular AI techniques, has been applied to group data points by implementing a multidimensional algorithm enabling us to handle daily data readings for several parameters over one year and for about two million trucks driving over the globe. In theory, data points that fall in the same group should have similar characteristics called features. In practice, each cluster of vehicles should represent a certain transport mission characterized by its unique usage. In the next step as a verification of the identified clusters in addition to statistical methods, a comparison of the output with information collected in interviews with customers in different transport applications around the world has been performed. Combining the clusters and

customer studies with vehicle domain knowledge resulted in identifying the Transport Application Descriptions (TAD). This study also shows how the proposed method can be applied to assess various transport solutions for different customer applications, with the aim of identifying the optimal transport solutions.

1. INTRODUCTION

Understanding the usage of vehicles and the environment in which they are operated is fundamental to developing transportation solutions (Edlund et al., 2004). By comprehensively analyzing usage patterns and incorporating direct customer feedback, it becomes possible to derive precise requirements that inform the design of optimized and efficient transport systems. The transport application descriptions (TAD) provided in this study offer a structured way of including customer usage patterns in product development. Having the transport applications defined, we can evaluate and design solutions that address real customer needs, enabling the development of more sustainable products.

Achieving a holistic understanding of truck usage requires not only evaluating vehicle performance and the operational environment but also integrating insights from customer experiences. This integrated perspective, enriched by customer input, is essential for creating solutions that are both effective and sustainable, ensuring that product development aligns closely with real-world needs and expectations.

In this context, digitalization has emerged as a powerful enabler for companies seeking to enhance efficiency and drive sustainable product development. Advanced digital tools and telematics systems facilitate real-time data collection and analysis, allowing the companies to monitor vehicle usage more accurately and respond to evolving customer requirements (Ghafaripasand et al., 2022). By utilizing digital technologies, the companies will be able to optimize design processes while reducing resource consumption, contributing to more sustainable and customer-centric transportation solutions.

2. OBJECTIVES/PROBLEM STATEMENT

Vehicle manufacturers are committed to developing the right solutions for their customers which are aligned with the actual usage patterns and

transportation applications. By thoroughly understanding the performance demands and operational environment conditions, the aim is to optimize performance, improve efficiency, and ensure long-term sustainability. This approach enables us to deliver solutions that meet industry needs while minimizing environmental impact.

New technologies such as battery electric vehicles and hydrogen vehicles face more significant energy limitations compared to diesel trucks, due to battery capacity limits and hydrogen production and storage challenges (Ajanovic, 2023). The energy restriction highlights the importance of understanding how the vehicles are utilized in real-world operations by the customers to select and develop the right technology solution based on the actual transport applications.

The current operational fleet of customer vehicles is predominantly powered by diesel engines, which do not face the same energy limitations as battery electric vehicles and hydrogen vehicles. However, analyzing the usage of diesel vehicles is still considered to be relevant as the logistics system is likely to remain static as production units and logistics hubs are expected to remain unchanged at least in the short to medium term.

3. METHODOLOGY

To identify the transport application of the trucks through a comprehensive and real-time perspective, it is essential to continuously collect the data with a proper frequency covering the entire market in which customers utilize the trucks.

To meet this requirement, telematics technology is employed to secure wireless logging and transmission of data from all connected trucks to the company database on a continuous basis, with data updates occurring at a daily frequency.

When studying transport applications, two dimensions of usage must be considered: truck utilization and truck mission. Utilization refers to the operational context of the truck's transport activity, such as long haul, regional haul, or local delivery. Mission, on the other hand, pertains to the type of cargo that is being transported, for example, general freight, car carrier, tanker, and so forth.

In this study, based on the expertise of company specialists with extensive vehicle knowledge and the availability of data, about fifteen parameters were selected to provide insights into the mission and utilization of the trucks.

Besides the usage parameters, the body connection variant is also selected as a factor to identify the type of cargo being transported. These parameters were chosen to cover both operational and logistical aspects of truck usage, enabling a comprehensive analysis of transport applications.

The data collected in this study includes information from approximately two million trucks globally, with data transmitted daily over a one-year period.

To conduct the analysis, the initial and essential step is to secure the quality of the data, achieved through a combination of cleaning and pre-processing techniques. Data validation and cleaning techniques include range checks, consistency checks, missing data imputation and duplicate removal. The pre-processing techniques encompass normalization and standardization, data transformation, data integration and noise filtering (Garcia et al., 2015).

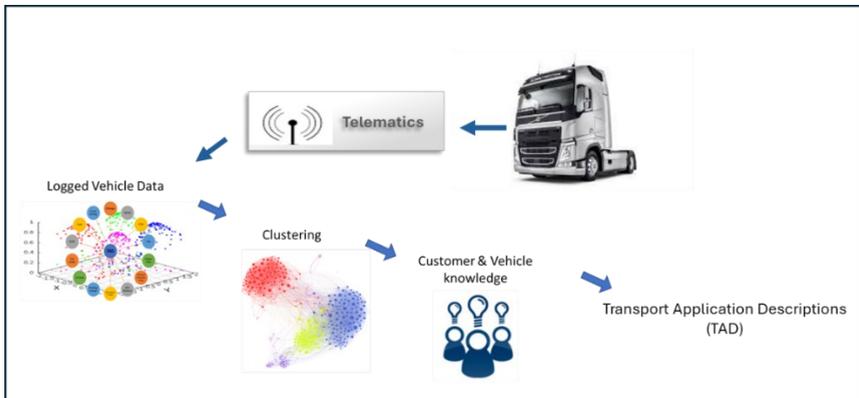


Figure 1: Schematic development process of Transport Applications Descriptions.

To cluster vehicles based on the selected usage parameters, the k-means algorithm which is a widely recognized and effective machine learning technique is employed. K-means clustering is known for its simplicity, efficiency, and ability to divide the big datasets into distinct groups of data by minimizing the variance between different data groups while maximizing the differences between them (Hastie et al., 2009), (Bishop, 2006). This method assigns the data points to clusters based on the nearest centroid and iteratively recalculates centroids until convergence which makes it suitable for clustering multi-dimensional vehicle usage data. Theoretically, data points within the same cluster should exhibit similar characteristics, referred to as features. Consequently, each vehicle cluster is expected to represent a distinct usage pattern.

In the subsequent step, to validate the identified clusters, a comprehensive verification process was undertaken. This process involved not only the application of statistical methods but also an empirical comparison of the clustering results with qualitative insights gathered from interviews conducted with customers operating in diverse transport applications globally. By integrating quantitative analysis with real-world experiential data, this approach ensures that the clusters accurately reflect practical usage patterns and transport missions. Such triangulation enhances the robustness and credibility of the findings, providing a well-rounded validation that aligns data-driven results with industry expertise and customer perspectives.

By integrating the clustering results, customer feedback, and in-depth vehicle domain expertise, the study successfully identified distinct Transport Application Descriptions (TADs). This multidisciplinary approach enabled a comprehensive understanding of vehicle usage patterns, ensuring that the classifications are both data-driven and grounded in practical industry knowledge. The synthesis of quantitative cluster analysis with qualitative customer insights and technical expertise provided a robust framework for accurately defining and characterizing the various transport applications.

In this study, clustering analyses were conducted separately for distinct economic regions characterized by comparable legislative frameworks that influence vehicle usage patterns. Factors such as speed limits, load regulations, and allowable driving mileage, which vary across regions, have a significant impact on how trucks are operated and utilized. By segmenting the data according to these regulatory environments, the analysis accounts for regional differences that affect transport behavior, ensuring that the resulting clusters more accurately reflect the specific operational conditions within each area. This tailored approach enhances the relevance and precision of the clustering outcomes, enabling a more nuanced understanding of transport applications across diverse economic and regulatory contexts.

The names of the identified TADs have two parts; one that specifies how the transport is performed, such as Long Haul and another one that indicates the type of cargo being transported, such as Aggregates.

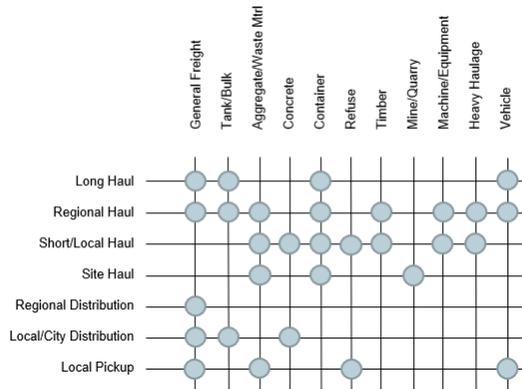


Figure 2: Identified transport applications.

4. BASIC RESULTS AND FINDINGS

Through a comprehensive analysis of the transport applications identified in this study, the importance of conducting a multidimensional clustering approach becomes increasingly evident.

To illustrate this point more clearly, consider the comparison between a general freight regional haul and general freight regional distribution. While an analysis of the daily distances driven reveals significant overlaps, a comparison of their operating radius highlights a significant distinction: the operating radius in regional haul is much greater than that of regional distribution (see Fig. 3).

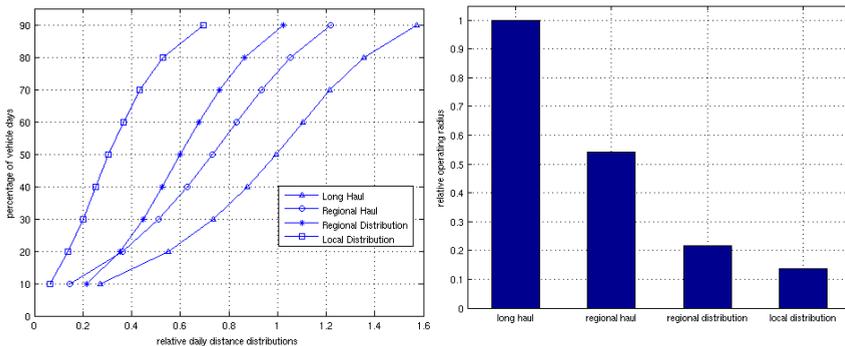


Figure 3: Daily distance (left) and average operating radius (right) for general freight applications in Europe

Moreover, additional operational parameters further differentiate these vehicle categories. Factors such as the average distance between stops, frequency of curve driving, and other operational characteristics exhibit clear variations that are not captured by mileage alone. This example underscores the necessity of a multidimensional clustering approach, which integrates multiple variables to accurately characterize and segment transport applications.

Another noteworthy finding of this study is that, although environmental parameters such as road conditions and topography were not explicitly included in the clustering process, a subsequent comparison of the identified transport applications against these factors reveals a logical and meaningful alignment. For instance, long haul vehicles mainly operate on well maintained motorways and travel between regions, which means they are likely to encounter a mix of flat and hilly terrains. In contrast, local or regional vehicles tend to stay within a region meaning that they are more likely to encounter either flat or hilly terrains. They also operate in cities and on smaller roads of lesser quality to a larger extent than long haul vehicles. Therefore, local and regional vehicles will have a higher proportion of vehicles running in rough road conditions and in flat or hilly terrain as shown in Fig. 4.

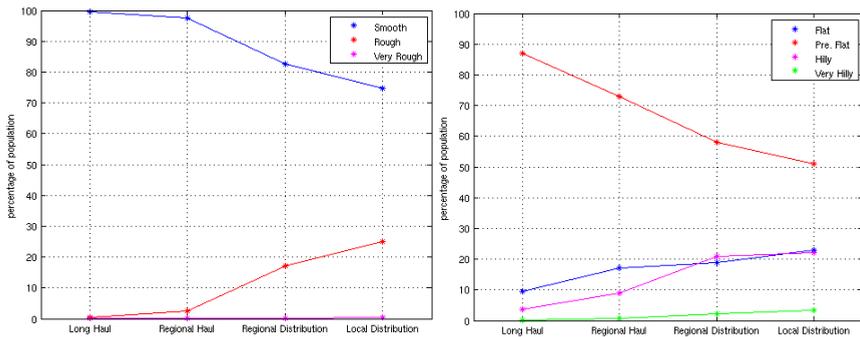


Figure 4: Road condition (left) and Road topography (right) for general freight vehicles in Europe

This observed correlation suggests that the methodology effectively captures underlying operational distinctions, even without directly incorporating environmental variables in the clustering. It also highlights the importance of considering such external factors in future analyses to further refine the understanding of transport applications. Considering the environmental parameters could enhance the precision of vehicle design and operational strategies,

contributing to improved performance and sustainability across different transport applications.

5. EVALUATION OF SOLUTIONS

The Transport Application Descriptions (TADs) can be used to evaluate how future solutions would perform if they were to run in the same transport missions as current diesel vehicles.

This is exemplified by evaluating two hypothetical but realistic battery electric vehicle solutions in two different applications, General Freight Regional Haul and Liquid Bulk Regional Haul. The daily distance distribution is very similar in the two applications but the weight that is transported differs as shown in Fig. 5. In the liquid bulk application, the vehicles operate either full or empty whereas the general freight vehicles operate with varying load.

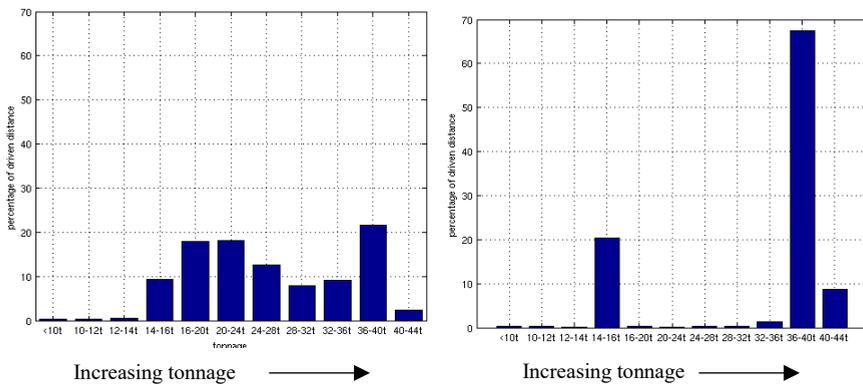


Figure 5: Weight distribution: general freight (left), liquid bulk (right)

The difference between the two evaluated vehicles is that one is focused on range (more batteries) and the other is focused on payload (less batteries). The vehicles are evaluated with respect to two parameters: payload and range, which are crucial for understanding transport mission fulfilment. The vehicles are assumed to start every day with fully charged batteries and are allowed one opportunity charge per day if necessary. Moreover, it is assumed that charging is available when needed and that using it does not interfere with the overall transport mission.

If range is not enough after one opportunity charge the mission is said to have failed on range, and if the vehicle could not have enough payload capacity for the mission it is said to fail on payload. The results are displayed in Fig. 6.

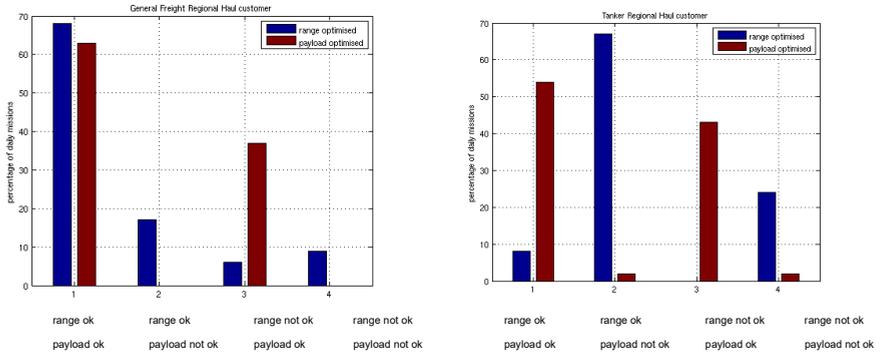


Figure 6: Vehicle performance plots: general freight (left), liquid bulk (right)

For the general freight application, the range-optimized vehicle performs well and succeeds in 70% of the missions and for 20% more of the missions it has sufficient range but must leave some cargo behind. The payload-optimized vehicle succeeds in 63% of the missions but lacks the range for the rest.

For the liquid bulk application, the payload-optimized vehicle performs similarly as for general freight, with only a slight drop in successful missions due to a higher energy need because of the higher average payload. The range-optimized vehicle has the range for 75% of the missions but must leave payload behind for most of them, and for 25% it lacks both range and payload capacity.

Of the two vehicle solutions, the range-optimized vehicle performs better for the general freight application. For the liquid bulk application, it is not as clear which vehicle solution performs the best but with realistic assumptions on the cost of opportunity charging and the reduced income due to lack of payload capacity, the payload-optimized vehicle will be the cheaper to operate. This highlights the importance of understanding transport applications in order to develop the right solutions for customer needs.

6. CONCLUSIONS

Digitalization plays a significant role in sustainable development by enabling data driven decision making. In this study, telematics technology has served

as a powerful enabler for data collection, which, when combined with analytics and AI techniques, significantly enhanced our understanding of vehicle usage patterns.

Regarding the usage patterns, this study highlights the critical importance of employing multidimensional clustering rather than relying on a single parameter. Analyzing usage from multiple perspectives is essential to effectively distinguish between the utilization of different applications.

In addition, this study revealed that the operating environment of trucks can vary across different transport applications. Recognizing these differences provides valuable insights and a solid foundation for effective solution design. A realistic understanding of the truck usage enables an accurate evaluation of solutions, ensuring that they are well-aligned with actual needs and remain sustainable by keeping the customer at the center of the analysis.

Moreover, the degree of flexibility available in solution design can vary significantly depending on the vehicle technology. While diesel trucks often allow for greater operational margin, electric and hydrogen trucks require more precise optimization due to energy storage and charging limitations, making it essential to thoroughly understand the real needs of the customer.

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Day 2 Session: Innovations in Sustainable Transport

Enhancing energy efficiency and environmental sustainability through regional battery-powered train energy transfer systems

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EXTENDED ABSTRACT

The urgent need to decarbonize both the energy and transportation sectors stems from their combined responsibility for over 60% of global greenhouse gas emissions [1]. As climate change accelerates, international frameworks such as the Paris Agreement and regional policy initiatives like the European Green Deal have set ambitious targets for achieving net-zero emissions by mid-century. In particular, the EU aims to reduce net greenhouse gas emissions by at least 55% by 2030 and reach climate neutrality by 2050. These goals require systemic shifts across infrastructure, including energy production, storage, and mobility systems. Consequently, there is a growing demand for distributed, low-carbon solutions capable of addressing grid limitations while enabling resilient, renewable-powered energy access, especially in rural or environmentally protected regions [2], [3], [4]. While renewable energy adoption is expanding rapidly, challenges persist in matching generation with demand, particularly in remote areas where building grid extensions, even for clean energy, is economically infeasible or ecologically disruptive. Simultaneously, the electrification of regional rail offers a promising platform not

only for clean transportation but also for innovative energy distribution [5], [6], [7]. This work proposes a novel concept: battery-powered regional trains acting as mobile energy carriers that transport passengers and energy simultaneously. Inspired by the principles of Vehicle-to-Grid (V2G) [8] and Vehicle-to-Vehicle (V2V) [9] systems, this model envisions trains charged via renewables at depots or nodes with excess supply, then delivering clean energy to low-access or off-grid areas to power station operations, auxiliary infrastructure, microgrids, or even recharge other vehicles. The concept is particularly well suited for regional rail lines that traverse topographically diverse or partially electrified corridors. A case study modeled using MATLAB simulations on the Borlänge–Malung railway in Sweden exemplifies this approach, based on train performance and demand scenarios developed within the Horizon Europe FutuRe Flagship Project [10]. With significant elevation differences, traction energy consumption for uphill trips is found to be approximately 40% higher than for downhill returns. In conventional planning, this asymmetry would necessitate sizing batteries for worst-case (uphill) demand, resulting in oversizing and added environmental burden. However, by enabling energy transfers between downhill and uphill trains, either directly or via rail-side energy hubs, battery capacity can be optimized, avoiding the cost and emissions associated with redundant storage capacity. This energy-balancing approach is topography-aware and dynamically adaptive to route-specific operational demands. To assess operational feasibility, the proposal incorporates modeling of traction energy, battery aging, and auxiliary energy demand. Battery degradation is simulated using a Rainflow counting algorithm applied to time-series state-of-charge (SOC) profiles under various speed and energy-use conditions. This method, combined with depth-of-discharge-based cycle-life curves [11], [12], [13], offers reliable projections of battery life, enabling right-sizing of energy storage and avoiding premature replacements. Notably, the carbon footprint of lithium iron phosphate (LFP) battery manufacturing is estimated at around 55 kgCO₂eq per kilowatt-hour [14], reinforcing the need to avoid excess capacity that would otherwise inflate upstream emissions. Furthermore, auxiliary energy demands, particularly for Heating, Ventilation, and Air Conditioning (HVAC) systems, are non-negligible and fluctuate significantly based on weather conditions and passenger load. A one-dimensional thermal simulation conducted as part of the FutuRe project shows that HVAC energy consumption is highly sensitive to variations in both occupancy and ambient temperature. For instance, at 28°C, an empty train requires less than one-third the ventilation and cooling energy of a fully loaded one, along with an estimated 8% reduction in traction energy. These variations not only affect battery sizing but also offer potential for surplus energy reallocation in real time. Accurate prediction of auxiliary

loads allows for more dynamic energy management and identifies opportunities to supply other users, such as e-bike or EV charging stations in isolated locations, without overburdening system resources. From an energy systems perspective, these mobile energy carriers provide flexibility at multiple levels. In remote locations, where even renewable power plant construction could damage delicate ecosystems, trains offer a non-intrusive alternative for clean energy delivery. During periods of low demand, they can store surplus energy; during peak hours, they can discharge to relieve grid stress and reduce dependency on fossil-based balancing sources. The system is especially valuable in regions where electricity consumption is limited to narrow time windows, such as seasonal tourism destinations or mobile research sites, where permanent grid infrastructure is not justified. Moreover, Europe's grid average emissions remain relatively high at 244 g CO₂ eq/kWh (2019–2022) [15], making renewable-charged trains a cleaner intermediary that reduces transmission losses and improves localized carbon performance. Incorporating V2G and V2V functionalities into rail infrastructure, however, introduces technical challenges. These include the need for standardized charging interfaces, predictive scheduling, real-time energy exchange coordination, and robust battery health monitoring systems. In conclusion, this extended abstract proposes a shift in how battery-electric trains are conceptualized, not as passive consumers of electricity but as intelligent, mobile contributors to sustainable energy networks. In addition to providing clean transportation, these trains have the potential to deliver decentralized, on-demand, and environmentally sensitive energy services. With the integration of topography-based routing, auxiliary load prediction, and advanced battery lifecycle modeling, this concept could enable future decentralized, zero-carbon mobility and energy systems, especially in areas where traditional infrastructure is neither feasible nor desirable.

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Automated train preparation and operation: A target costing based approach for a regional line in Germany

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EXTENDED ABSTRACT

By outlining highly automated railway operation scenarios where no activities by operating personnel is required on the train the project ARTE aims to examine aspects of automation from different perspectives. One of them is that the lack of operating personnel such as train drivers can lead to cancellation and delays and further to dissatisfaction with the railway mode from a customer perspective as well as penalty payments and an unprofitable operation for the operator. Also, automation promises higher frequency of trains during the day and more reliable train services at night by presumably lower operating costs and better usage of infrastructure. However, in order for these new technical solutions to catch on and be implemented in the market the cost efficiency has to be evaluated and proven. This extended abstract gives an insight into the target cost-based approach that has been developed to evaluate an economically feasible implementation of automation technology for regional railway. The aim in this project was however not to change basic functions and system architecture of rail operation, but to automate existing tasks. Even though basic functions remain the same, automatization of railway operation leads to a change in human task allocation on the side of rail workers. In this project the focus was on the train driver, precisely on all tasks performed by the train driver today including preparatory as well as follow up tasks. To evaluate the operational implementation of all of the tasks

performed by a train driver today, each task was analysed. The aim of the initial analysis was to examine to what extent each task can be replaced by automation technology. Tasks where automation is not yet possible have been assigned either to local staff or to a remote operator if they can be done from remote but have to be initialised or supervised by a person. Local staff can be either a person with a maintenance background with special technical knowledge who performs tasks directly at the train outside of passenger journeys. Or a train attendant when the tasks are performed during the journey itself when passengers are on board. This analysis of each task and the relocation in the future with automation technology is needed as a first step to visualise not only the shift of functions but with it the shift of cost drivers for the performance of the railway operation. To evaluate the economic potential according to the results of the analysis done this shift of functions from humans to technology has been monetized. Different approaches from the literature were discussed to estimate how expensive automated train operation would be. As however there are not yet reliable market prices for automation solutions for the individual tasks of a train driver available the further economic analysis focused on examining how high cost for the automatization technology can be to ensure that the business case is at least on the same level as the status quo. In the literature target costs refer to the so-called allowable costs of a product. This involves determining what proportion of the added value of a product is accounted for by the individual components. The labour costs for the work today performed by a human train driver can be understood as a first approximation of the cost that the technology which will do the same tasks in the future may also cause. Therefore, a target cost-based approach has been developed to estimate the costs that can be spent for new technology instead of human labour. When adapting this approach to a railway operator, the relevant components of the product correspond to the manually performed process steps of preparation, operation and post-processing of a train ride. In a first step therefore the activities of the train driver have been analysed and relocated according to the automation solution. In a second step each task was assigned the value of how much time of a working shift is allocated it. Each task has then been monetized with the individual personnel cost of the train driver or in case of a relocation of the task to the personnel costs of the responsible job profile. Values for the personnel costs can be taken from a specific company if they are available. For the purpose of creating a reproducible methodology however publicly available data from collective agreement pay scale values have been used along with surcharges and working schedule efficiency values from the 2030 Federal Transport Plan of Germany. Applying the cost values to the tasks of a train driver today and to the relocated tasks done by humans in the future scenario it results in a difference in costs per

year. The amount of this difference in costs can then be seen as the target cost for the automation technology needed to replace the physical train driver. To cope for uncertainties in the calculation for technologies which are not yet established in the market sensitivity analysis on individual aspects can be done. In this case a sensitivity analysis has been done on the number of remote train operators needed to supervise a certain operational programme. The application of the methodology to a specific use case showed target costs which can be understood as a lower limit for the automation of the defined tasks. It can thus be used to support decision making when assessing the economic viability of automating regional railway lines. As the framework conditions may differ in other applications, the target costs must be determined on a case-by-case basis. For this purpose, detailed methodological instructions for calculating the target costs with the individual circumstances for each railway undertaking have been described. This includes detailed brake up of work tasks depending on an undertakings business case. As a conclusion this contribution presents an approach for evaluating the cost-efficient implementation of new technology to increase efficiency through the automation of railway operations.

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Advancing the quantification of tyre wear and particulate emissions on an outer drum test bed: challenges and laboratory solutions

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EXTENDED ABSTRACT

Tyre wear is a major source of environmental microplastics and airborne particles smaller than 10 µm, which pose significant health risks by reaching the lungs and other organs [1]. While tyre wear can reach the immediate environment, from roads to the world's oceans, causing pollution, airborne particles can potentially lead to aggravation of asthma, oxidative stress in various organs, Alzheimer's disease and neurodegeneration [2–5]. Accurate quantification and regulatory measures are therefore essential. Together with brake wear, tyre wear itself is already the focus of future regulations (EURO 7), while airborne tyre wear particle (TWP) emissions are not yet considered and are complex to measure. The regulation on brake wear will only focus on the airborne emissions of the brakes, with a limit already set. The regulation work for tyre wear, which is only focussing on the overall mass loss of the tyres, is still ongoing. There is no limit in sight yet. [5]

While the measurement of airborne TWP emissions is difficult in real-world environments due to the high number of background emissions, the measurement on indoor drums is complex due to the need for degumming methods to prevent the tyre from sticking to the drum and to achieve realistic tyre wear behaviour. These degumming methods are usually carried out using talcum powder, which affects the particulate measurements. The airborne talc particles affect the measurement of particle number (PN), particle mass (PM) and size distribution.

Therefore, this study focuses on the development of a reliable method for the simultaneous quantification of tyre wear and airborne TWPs under realistic laboratory conditions. The test setup at the Institute of Automotive Engineering at the Graz University of Technology consists of an outer drum test bench with a flow-optimised enclosure that minimises the ingress of background particles. The enclosure features a reduced gap baseplate and an airflow system that prevents particle exchange between the enclosure and the environment. This configuration, coupled with a GTR-24 brake wear compliant sampling system, facilitates accurate particle measurements. Key instruments include two AVL particle counters for PN concentration, two samplers for PM, and an ELPI+ (Electrical Low Pressure Impactor) for size distribution analysis. The test cycle used is the so-called JASIC cycle, which has been established by the Task Force on Tyre Abrasion (TFTA) [6] as a future cycle for the regulation of tyre wear. This cycle is a combination of the WLTC and the Japanese Curve and Slope Cycle and consists of two speed sections (60 & 100 km/h) with alternating lateral and longitudinal forces. A single cycle takes 3 hours and 28 minutes to complete, covering a distance of 250 km. Normally this cycle is repeated 20 times for a total of 5,000 km to evaluate tyre wear over distance. [6]

The results show that minimising background emissions is crucial for accurate tyre particle analysis. The air barrier and the flow-optimised base plate significantly reduced background emissions, which is a major advantage compared to real-world measurements. The use of talc powder as a degumming method increased tyre wear rates by a factor of 10 compared to measurements without it: Without talc powder the wear rate of the tyre was around 3 mg/km/tyre. With the use of the degumming method the wear rate increased to more than 30 mg/km/tyre. However, the talc added complexity to the particle measurements by contributing significantly to both PM and PN. Keeping the PN concentration of the talc powder constant helps to distinguish between talc and tyre particles: As TWP emissions are mainly correlating with lateral forces during the test cycle, the PN peaks are clearly visible in the measurement signal. A further distinction is seen in the size distribution analysis, which showed clear differences between talc particles and TWPs, with talc contributing predominantly to the coarser particle fractions (PM₁₀) compared to finer particles (PM_{2.5}). Further studies of PM showed that talc was the major contributor to the mass in the PM filters. Density studies of the filters, as well as mass comparisons with reference filters made with talc powder only, showed that the airborne TWPs contributed only a small percentage of the mass in the filters. This indicated that less than 5% of tyre wear was also airborne TWP emissions. With PM₁₀ values around 1 mg/km/tyre, the

airborne mass coming from the tyre is comparable to the airborne mass coming from the brakes. However, the total mass loss of the tyre dominates, contributing to microplastics in the environment.

The study shows that it is possible to measure tyre wear and wear particles in the laboratory under controlled conditions. However, challenges remain. Real-world measurements are hampered by background emissions and resuspension of road dust, while laboratory setups struggle to achieve realistic wear rates without degumming methods. Measurement of tyre PN and PM on the indoor drum is hindered by the high airborne concentration of talcum powder. Investigations of PM filters and PN concentrations showed a clear tendency that only a small number of airborne particles originate from the tyre itself.

For future research, it is essential to find methods that can distinguish between talc powder and TWPs. This is important in order to find a suitable test bench method to measure both tyre wear and TWPs. Ultimately the aim should be to find a correlation between real world measurements and test bench measurements. This will lead to a comparison of real-world events with testbench events, which will lead to a reduction in the burden of tyre testing and regulation. This research highlights the importance of continued efforts to refine tyre wear and TWP measurement techniques. Reliable methods are essential not only for assessing the environmental and health impacts of tyre emissions, but also for informing regulatory frameworks to mitigate these impacts.

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Overcoming institutional barriers in socio-technical transitions: The case of ship electrification project

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ABSTRACT

This study explores the transition to all-electric RoPax ferry transportation, focusing on the institutional structures within the current business ecosystem that hinder this shift. RoPax shipping, which combines wheeled cargo transport with passenger services, significantly contributes to greenhouse gas emissions due to its reliance on internal combustion engines. Although recent regulations from the International Maritime Organization and the European Union promote alternative fuels, the adoption of electric vessels remains limited. Drawing on empirical data from a two-year project developing an electric RoPax vessel for a Baltic Sea route, this research involves collaboration with a shipyard, a ship operator, and a local energy company. Utilizing a framework that integrates the Multi-Level Perspective on socio-technical transitions, institutional theory, and business ecosystem analysis, the study reveals that the stability of the socio-technical regime is maintained through entrenched business ecosystem structures. Findings indicate that existing value creation configurations obstruct the transition to electric vessels, emphasizing that business ecosystems reflect embedded institutional arrangements. The proposed framework illustrates how regime stability is shaped by interdependent actor roles and investment sequences, highlighting the need for structural reconfiguration to facilitate the integration of niche innovations into the dominant regime. The study concludes that successful transitions require not only technological advancements but also a comprehensive restructuring of ecosystem roles and responsibilities to overcome barriers and enable sustainable practices in the maritime industry.

1. INTRODUCTION

RoPax (Roll-on and Passenger) shipping combines the transport of wheeled cargo, such as trucks and trailers, with passenger services, often offering overnight accommodation and entertainment options. This mode is particularly prominent in Europe and is a relatively high source of emissions because of the relatively high speed of the ships. Today, these ships rely on internal combustion engines (ICE) powered by oil or in some cases LNG. Recent regulations introduced by the International Maritime Organization (IMO) and the European Union (EU) aim to push shipowners toward alternative fuels and propulsion technologies, though adoption of options like LNG remains limited. Considering these developments, all-electric battery-powered ships (further, ‘electric ships’) have the potential to bring GHG emissions to zero, depending on the grid mix where the ship is charged, while simultaneously reducing other environmental impacts, such as noise pollution, particle emissions and localised pollutant emissions.

All-electric battery-based powertrains have, however, long been held unfeasible for large vessels and long distances. The argument often cited is that batteries would need to be prohibitively large and expensive, making the concept impractical. While short-distance road ferries have demonstrated the viability of battery-electric propulsion (Rivero, 2025), larger RoPax vessels – capable of carrying hundreds of vehicles and more than 2000 passengers – have traditionally not been considered viable candidates for being equipped with battery powertrains. Recent discussions suggest that RoPax ferry routes could be suitable for electrification, too. Nevertheless, significant challenges remain, particularly regarding the operational, investment, and business model implications of transitioning to all-electric RoPax ferries. That is, a wider business ecosystem is affected (Adner, 2021), and a socio-technical transition needs to take place for the battery technology to compete with the dominant regime of ICE-powered RoPax ships (Geels, 2002).

This study examines how institutional structures within current business ecosystem constrain the transition to electric RoPax ferry transportation. It draws on empirical material from a two-year project developing the concept for an electric RoPax vessel operating between two countries in the Baltic Sea. The analysis is based on project communications and collaboration with a shipyard, a ship operator, and a local energy company, all working to create a feasible scenario for implementing the electric ferry on the focal route.

To analyse these dynamics, this study draws on a theoretical framework that integrates the Multi-Level Perspective (MLP) on socio-technical transitions,

institutional theory, and the concept of business ecosystems, which is described in the following section. By viewing regimes as institutionalised business ecosystems, we aim to achieve a more nuanced understanding of how industry structures resist or enable transition, particularly when technological change requires reconfiguring how value is created and distributed.

2. LITERATURE REVIEW

The transition to electrified shipping challenges not only technologies but also established industry structures, operational practices, and value creation logics. Analysing such transitions requires frameworks that capture both systemic stability and change. The MLP on socio-technical transitions and institutional theory have become central in this regard. In addition, the concept of business ecosystems highlights how value creation structures — the configuration of roles, activities, and interdependencies — form the basis for and stabilise socio-technical regimes. We integrate these perspectives to build a foundation for analysing the institutional and structural barriers to the electrification of shipping in the focal case.

The connection between the MLP and institutional theory has gained increasing attention in socio-technical transition studies. The MLP, developed by Geels (2002; 2011), conceptualizes transitions as interactions between three analytical levels: niche innovations, socio-technical regimes, and socio-technical landscape. It provides a structured way to understand how radical innovations emerge in protected niches, challenge dominant socio-technical regimes, and eventually reshape socio-technical systems under pressure from broader landscape developments. Institutional theory, in turn, focuses on how formal and informal rules, norms, and cognitive structures influence organizational behaviour and sectoral change (Scott, 2008). Institutional logics, legitimacy, and isomorphic pressures are key mechanisms through which institutional structures shape and stabilize socio-technical regimes (DiMaggio & Powell, 1983).

A number of attempts to integrate these perspectives to enhance the understanding of transition dynamics have been made. Geels and Schot (2007) highlighted the role of institutional logics in shaping regime stability and how institutional change interacts with technological and economic shifts in transition processes. Fuenfschilling and Truffer (2014) further developed this integration by examining how institutional structures define regime characteristics and influence transition pathways. Similarly, Raven (2004) investigated the role of institutional entrepreneurship in niche development, emphasizing

how actors navigate institutional constraints to promote innovative practices. Institutional structures define the stability of regimes and the opportunities for niches to scale.

In the MLP, the socio-technical regime refers to the dominant rule set or system of actors, institutions, technologies, and user practices that stabilizes existing sectors (Markard and Truffer, 2008; Sutherland et al., 2015). Regimes are characterised by self-reinforcing structures, incremental innovation, and resistance to radical change (Fuenfschilling & Truffer, 2014), exhibiting strong path dependencies and technological or institutional lock-ins (Klitkou et al., 2015). Regime actors are often oriented toward system optimization rather than transformation, and they tend to defend the status quo. While regimes represent the established way production systems are organised in industries, the MLP has been criticised for neglecting actors and their actions (Bünger & Schiller, 2022).

The concept of business ecosystems can address this shortcoming by explicating the configuration of roles, interdependencies, and value creation logics among firms within a regime. Business ecosystems are communities of various actors that are interacting to generate a solution for a specific need (Pidun et al., 2019). In other words, an ecosystem is typically defined by the value creation structure with the aid of which actors deliver a value proposition to the end customers (Adner, 2021). Business ecosystems can also be formed to enable and support the business activities of a keystone company that leads the activities in fulfilling the needs of the end customers (Iansiti & Levien, 2004). To make this happen, some level of orchestration is typically involved within ecosystems (Autio, 2022). However, individual actors are not controlled hierarchically in ecosystems, which makes ecosystems different from supply chains (Jacobides et al., 2018).

Similarly to acknowledging the institutional character of regimes within the MLP, scholars have applied institutional theory to business ecosystems, identifying institutional dynamics as a key layer that shapes how ecosystems emerge and evolve (Autio, 2022). Thomas and Ritala (2021) examine ecosystem legitimacy emergence through an institutional lens, conceptualizing legitimacy as a collective process where orchestrators, complementors, and external actors engage in discursive, performative, and identity-building activities. Tsvetkova et al. (2021) further embed institutional theory into the study of business ecosystems by exploring the regulative, normative, and cultural-cognitive institutional barriers affecting the transition to autonomous shipping ecosystems. They demonstrate that institutional lock-ins can prevent new business models from creating and capturing value, and that the structure of

incumbent business ecosystems, manifested in the value creation structure (who does what, who gets what) is in itself an institution.

Building on this understanding, we argue that the structure of business ecosystems, particularly the configuration of value creation activities, constitutes a crucial but under-theorised element of socio-technical regimes. These value creation structures shape roles, power relations, and coordination patterns, and because they are institutionalised, they help stabilise regimes and make change difficult. Incorporating the business ecosystem perspective into the MLP allows for a more granular analysis of regime dynamics, moving beyond the traditional focus on policy and technology. It can enhance our understanding of how ecosystems facilitate or resist transitions. In this study, we apply this integrated framework to an empirical case, exploring how institutional structures and business ecosystem configurations shape the feasibility of transitioning to electric RoPax ferry transport.

3. METHODOLOGY

This study investigates the institutional barriers to electrifying RoPax ferry transport through a case study situated in the Baltic Sea region. The case forms part of a two-year project assessing the feasibility of deploying an all-electric RoPax vessel operating between two countries. The project involved collaboration between a shipyard, a ship operator, and a local energy provider, all engaged in developing a viable concept for electric ferry operations on the focal route. A qualitative, exploratory case study approach was adopted, suitable for analysing complex socio-technical transitions in context-specific settings (Gustafsson and Tsvetkova, 2017).

Empirical material was gathered from a broad set of sources. Project communications provided the core of the material, including meeting notes, memos, and email correspondence, complemented by industry publications, brochures supplied by companies, policy papers, and data such as RoPax schedules, emissions, fuel consumption, route distances, vessel size, speed, and energy prices in different countries. Insights were collected through continuous discussions with stakeholders, which over the course of the project developed into more intensive exchanges once feasibility assessments began to produce concrete implications. These discussions were not structured as formal interviews but as consecutive exchanges that gradually deepened understanding of the stakeholders' interests and positions.

In total, the study drew on discussions with experts from different organisational domains: shipyards (around 20 persons), shipowners (around 20

persons), ports (around 20 persons), energy companies (around 10 persons), policymakers at national and EU level (around 20 persons), academics (around 20 persons), and technology suppliers (around 30 persons). Stakeholders were located both in Europe and in China, which made it possible to capture international perspectives on the technological and institutional conditions for electric RoPax vessels. Discussions with each type of stakeholder centred on what electrification would imply from their specific standpoint, for example, shipyards focusing on design and construction challenges, ship-owners on operational and business model implications, and policymakers on regulatory and infrastructural considerations. This allowed the analysis to build towards an overall understanding of the interests, conflicts, and institutional barriers embedded in the wider business ecosystem.

The material was analysed using directed qualitative content analysis (Hsieh and Shannon, 2005). The approach was primarily abductive (Dubois and Gadde, 2002): institutional theory and the MLP served as guiding frameworks, but analysis was sensitive to additional themes emerging from the data. Initial coding was informed by concepts such as institutional barriers, niches, regimes, and ecosystem roles, while inductive categorisation was applied when recurring issues surfaced beyond the pre-defined categories, for instance related to energy pricing, cross-border electricity supply, and policy coordination. This iterative process enabled the combination of theoretical framing with empirical richness, producing a consolidated view of the institutional barriers shaping the feasibility of electric RoPax ferry deployment.

4. ANALYSIS

Following the theoretical framework presented in section 2, Table 1 illustrates how the transition from conventional diesel-powered RoPax vessels to electric ships involves not only technological substitution, but also profound shifts in both socio-technical regimes and business ecosystem structure. This transformation unfolds across several key areas of industry logic: design, manufacturing, operations, and maintenance. We provide several individual examples of current institutional logics, and the shift required for the transition to all-electric battery-powered ships, which are not exhaustive.

In the current regime, the design logic is strongly rooted in an engineer-to-order tradition. Shipyards are positioned primarily as executors of unique customer specifications, with relatively little influence over vessel conceptualisation. This role allocation results in long construction times, high costs, and limited economies of scale. Value creation is tightly linked to customisation,

while value capture remains fragmented, depending on individual project contracts. By contrast, in case of electric ship construction, it is possible to shift to configure-to-order modular designs, albeit not necessary. It would re-organise roles within the ecosystem, positioning shipyards as solution configurators and enabling faster construction, lower costs, and improved standardisation. This transformation also restructures value creation around modular efficiency and increases the potential for learning effects across projects. In principle, this change in logic is technologically speaking independent of propulsion technology. Rather, the technological change enables opening a lock-in in the design process of the vessel.

Table 1: Analysis of institutional logics in the current and new business ecosystem structure.

Elements in the current regime	Existing business ecosystem		New business ecosystem	
	Regime characteristics	Business ecosystem structure	Regime characteristics	Business ecosystem structure
Design logic	Ships engineered-to-order; customised designs	Shipyards follow owner specifications; little design ownership; limited standardisation and learning.	Configure-to-order, modular designs	Shipyards act as solution configurators; modular production enables faster delivery and learning across projects
Manufacturing logic	Construction built around early diesel engine installation	Capital tied up early; fixed supplier relationships; limited flexibility in scheduling and procurement	Batteries installed late, flexible sequencing	Capital commitment deferred; more adaptable

				supply chains and project financing
Operational logic	Fossil fuel bunkering once or a few times a week; low infrastructure demands	Operators act independently; minimal coordination with ports	Charging at every port call; infrastructure dependency	Ports become service partners; tighter coordination and shared operational responsibility
Maintenance logic	Onboard engine maintenance requires crew	Crew needed for maintaining ship during operations	Minimal maintenance crew needed onboard	Smaller crews possible; potential to reduce speeds and costs; new land-based service roles emerge

Manufacturing logic in the conventional ecosystem is centred around the early installation of diesel engines (simply because it cannot be fitted into the vessel at a later stage due to its bulkiness), a practice that heavily influences the sequence of construction activities. The value chain is organised to accommodate this early capital commitment, embedding inflexible production routines and financial risk into the ecosystem. Capital is tied up early, shaping how actors coordinate investments and allocate responsibilities. In an electric ship, batteries can be installed at a late stage, allowing for greater flexibility in construction scheduling and financing. This alters the underlying value creation logic, enabling later capital commitment and reducing risk exposure during earlier phases of production.

Operational logic also reflects current institutional arrangements. Traditional ships require bunkering once or a few times a week, allowing port operations to remain flexible and relatively uncoordinated across infrastructure providers. Roles and responsibilities between ship operators and ports are loosely coupled, and value capture remains localised and opportunistic. Electrification disrupts this model: charging is required at every port call, which in turn requires standardised infrastructure and tighter operational coordination between ports and operators. The shift implies a redistribution of roles, with ports becoming enablers of daily operations, and alters value creation by embedding it within a more integrated, service-based ecosystem. New actors, such as local electricity grids, become important actors in the ecosystem, too.

Finally, maintenance logic can also change. Conventional vessels depend on onboard maintenance crews primarily tasked with managing ICE-based propulsion systems. This requirement sustains a business model where crew-related costs form a significant fixed expense, incentivising higher operational speeds and cost structures optimised for high-crew configurations. Battery systems, however, reduce the need for onboard maintenance, enabling a business model based on smaller crews and potentially lower operational speeds. This shift not only affects operational and maintenance logics but also redistributes roles across the ecosystem, creating opportunities for land-based service providers and altering how and where value is captured.

Altogether, these transformations reveal that the transition to electric RoPax ferry systems is not merely a technological substitution but involves a reconfiguration of institutionalised business ecosystem structures. Changes in roles, activities, value creation, and value capture must occur simultaneously to enable a successful transition, reinforcing the argument that business ecosystems form a critical, yet often overlooked, dimension of socio-technical regimes.

5. DISCUSSION AND CONCLUSIONS

This study demonstrates that socio-technical regime stability is maintained not only through technological systems and formal rules, but also through institutionalised business ecosystem structures. By analysing how design, manufacturing, operations, and maintenance logics are embedded in the incumbent maritime ecosystem, we show that value creation configurations constrain the transition to electric RoPax vessels. These findings support the view that business ecosystems are not neutral coordination mechanisms but reflect embedded institutional arrangements (Autio, 2022; Thomas and

Ritala, 2021). We also observed a reverse relationship, namely, how the technology shift enables a change in design logic, a part of the institutional arrangement. Hence, these changes are reciprocal in nature.

To conceptualise this, we propose a framework that integrates the Multi-Level Perspective with institutional theory and business ecosystem analysis. As illustrated in Figure 1, the regime can be understood as being structured by an institutionalised business ecosystem, where roles, routines, and value creation logics stabilise incumbent practices. Transition becomes possible when institutional work reconfigures this structure through changing roles and value creation logics so that niche innovations can align with viable ecosystem configurations and move from niche to regime level.

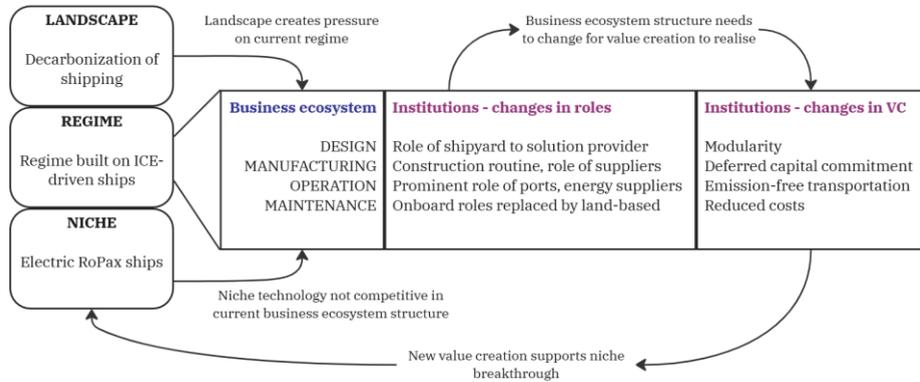


Figure 1: Regime reconfiguration through business ecosystem change.

Our analysis contributes to MLP transition studies by specifying how regime characteristics are operationalised through interdependent actor roles, investment sequences, and infrastructure dependencies (Geels, 2002; Markard & Truffer, 2008). In contrast to the common emphasis on public policy and technology as regime elements, we highlight how industrial practices, such as when capital is committed, how ships are designed, or which actors manage bunkering, serve to stabilise the dominant regime. This responds to critiques that regimes in MLP are often underspecified in terms of actor strategies and economic structures (Bünger & Schiller, 2022; Markard & Truffer, 2008).

From an institutional perspective, the case illustrates how ecosystem-level change requires more than legitimacy-building or normative alignment: it involves reconfiguring structural dependencies and redistributing responsibilities between firms (DiMaggio & Powell, 1983; Scott, 2008). For instance,

shifting battery installation to the end of the production process alters capital flows, and port charging requires new role definitions and infrastructure investment. These are both examples of ecosystem restructuring as institutional work (Fuenfschilling & Truffer, 2014; Raven, 2004).

Rather than assuming that technological change alone can drive transitions, our findings show how the absence of viable alternative business ecosystem structures can block progress, even when technical solutions and regulatory support are in place. This aligns with calls to pay more attention to “missing roles” or “ecosystem gaps” in transition pathways (Tsvetkova et al., 2021).

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Day 2 Session: Bridging Sustainability and Design I

User Roles for Circular Product Development Software

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ABSTRACT

Global resource scarcity heightens the need to develop sustainable, circular products. Yet this is challenging due to interdependent criteria and the complexity of modern products. Model-based software can mitigate this by mapping key dependencies and evaluating designs for circular economy performance and sustainability. Before building such tools, user groups and roles must be clearly defined to protect sensitive data, improve user experience, and align workflows with stakeholder needs – especially those of developers. This paper defines roles for a model-based tool for circular and sustainable product development within the Cyclometric project. It introduces a methodology for role definition, followed by a formal evaluation of the developed roles.

1. INTRODUCTION

Designing sustainable, circular products requires addressing diverse criteria – sustainable manufacturability, recyclability, meaningful use, and long-lasting business models – across all development phases and the entire product life cycle. This is inherently complex due to interdependent criteria, differing approaches to closing material loops, and the complexity of products like cars or consumer electronics (Block, Ardilio, & Keicher, 2024). Model-based software tools can mitigate this complexity by mapping dependencies among

these criteria, evaluating designs for circularity and sustainability, and providing a single source of truth for required data (see, e.g., (Schwahn, Potinecke, Block, Werner, & Tarlosy, 2024)). Yet, effective use of these tools requires clear user and role definitions to integrate sustainability into workflows, manage access, and align user experience (Akuthota, 2025; Herzberg, 2023; Lanchec, 2024). Existing engineering and lifecycle assessment software often comes with predefined roles (see e.g., (Capella, 2025; Dassault Systèmes, 2023; Oraby, Briem, Bippus, Rupp, & Zibek, 2024; SPARX SYSTEMS, 2025)). Yet the role definitions often focus on access permissions, interface settings, and the management of content and collaboration areas, but do not consider – nor support – the tasks within the development process of circular products. Thus, this publication defines and evaluates roles for a circular, model-based software tool from the perspective of circular development processes.

2. METHODOLOGY TO DEVELOP ROLES

Roles can be systematically derived from development process models. They outline product-development tasks and partially generalized roles. This paper adopts the Munich development process model as the foundational framework (Lindemann, 2009). The Munich process model is a systematic approach that structures development projects by dividing development into seven distinct phases (see Figure 1), each with specific goals and deliverables, facilitating continuous feedback and refinement. Five workshops were held, each with five to eight experts from the fields of sustainable product development, MBSE and LCA, to adapt this model towards circular product development. The experts collected tasks, necessary input and output information based on this adapted Munich process model. This data was then used to structure and define the user roles.

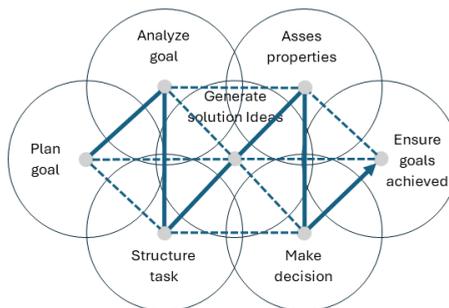


Figure 1: Munich development process model (Lindemann, 2009)

3. USER ROLES FOR CIRCULAR PRODUCT DEVELOPMENT SOFTWARE

Five roles were identified which are relevant for circular software tools: CE Problem Systemiser, CE System Analyst, CE Quality Tester, CE Solution Developer, and CE Solution Decision Maker (see Figure 2).

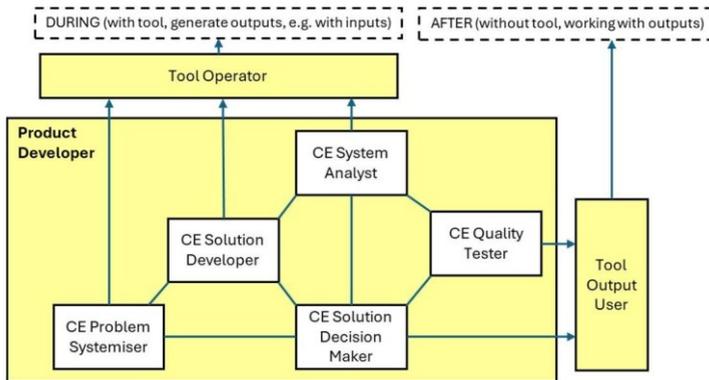


Figure 2: Definition CE Product Developer based on the Munich Model

The **CE Problem Systemiser** structures the CE problem by linking company goals to product architecture characteristics. Their focus is systematically determining relevant product characteristics where circular strategies can be applied effectively, in close collaboration with the CE Solution Developer and CE Solution Decision Maker. Furthermore, they prioritize design patterns to follow, structure the problem in terms of its dependencies and interfaces and define tasks per component, to focus the solution search.

The **CE System Analyst** identifies relevant design features from a structured understanding of the problem and quantifies sustainability impacts. They indicate the effects of circular design measures to provide reliable information for engineering design decisions. Their focus is analyzing product, material, and process characteristics for circularity, working with the CE Solution Developer, CE Quality Tester, and CE Solution Decision Maker.

The **CE Quality Tester** reviews planned CE strategies and evaluates risks of goal deviation. They ensure preventive goal achievement by verifying that circular measures fit requirements and by analyzing causes and impacts when issues arise.

The **CE Solution Developer** identifies effective circular measures, adapts the product's design and combines ideas into an overall concept, including

alternatives. They resolve conflicting goals and design circular, sustainable components, providing engineering design proposals to support decision-making.

The **CE Solution Decision Maker** evaluates solution ideas and alternatives against strategic requirements and company objectives and provides feedback on design drafts. They consider cost implications across design, production, and after-sales and make final selections of product architecture, materials, joining methods, and design details.

4. EVALUATION

An indicative application with an automotive manufacturer evaluated the role definitions. In a workshop with a sustainability officer, a sustainability expert, two engineers, and a project manager, we presented the roles embedded in a workflow of the MBSE software tool “CycloP” for early circular product development (see (BMBF, PTKA, 2025)). Currently, the manufacturer lacks a formal role model: A separate sustainability department (officer and LCA experts) performs LCAs on request and is weakly integrated with engineering. Consequently, the participants saw benefit in the role definitions, judged the roles suitable and aligned with engineering processes, and found them clear and complete. They noted the need to map roles to individuals within the development organization and integrate them with existing engineering roles. Consequently, this aspect still needs to be defined as it requires alignment with tasks already assigned based on existing engineering processes. In general, the roles were found to be sufficient for current tasks.

5. OUTLOOK

While the roles align with the evaluated practical requirements, broader validation is needed to confirm their applicability across diverse software tools and organizations. Future work should test the roles in varied tools and organizational contexts, with insights from these applications informing refinements. This will help ensure the roles remain adaptable and effective in different industrial environments.

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Mind the gap: An in-depth analysis of methodological frameworks for integrating environmental criteria in MEAT-based public tenders for metro rolling stock platforms

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EXTENDED ABSTRACT

Public procurement has increasingly emerged as a key strategic lever for achieving environmental policy goals [1], particularly in sectors like public transportation where long asset lifetimes and significant upstream and operational emissions make early intervention impactful. Within this landscape, the ecological decision making in procurement of metro rolling stock plays a pivotal role, as choices made today regarding vehicle design, energy use, and materials have lasting consequences for carbon emissions, local air quality, and resource efficiency over several decades [2]. European procurement law, notably through the Most Economically Advantageous Tender (MEAT) principle enshrined in EU Directives, allows contracting authorities to integrate environmental criteria alongside cost and technical performance [3,4]. However, in practice, many public transport authorities (PTAs) struggle to embed environmental performance in a methodologically sound, practically feasible, and legally defensible manner [1] – often supported by the eco-design paradox [5]. The complexity of rigorous Life Cycle Assessments (LCA), combined with limited in-house expertise and data access at early tender stages, often leads to either a minimal consideration of environmental impacts or the application of generic, non-comparable criteria.

This paper addresses this gap by proposing a streamlined yet structured method for integrating environmental performance into the MEAT evaluation of metro rolling stock tenders, with a focus on greenhouse gas emissions over the entire vehicle lifecycle. Drawing on the principles of the *TU Delft's* “Fast Track method” [6] and adapting them to the context of public tenders in the metro sector, a simplified LCA framework is operationalised that balances methodological rigor related to *ISO 14040* [7] and the *Product category rules for rolling stock and parts thereof (PCR)* [8] with feasibility subject to real-world constraints such as limited data at lower technology readiness level (TRL).

The Fast Track LCA methodology applied follows the *ISO 14040* framework, comprising objective and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. Based on the developed model, the CO₂ footprint and other key environmental indicators of metro rolling stock are assessed at an early stage of product development, aligned with procurement specifications and the applicable PCR. The system boundaries encompass the entire life cycle, which divided into upstream (raw material extraction and processing), core (assembly and transport), downstream use (operation and maintenance), and end-of-life (recycling, incineration, disposal) phases. Due to the limited primary data available during the tendering stages, the LCI uses secondary data sources based on *UNIFE's* 16 material categories [9] and the metro's high-level Bill of Materials. Operational energy use and maintenance spare parts are crucial contributors to the impact of environmental emissions, given the frequent acceleration of the metro and the use of auxiliary systems. The end-of-life assessment incorporates the *UNIFE* factors for material recycling, energy recovery, and waste [9] to realistically model the impact of disposal.

The LCIA focuses primarily on Global Warming Potential (GWP), using the open-source *IDEMAT* database [10]. The results are then visualised and interpreted to identify environmental hotspots and provide a transparent comparison between tender submissions, facilitating informed design improvements and procurement decisions.

To validate the developed streamlined LCA model, data from a reference metro trainset in Vienna was used to analyse the GWP across the life cycle phases. The results indicate that the core phase contributes minimally to the total GWP ($\sim 4.4 \times 10^{-5}$ kg CO₂eq), while the downstream use phase accounts for the majority of emissions ($\sim 1.45 \times 10^{-2}$ kg CO₂eq). Upstream material production accounts for roughly 8% of the total GWP. The analysis of the material hotspots revealed that ferrous and non-ferrous metals (especially

aluminium) make the largest contribution (35% each), followed by industrial batteries (20%), with control units and elastomers represent a smaller share.

To assess the sensitivity of the model, three additional scenarios were added: an eco-optimised metro variant and two geographic contexts (Vienna and Seoul). The eco-friendly variants showed modest upstream GWP reductions due to the choice of sustainable materials. In the scenarios for Seoul, core phase emissions were slightly higher due to longer transport distances. The downstream phase exhibited the largest differences, with the higher carbon intensity of the local electricity mix in Seoul leading to much higher operational emissions. Nevertheless, energy-efficient design significantly reduced the negative impact on the environment in both regions.

The study demonstrates that a high-level BOM approach in combination with open-source LCI data (e.g. *IDEMAT*) provides a resource-efficient yet robust environmental assessment suitable for early-stage procurement decisions. In line with *UNIFE*, PCR and EPD guidelines, this method enhances transparency and supports the environmental awareness among contracting authorities. The flexibility of the model allows it to be adapted to different rolling stock types and encourages innovation in the areas of energy efficiency and circular economy. As public transport increasingly integrates sustainable technologies and renewable energy, such environmental evaluation frameworks will be essential. Future advancements, including AI-driven tools and *Digital Product Passports*, promise to improve assessment accuracy and stakeholder collaboration. Overall, the integration of environmental criteria into procurement fosters sustainable public transport systems that are in line with international climate goals.

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Estimating potentials and trade-offs of material utilization in automotive applications

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EXTENDED ABSTRACT

The automotive sector has the potential to significantly contribute to the European Union's (EU) circular economy and climate change mitigation pathway (European Commission, 2020). By enabling circularity within the design stage of a passenger car this is a chance to enable the EU to meet their policy-goals.

Regarding our goal, first an introduction to the general problem in automotive industry and sustainability practices is needed. A passenger vehicle consists of multiple components, which again may consist of a mixture of materials (Delogu et al., 2017). One of these components being crash-management-systems (Delogu et al., 2017). These typically consist of aluminium or steel, which are energy intensive to produce (Delogu et al., 2017; IEA, 2023). The technical and design feasibility of using wood-based materials as substitutes for conventional materials in passenger vehicles and the use of wood within automotive industry have already been investigated (Delogu et al., 2017; Mair-Bauernfeind et al., 2020; Müller et al., 2020). We show how shifting biomass in form of wood into the design-stage of crash-management-systems impacts global warming potential (GWP) of these systems, also under different future pathways. A circular economy related factor we want to discuss, is the efficient and cascading use of wood, when applying it to a use case, before it is intended for energy recovery (Mair & Stern, 2017).

For this extended abstract we specifically consider the beginning-of-life stage of the automotive industry, where the materials for a passenger-vehicle are chosen. Here specifically front-crash-management (CMS) systems and their material composition are considered. Meaning that an estimation of the GWP

of different material options for CMS will be made for the time-horizon of 2050. This can be done by deriving material data in already existing databases and using already accessible models, that project the data into the future. Further, a system dynamics model will be used, to estimate trade-offs between sectors, if material usage shifts.

To calculate the difference in GWP for the conventional and novel material compositions, we use the database ecoinvent (v3.8) (ecoinvent, 2021), which provides information on GWP of an abundance of (although not all) materials and processed materials. This estimation is also based on the region the materials are retrieved and processed.

We further consider the possibility that in the future the GWP for the materials changes, especially regarding the evolving energy-mix in a region and technological advancements. This we account for by calculating the GWP for different shared-socioeconomic-pathway scenarios (SSP scenarios). This can be achieved using the model of PREMISE (Sacchi et al., 2022), which allows for calculations of SSP scenarios under different time-horizons. We consider the time horizon of 2050, regarding the GWP of the materials used in the respective CMS.

Within the Project of CARpenTiER the GWP under three different SSP scenarios was determined, by using the model REMIND (Baumstark et al., 2021) within the PREMISE (Sacchi et al., 2022) framework:

- SSP1: optimistic evolvement of the population, also regarding climate change mitigation, with decreased consumption (global mean surface temperature increase (GMST) at 2100y (base 2015y): 2.3-2.8 °C) (Paul Scherrer Institut, Potsdam Institute for Climate Impact Research, 2025; Riahi et al., 2017)
- SSP2: based on historical evidence on how and how fast changes are implemented this constitutes a scenario where some climate mitigation is done, but not as much as in SSP1 (GMST 2100y: ~3.5 °C) (Paul Scherrer Institut, Potsdam Institute for Climate Impact Research, 2025; Riahi et al., 2017)
- SSP5: Development of the economy relies largely on fossil resources, but it is considered that some of the processes we use become more efficient (GMST 2100y: ~4.5 °C) (Paul Scherrer Institut, Potsdam Institute for Climate Impact Research, 2025; Riahi et al., 2017)

The GWP under the SSP scenarios of conventional materials for crash-management-systems (CMS) as well as a novel approach to materials for CMS

(emerging from the Project CARpenTiER) is derived. We chose to calculate the GWP of different wood-processes as well as different coating materials for the wood within the analysis, to make find out whether the choice of (renewable) materials in the alternative CMS would make a considerable difference.

The materials of conventional CMS, where derived using the values of Delogu et al. (2017). Then the GWP for each of the SSP scenarios was calculated.

What we found can be summarized in 3 main points:

- 1) For each of the alternative CMS options, the GWP is lower than the GWP of the conventional CMS.
- 2) The GWP of each of the alternative CMS options do not differ significantly, which coating is chosen may be the most relevant factor, when it comes to end-of-life use cases of the alternative CMS.
- 3) The substitution effect decreases with the SSP-scenario. While all of the SSP scenarios show some saving compared to the conventional CMS, the savings decrease with the climate change mitigation rigidity of the SSP scenario.

The learnings of these results indicate that there is potential of substitution of conventional materials such as steel and alloy with wood-based resources. In any given case the wood-based resources yield a better result regarding their GWP than the conventional materials.

What needs to be considered is the end-of-life stage of the respective compared materials. If the CMS reaches its end-of-life, the renewable materials may not be suitable for re-use or re-cycling, depending on the coating materials used. The processing of the renewable materials may be complex and costly (if it is not used for reclaiming energy), while the re-cycling of the conventional materials may be energy-intensive but in other ways efficient (monetary cost or yield of re-cycled material).

For the next steps the WOODSIM system dynamics model (Boiger et al., 2024) is a helpful tool to estimate the trade-offs between sectors, if wood was to be implemented into CMS in the automotive sector.

When estimating the trade-offs between different sectors within the system dynamics model, we can show additional more complex connections regarding wood use. Such complex aspects can be emerging side-streams, in production of wood-based CMS and the evolution of trade-offs.

We discuss the aspects of changing to wood-based solutions in automotive design stage. We estimate the potential of sustainability-by-design in CMS under multiple future pathways. The system dynamics approach will allow us to discuss the issues arising from cascading use of wood in the wood-based sector.

ACKNOWLEDGEMENTS

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Design-to-CO₂ 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.

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-CO₂). 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.

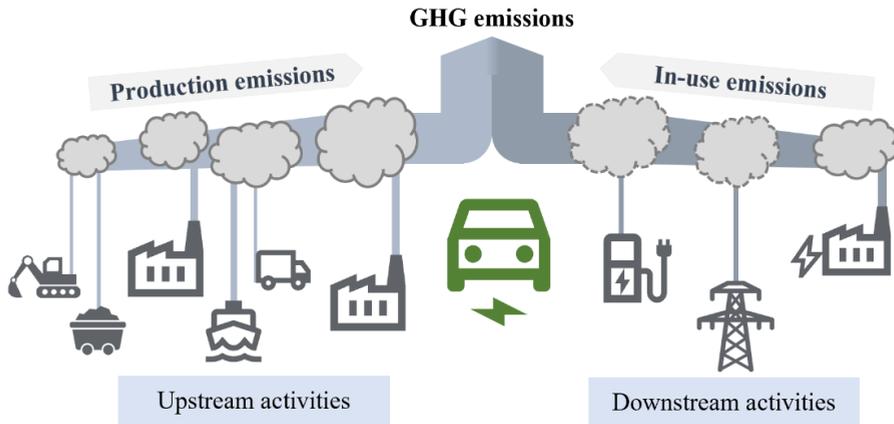


Figure 1: Schematic illustration of production and in-use emissions of an EV

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.

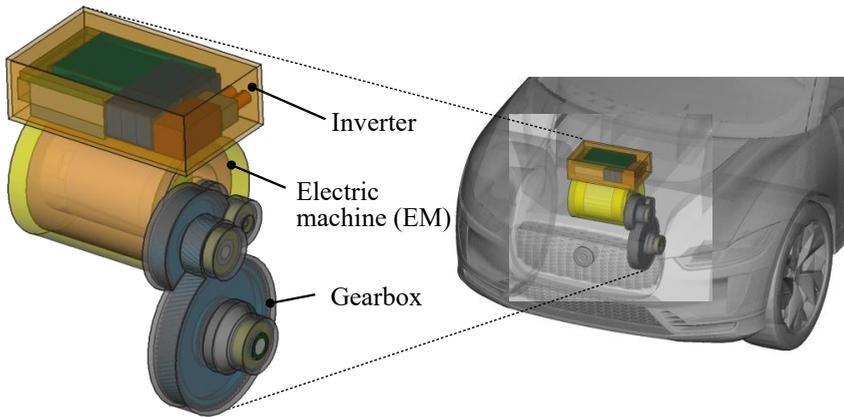


Figure 2: Visualisation of e-drive architecture; vehicle model from [5]

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].

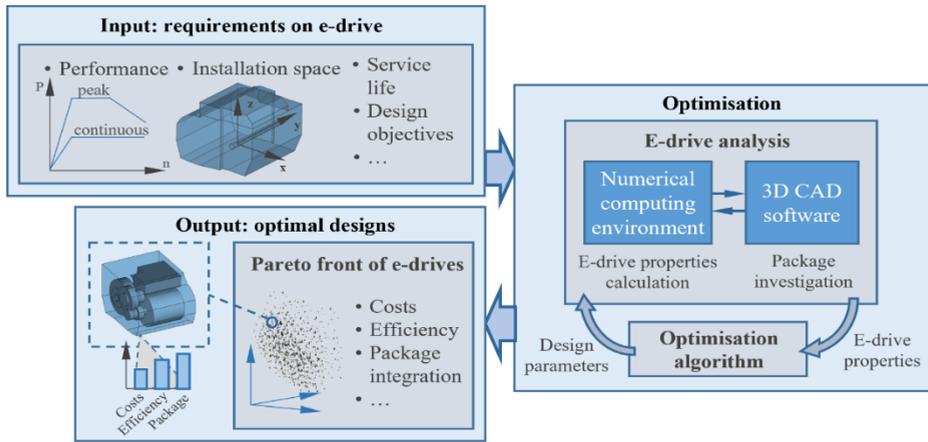


Figure 3: Simplified visualisation of e-drive optimisation process with OPED [8]

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

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

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].

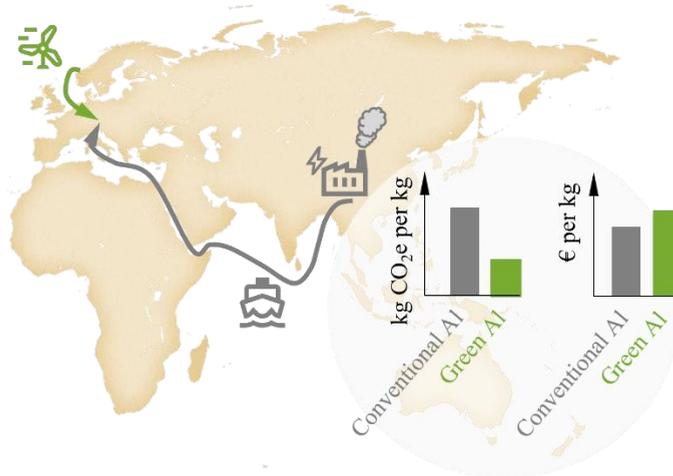


Figure 4: Example of supply chain options for aluminium with associated carbon footprint and cost

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 x^{\rightarrow}_{eDrive} in OPED (which define the full e-drive design) with the new supply chain parameters x^{\rightarrow}_{SC} yields the new total set of optimisation parameters

$$x^{\rightarrow} = (x_{SC1}, x_{SC2}, \dots, x_{eDrive1}, x_{eDrive2}, \dots). \quad (2)$$

Every value of x^{\rightarrow} 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 CO₂-equivalent GHG emissions $m_{CO_2 \text{ tot}}$ 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

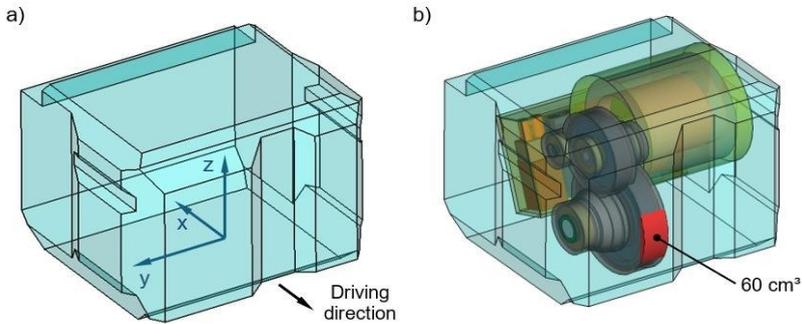


Figure 5: CAD visualisations of e-drive installation space: a) available space, b) package metric definition

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 CO₂-equivalent GHG emissions $m_{\text{CO}_2 \text{ tot}}$ ”. 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 $m_{\text{CO}_2 \text{ tot}}$ 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 $m_{\text{CO}_2 \text{ tot}}$ 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.

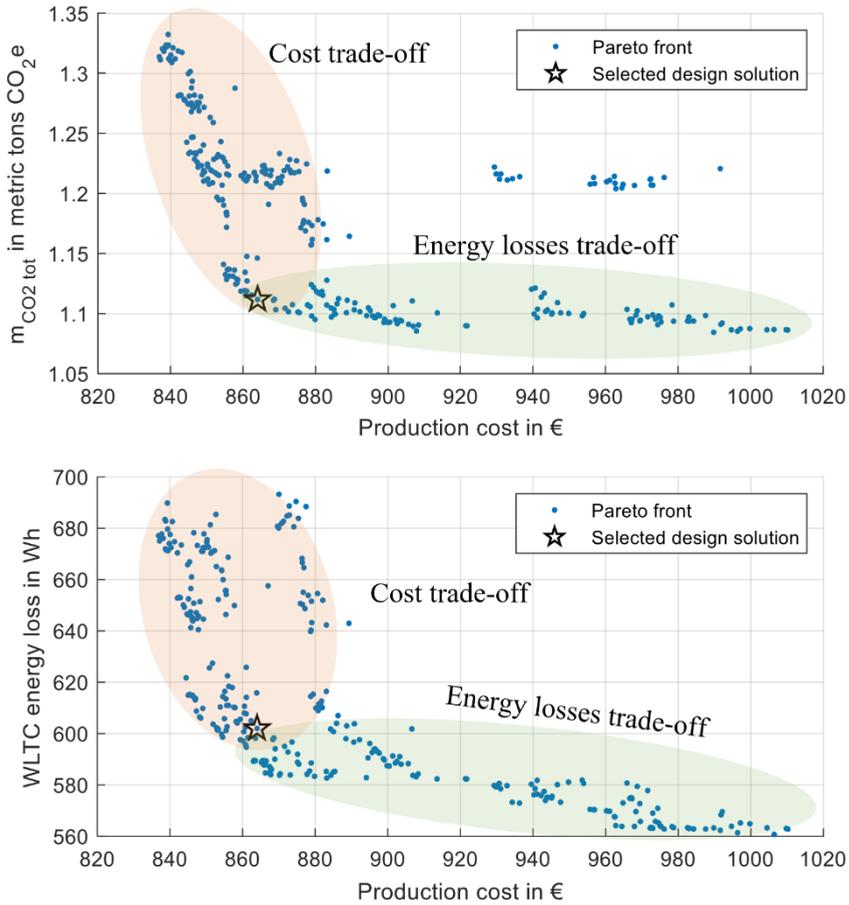


Figure 6: Projections of the obtained Pareto front approximation; only solutions that fit inside the installation space are shown

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 cm ³	0

$m_{CO2\ tot}$ in metric tons CO₂e

1.112

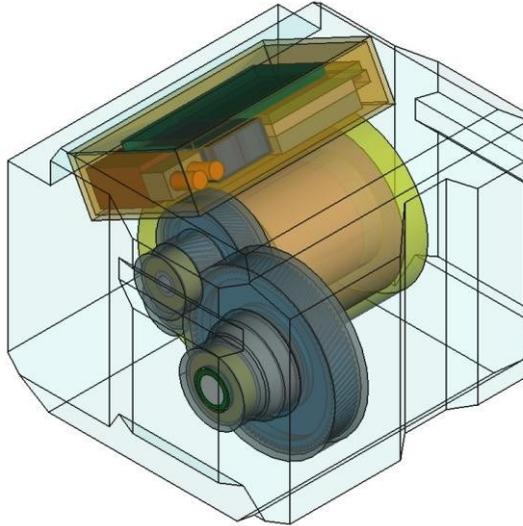


Figure 7: CAD visualisation of selected design solution inside the available installation space

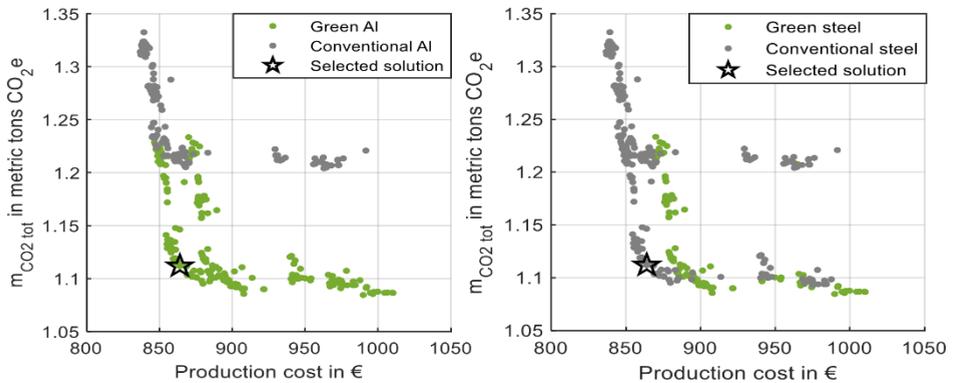


Figure 8: Visualisation of optimal supply chain selection

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 CO₂e (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 CO₂e (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 CO₂equivalent 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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Day 2 Session: Societal perspective in de-carbonized transport solutions

Social consequences of replacing steel or aluminium in automotive applications

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EXTENDED ABSTRACT

Wood-based materials offer a promising lightweight alternative to conventional materials like steel or aluminium to reduce fuel consumption and thus the environmental impacts of vehicles [1,2]. So far, research has been carried out to investigate the environmental impacts using alternative lightweight materials as an eco-design measure [3,4], though little is known about the potential social consequences. In general, research on the modeling of social consequences has been sparse, with merely two case studies investigating this approach [5,6]. Consequences differ from impacts in that they not only examine the effects of a change within the product system itself but apply broader system boundaries to account for indirect and market-level effects (e.g., how the allocation of raw materials across industries in a region is affected). The aim of this study is to analyse the social consequences of using wood for automotive applications including potential side-effects on other forest-based industries in Austria. The social consequences of replacing conventional materials with wood in the Austrian automotive industry were analysed by linking 11 social indicators (e.g., fatal and non-fatal occupational injuries, women in managerial positions) with labour input in forest-based industries and material flows in the system dynamics model WOODSIM [7]. The WOODSIM model (Figure 1) depicts the Austrian wood utilization system and allows to simulate direct and indirect effects on the social performance of industries resulting from shifts in wood supply across the industries of the forest-based sector [7,8].

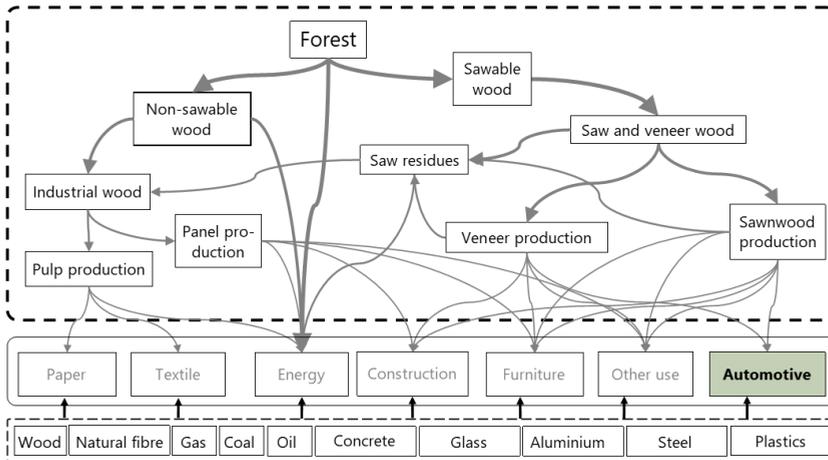


Figure 1: Schematic representation of the investigated system based on [7,8].

The sectoral performance of industries was calculated by using sectoral-specific data from official administrative bodies such as the Austrian Labor Market Service (AMS), the Austrian Chamber of Commerce (WKO), and Statistics Austria as well as more aggregated data from other sources (e.g., ILO, WHO) to depict social risks of global value chains. To illustrate the variability of effects depending on the specific application, two wood-based innovations were investigated: a wood-based side impact beam (SIB) for passenger cars replacing a steel-based SIB [2] and a wood-hybrid battery compartment for battery electric vehicles (WBC) replacing aluminium and steel [9,10]. In addition, these two innovations were compared to wood-based innovations in other sectors, namely in the construction and textile sector. To make the replacement scenarios comparable the same amount of additionally used wood for the SIB and the WBC was assumed (i.e., 25,000 m³).

Modelling the system dynamics of social consequences showed that steel is connected with higher risks regarding fatal occupational injuries than aluminium, resulting in less social consequences for the WBC. The high-risk countries for this indicator are especially the Ukraine, the Russian Federation and Chile [8]. An improvement in the social performance can be thus achieved by taking measures improve the working conditions in the companies of the value chain or designing the value chain in a way that only suppliers from low-risk countries (e.g., Sweden, Greece) are chosen. Comparing innovations of different industries shows that the automotive industry has the potential to result in bigger improvements than the construction or textile industry. This is mainly due to the transition of value chains from globalized to primarily

regional ones. Hardly any effects can be observed if the replaced materials are largely sourced from Austria or neighbouring countries. Given the limited availability of wood, and assuming a consistently sufficient demand to clear the wood market, significant indirect effects on other wood-processing industries were observed. For example, the incorporation of wood in automotive applications leads to indirect consequences for the "other use" industry, as materials with greater social risks are being utilized to replace the wood that has transitioned to the automotive sector [8]. These findings can be used to identify optimization potentials in the Austrian wood utilization system in terms of its social performance. However, some of the results may be biased due to the poor data situation for the indicator of non-fatal occupational accidents [8]. Austria reports the highest number of non-fatal accidents, while countries that are transitioning or developing tend to have significantly lower figures. This discrepancy may be attributed to varying reporting practices across different regions of the world. This work offers a first attempt to model the social consequences of an innovation with system dynamics modelling which is essential to not overestimate positive effects when analysing consequences. Future studies may focus on optimizing systems with respect to various objectives, particularly aiming to reduce environmental and social impacts.

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Guiding the research on bio-based supercapacitors towards a socially viable value chain development

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ABSTRACT

The transition to sustainable and resource-efficient vehicles is crucial for addressing social conditions and advancing electromobility. Conventional batteries using materials like lithium and cobalt are linked to significant social issues, prompting research into alternatives that avoid those issues. This study evaluates a bio-based supercapacitor under development in the EU project EMPHASIS through a Social Life Cycle Assessment (SLCA), aiming to enhance the social sustainability of electromobility. Supercapacitors offer advantages over batteries, including high power density, rapid charge-discharge cycles, and long operational life. The bio-based supercapacitor utilizes renewable resources for electrodes and bio-electrolytes, avoiding critical raw materials and toxic substances. These innovations promise reduced social impacts compared to conventional energy storage systems. Conducting SLCA during product development faces challenges like uncertain value chains and limited data availability. However, early social sustainability assessments are essential for creating sustainable products. Social risk mapping through expert workshops and secondary data highlights potential impacts across the supercapacitor's hypothetical global value chain. Resource extraction and end-of-life phases are identified as having the highest social implications, particularly for workers. The study underscores the potential of bio-based supercapacitors to significantly improve the social sustainability of electromobility. By leveraging renewable resources and fair manufacturing practices, they can reduce social risks while contributing to broader goals of equity and

sustainable development. These findings provide valuable insights for stakeholders in the automotive and energy sectors, emphasizing the importance of integrating social innovation into next-generation supercapacitor development.

1. INTRODUCTION

Electric vehicles (EV) are a popular alternative to conventional combustion engine vehicles due to their potential for lower greenhouse gas emissions and reduced fossil fuel dependency (Alanazi, 2023). EVs require power sources with high energy density and a long cycle life. Materials used should be cost-effective and available abundantly (Yoo et al., 2014). Rechargeable batteries, such as lithium-ion batteries, are currently the state of the art power source for EVs. However, batteries have several disadvantages, including material ageing, degradation and limited cycling performance (Azega et al., 2024; Schmalstieg et al., 2013; Zhao et al., 2020). Supercapacitors (SC) can be regarded as alternatives to conventional batteries due to their longer life span, ability to be rapidly (dis-) charged, higher cycling performance and minimal material aging or degradation (Azega et al., 2024).

SCs offer advantages in performance, as well as environmental sustainability, compared to batteries but no studies have been performed on their social implications. Achieving social sustainability represents an essential part of sustainable development but has been largely neglected compared to the economic and environmental pillars of sustainability (Hutchins & Sutherland, 2008). Mining activities for lithium or other critical raw materials are associated with social impacts such as “child labour” and “occupational accidents” and are responsible for the severe social impacts of battery and SC value chains and affect multiple stakeholder groups involved in that value chain (Rahimpour et al., 2024). ‘Value chain’ in this context is defined as the complete sequence of activities, processes and actors involved in creating a product or service along its entire life cycle from conception to disposal while systematically considering the associated social and socio-economic impacts at each stage (as depicted in Figure 1) (UNEP, 2020). The SC developed in the EU project EMPHASIS uses bio-based materials like cellulose, lignin and grape molasses produced within the European Union for the current collector and electrode and avoids the use of critical raw materials and mining activities. However, its value chain may still exhibit severe social impacts as studies have shown that upstream processes in agriculture present a high potential for social risks regarding for example poverty, rural development and job

security, especially in countries exporting bio-based materials (Spierling et al., 2018).

Social Life Cycle Assessment (SLCA) is a method used to assess potential social impacts of the bio-based SC along its value chain. SLCA mostly deals with qualitative information such as acceptable working conditions, respect for human and civil rights and equality (Ashby, 2024) and is devoted to the evaluation of potential positive and negative social and socio-economic impacts of a product (Colombo et al., 2024; Dahiya et al., 2020). Noteworthy social hotspots in SLCA on batteries are “child labour”, “forced labour”, “corruption” (Popien et al., 2023; Shi et al., 2023), “labour rights and decent work”, “health and safety” and “human rights” (Thies et al., 2019).

Assessing the sustainability impacts of any product poses complex challenges but in particular for emerging technologies at a low technology readiness level (TRL). Most sustainability assessments are conducted for established systems already in the market, meaning that they are produced on industrial scale and follow a fully determined production process (Blanco et al., 2020). In recent years, environmental assessments, in particular LCAs, focusing on emerging technologies have emerged (prospective or ex-ante LCA) (Cucurachi et al., 2018) and multiple upscaling frameworks have been developed for LCA of emerging technologies (Simon et al., 2014; Tsoy et al., 2020; Weyand et al., 2023). These frameworks recognize that innovations and technologies can most easily be changed and optimized during the development phase of a product (Bergerson et al., 2020; Hetherington et al., 2014). SLCA studies on emerging technologies are challenging because the assessment of social impacts requires data accurately representing the value chain for industrial scale production (Cecere et al., 2024) which is often not available and upscaling a value chain remains difficult. Data collection and data availability represent the largest challenges in any SLCA study but especially when dealing with emerging technologies. Social impacts are hard to predict and are likely to be underestimated during upscaling from laboratory to industrial scale. Some studies have attempted to develop methods to conduct SLCA on different stages of technology development. For example, Haase et al. (Haase et al., 2022) identified specific indicators can already be assessed during the early stages of development of technologies used in the energy sector. Another study showed that sensitivity analysis with alternative scenarios (change production country or energy mix) can increase or decrease social risks due to value chain complexities and therefore proofed the importance of conducting SLCAs already early on in the development phase as it can mitigate future risks and support the development of socially sustainable extraction or production processes (Muller et al., 2021). To combat the lack of product- or site-

specific data, early stage SLCA can use generic or country-specific data to create a preliminary estimation of potential social risks and benefits (Groiß-Fürtner et al., 2023; Mair-Bauernfeind et al., 2020). Generic SLCA is not able to identify the “real-life” social implications but can provide preliminary information on potential social problems, risks, benefits and opportunities (Groiß-Fürtner et al., 2023).

The prioritisation of social factors and impacts is an important first step when conducting a SLCA study as it indicates where the focus should lie (Fürtner et al., 2021), in this study this is done with a stakeholder workshop with stakeholders involved in the development of the SC. The potential social risk of the SC is determined using multiple SLCA approaches. The study shows that bio-based SCs can substantially reduce the social impact of electromobility by using renewable resources, avoiding critical raw materials and ensuring fair manufacturing practices.

2. MATERIALS AND METHODS

SLCA follows the framework for Life Cycle Assessment (LCA) set out in the ISO Norms 14040/44 for Life Cycle Assessment (ISO 14040:2006, n.d.), the ISO Norm 14075 for Social Life Cycle Assessment (ISO 14075:2024, n.d.) and the Guidelines for Social Life Cycle Assessment of Products and Organisations 2020 established by the United Nations Environment Programme (UNEP) (UNEP, 2020). Social impacts are considered to be the consequences on stakeholders in the context of activities along a products value chain, such as resource extraction, manufacturing, distribution, use, recycling and final disposal (UNEP, 2020). SLCA aims to improve a products value chain by providing information on the socio-economic impacts of the product to decision-makers, researchers and developers (Thies et al., 2019). SLCA is complementary to the environmental and economic assessment of a product and thereby provides a more holistic and comprehensive picture of a products sustainability (UNEP, 2020). The assessment is an iterative process that involves multiple steps including completeness, consistency, sensitivity and quality

checks. The sensitivity analysis identifies the significant social impacts, risks, stakeholder groups and life cycle phases (UNEP, 2020).

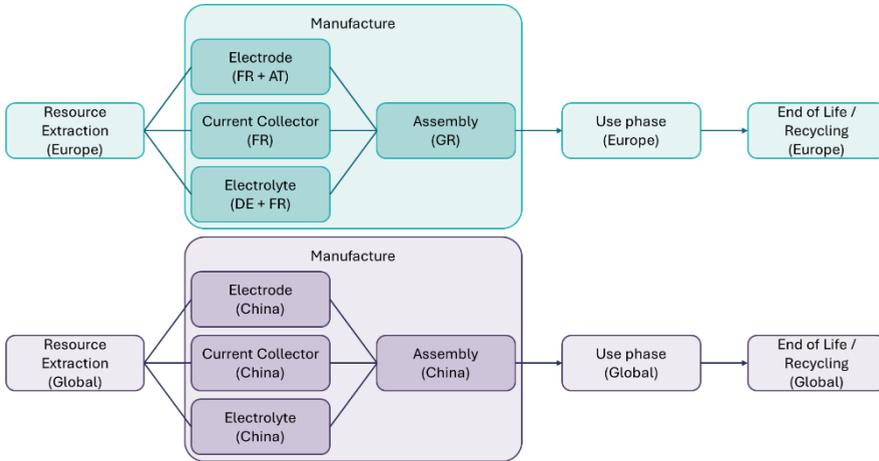


Figure 1: European (top/turquoise) and Global (bottom/purple) value chain of the SC, including country references (source: own figure)

The bio-based SC is currently in development, with production on laboratory scale and a European value chain, with production specifically taking place in Austria, France, Germany and Greece. For an upscaled production a hypothetical global value chain is created with production moving to Asia Pacific, as this region currently produces 38% of the global SCs (Kings Research, 2024). For this assessment China is assumed as the producing country. It can also be assumed that the global value chain has a higher social impact than the European value chain, as developing countries typically exhibit higher social impacts and risks than developed countries (Shi et al., 2023). The European and Global value chains, including the reference regions for resource extraction, manufacturing, use and end of life, are depicted in Figure 1. Transport between the individual production sites is not included in the assessment, as it can be assumed that in an industrial and global value chain production of the electrode, current collector and electrolyte and their assembly are done at the same production site.

A workshop on the prioritisation of social factors in SLCA was held together with the project partners in EMPHASIS in June 2024. The 17 participating project partners were asked to think about any social factors relating to SC production, use and disposal that might positively or negatively affect

workers, society, local communities, value chain actors, consumers or children. All workshop participants can be regarded as being experts in the value chain. As part of the workshop the workshop participants were asked to answer three questions on the platform Mentimeter: 1) What is the area with the highest social impact in SC value chains?, 2) How would you rank the stakeholder groups regarding their vulnerability? and 3) What other stakeholder groups do you perceive as important? In a world café setting, the participants were asked to identify negative and positive social factors that affects each stakeholder group. The stakeholder groups local community and society, as well as consumers and children were grouped together into two larger stakeholder groups.

The potential social risk of the bio-based SC production is assessed using two SLCA approaches: the social risk assessment following the second-level SLCA methodology developed by Groß-Fürtner et al. (Groß-Fürtner et al., 2023) using country or sector specific secondary data and the Social Hotspots Database (SHDB) social risk mapping tool that provides information on the social risk of 132 social indicators for 57 sectors in countries worldwide (SHDB, 2022). For the second-level LCA the stakeholder groups workers, local communities and society across four production countries (Austria, Germany, Greece and France) are included in the assessment. The use of generic data for the assessment allows for an assessment already during the development phase when product specific data is not available and represents the start of an iterative and open-ended assessment process of the bio-based SCs value chain. The social indicators assessed in this study focus largely on the stakeholder group workers. The impact assessment uses the reference point method where the EU-27 averages serve as the reference points for all indicators. The assessment followed a method developed by Zira et al. (Zira et al., 2020), where the social risk potential is considered high with values above 0.5 and values below 0.5 are considered low risk.

The social risk mapping includes the hypothetical Global value chain with production in China. The indicators can be separated into “labour rights and decent work”, “health and safety”, “society”, “governance” and “community”. This web-based tool is used to assess the social risk associated with the automotive and chemical sector for the current European and the hypothetical Global value chain. Within the tool, social risk is categorized into low, medium, high and very high risk; indicators experiencing low risk in all five countries or have missing data for at least one country are omitted from the assessment, which leaves a total of 77 social indicators. Of those 77 indicators 14 are selected to be assessed focusing largely on workers’ health and safety as well as labour regulations.

3. RESULTS

3.1 PRIORITISATION WORKSHOP

The workshop revealed that recycling, production and resource extraction are seen as the three areas with the highest social impact. Consumers were ranked as the most vulnerable stakeholder group, followed by workers. Value chain actors were ranked as the least vulnerable stakeholder group. Policy makers and researchers were named as additional and important stakeholder groups.

For the stakeholder group workers the following social impacts were identified: reduced labour intensity of recycling and disposal (compared to batteries), lower toxicity due to reduced used of heavy metals and safety issues during production and recycling. Participants ranked the impact category “health and safety” as the most important, followed by “social benefits and social security”.

For the two stakeholder groups local community and society “safe and healthy living conditions” were ranked as the most important factor. This is followed by “local employment”, “pollution of the environment” and “consumption of local resources”. “Stress on local infrastructure”, “shift of population demographics” and “research courses for the local community” were ranked as the least impactful factors.

For the stakeholder group value chain actors the manufacturers, electricity providers and clients were ranked as the most impactful actors along the value chain. Actors such as policy makers and recycling companies were ranked as the least impactful value chain actors.

For the stakeholder groups children and consumers “health and safety”, “environmental impact” and “consumer privacy” were ranked as the most impactful social factors. For the stakeholder group children “education” was identified as an important social factor as well, especially regarding the gamification aspect of smart textiles.

3.2 SOCIAL RISK ASSESSMENT OF THE EUROPEAN VALUE CHAIN

The social risk assessment of the bio-based SC production in Austria, France, Germany, and Greece reveals varying levels of risk impacting workers and societal conditions. Austria shows overall moderate risk, primarily in worker

health and safety, with fatal and non-fatal accidents in the manufacturing sector posing the highest risk, but they are still under the EU-27 threshold value for high risk (0.7) (eurostat, 2024). Austria exhibits a strong performance in collective bargaining and research and development (R&D) with risk scores under 0.3 (International Labour Organization, 2025). France faces medium to high social risks, with non-fatal and fatal accidents posing high risks between 0.7 and 0.8 (eurostat, 2024). Unemployment among people with higher education also represents a relatively high risk of 0.6 (eurostat, 2025b). Similar to Austria, France also exhibits a strong performance in collective bargaining by enforcing worker rights (European Parliament. Directorate General for Internal Policies of the Union., 2016). Germany excels in most indicators with social risk values below 0.5 in almost all indicators. The indicators freedom of association, collective bargaining and non-fatal accidents have a relatively high social risk compared to the other indicators in Germany (Labour Rights Index, 2025). Nevertheless, Germany maintains a strong industrial base and R&D investment (eurostat, 2024). Greece exhibits the highest social risk among the four production countries, with substantial challenges in worker rights, unemployment of people with advanced education and societal conditions. Unemployment of people with advanced education poses a risk of almost 0.8, due to skill mismatches (eurostat, 2025a) and collective bargaining has a risk of 0.7 (European Parliament. Directorate General for Internal Policies of the Union., 2016). Worker rights are represented by the indicators vulnerability to modern slavery and working hours which have social risk values of 0.5 and 0.6, respectively (Poulimenakos et al., 2021).

3.3 SOCIAL RISK MAPPING FOR THE EUROPEAN AND GLOBAL VALUE CHAIN

The results of the social risk mapping show the varying degree of social risk in the four current production countries (Austria, Germany, Greece and France) and the potential production country (China) when producing on a global value chain. Overall, the results show that the European countries experience less social risk compared to China, with Greece experiencing the highest degree of social risk among the European countries. The social risk for two relevant sectors for SCs can be assumed to be the same in all indicators except for the overall country-sector risk of forced labour, where China experiences a medium risk in the automotive sector but a very high risk in the chemical sector.

Table 1: Social Risk Mapping of the four European value chain (Austria, Germany, Greece and France) and potential Global value chain (China) (adapted from the social risk mapping tool (SHDB, 2022)).

Social Risk Indicators	Austria	Germa	Greece	France	China
Risk of child labour					
Risk of forced labour					
Risk of human trafficking					
Risk of excessive working time					
Risks related to freedom of association, collective bargaining					
Risk of no paid annual leave					
Risks related to labour laws and labour conventions					
Unemployment level					
Risk of occupational toxics and hazards					
Risk of labour injuries and labour fatalities					
Risk to gender equality					

Risk to peace	    
Risk of corruption	    
Risk to democracy	    

Low risk:  medium risk:  high risk:  very high risk: 

In two of the 14 social indicators analysed in this study China experiences low social risk: “Risks related to labour laws and labour conventions” and “Unemployment level” but experiences very high risk in six indicators: “Risk of forced labour” (chemical sector), “Risk of human trafficking”, “Risks related to freedom of association, collective bargaining”, “Risk of occupational toxics and hazards”, “Risk to peace” and “Risk to democracy”.

Within the European countries Greece is the only one experiencing very high risk in the two social indicators “Risks related to freedom of association, collective bargaining” and “Unemployment level”. “Risk of no paid annual leave” and “Risk to gender equality” are the two indicators where Greece experiences low risk. Austria and Germany experience the lowest degree of risk with for indicators having medium risk and one having high risk, France has the indicators at medium risk and three indicators at high risk.

4. DISCUSSION

The transition to sustainable and socially responsible energy storage systems is critical for advancing electromobility and addressing the social challenges associated with SC production. By using multiple SLCA approaches the study identified key social risks and opportunities across the current European and a hypothetical Global value chain and provides valuable insights for stakeholders in the automotive and energy sectors.

The results of the workshop and the social risk assessments are confirmed by the literature on social assessments of batteries, with all of them highlighting the complex and multifaceted nature of social risks associated with battery and SC production and their value chains. Existing literature confirms that resource extraction is the life cycle stage associated with the highest social

risks, with social indicators such as labour right violations, unsafe working conditions and adverse impacts on the local community being the largest concern (Koesse et al., 2023; Popien et al., 2023; Souza et al., 2025). The prioritisation workshop consisted of mostly researchers involved in the development of the SC who prioritised consumers as the most vulnerable stakeholder group, this result is likely biased because the researchers focused on the potential risk exposure of the final product to consumers and not the production itself, which mostly impacts workers and local community.

The social risk assessment and mapping reveal substantial geographic variability in social risks, both within Europe and globally. Among the European countries studied, Austria and Germany exhibit relatively low social risks, while France faces medium risks, and Greece experiences the highest risks. Greece's challenges include high unemployment among educated workers, weak collective bargaining, and vulnerability to modern slavery (European Parliament. Directorate General for Internal Policies of the Union., 2016; eurostat, 2024, 2025a; Koesse et al., 2023). These findings align with broader research indicating that developed countries generally experience lower social risks compared to developing or emerging economies (Shi et al., 2023). When expanding the analysis to a global value chain, the inclusion of China highlights stark contrasts. While China demonstrates low risks in areas like labour laws and unemployment, it faces very high risks in critical indicators such as forced labour, human trafficking, occupational hazards, and risks to democracy and peace (eurostat, 2024; Poulimenakos et al., 2021). These results emphasize the importance of considering regional contexts and regulatory environments when assessing social risks.

The discrepancies observed between the social risk assessment and social risk mapping underscore the methodological challenges in SLCA. The choice of methodology, data sources, and indicators can significantly influence the results, as seen in the contrasting performance of France in different assessments (European Parliament. Directorate General for Internal Policies of the Union., 2016; eurostat, 2024). This variability highlights the need for standardized and transparent SLCA methodologies, such as those outlined by the UNEP guidelines (UNEP, 2020), to ensure consistency and comparability across studies (Koesse et al., 2023).

Data availability remains a substantial limitation in SLCA studies, particularly for upstream and downstream processes in less regulated regions. The reliance on generic or sectoral data rather than site-specific information can obscure social risks and leads to substantial levels of uncertainty in the results. Stakeholder involvement is critical for addressing these gaps and ensuring

that SLCA processes focus on the most relevant issues (Fürtner et al., 2021; Groß-Fürtner et al., 2023; Koese et al., 2023). Additionally, the method developed by Zira et al. (Zira et al., 2020) tends to exclude extremely high or low risk potentials, leading to more homogenous risk levels (Mair-Bauernfeind et al., 2024). Nevertheless, this method was still able to showcase potential areas of high risk indicating which areas should be focused on. Following the limitations of this study, the assessment cannot be used to identify product specific hotspots but is the first step to identifying the potential hotspots. However, addressing these challenges requires a holistic approach that integrates fair manufacturing practices, ethical sourcing, and robust worker protections throughout the value chain as well as data availability on a product level.

5. CONCLUSION

The findings from this study and the broader SLCA literature provide initial insights into the potential social risks associated with SC production in the five countries assessed. Due to the use of secondary and generic data, the results cannot depict the actual social risks associated with SC production but are able to identify potential social hotspots on a country- and sector-level. All four European countries perform relatively well in terms of social risk potential, indicating that developed countries are associated with relatively low social risks during production. The inclusion of China highlights the need for stringent due diligence and ethical sourcing practices to mitigate risks in areas such as forced labour and occupational hazards.

The findings highlight the importance of conducting early social sustainability assessments, even in the face of uncertain value chains and limited data availability, to guide the development of socially viable products. These initial results can serve as a roadmap for researchers, policymakers, and industry stakeholders, emphasizing the importance of aligning technological advancements with social responsibility to create a more sustainable future. The bio-based SCs represent a promising innovation for advancing social sustainability in electromobility. By using renewable resources, enforcing fair labour practices, and enabling social innovation next-generation energy storage systems can contribute to broader goals of equity and sustainable development. The results provide actionable insights for stakeholders in the automotive and energy sectors. By prioritising health and safety, social benefits, and local employment, policymakers and industry leaders can enhance the social sustainability of bio-based SCs.

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Exploring the acceptance of shared follow-me delivery robots: An extended UTAUT2 approach

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EXTENDED ABSTRACT

In response to pressing challenges such as climate change, air quality concerns, growing urban populations, and overloaded transport networks, autonomous vehicles (AVs) are increasingly seen as a promising solution [1, 2]. Among these AVs, follow-me delivery robots (DR follow) represent a novel and underexplored application that autonomously track and follow a human operator, using camera and/or LiDAR sensors [3]. Designed for pedestrian and cycling infrastructure, they reduce physical strain and integrate smoothly into dense urban environments [1, 3, 4]. Despite their growing technological maturity, the acceptance of DR follow robots remains largely unstudied [1].

To investigate this, the present study focuses on a use case where DR follow robots are part of a sharing system. In such a scenario, individuals can temporarily borrow a robot to transport goods or personal items over short distances, enhancing active transport.

To examine user acceptance in this context, this study applies the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) a widely used framework in technology acceptance research. In recent years, UTAUT2 has been increasingly applied and extended to investigate acceptance of various autonomous transportation solutions [5, 6, 7], demonstrating the model's adaptability and relevance for capturing behavioural intention and use behaviour across diverse contexts of autonomous transport.

To explore the acceptance of SDR follow, five focus groups were conducted with 22 non-experts and 11 experts in urban goods transport in Weiz and

Feldkirchen (Austria) between April and June 2024. In all groups, semi-structured interview guides ensured a balance between comparability and openness to new insights.

Sessions were moderated and recorded with consent. Non-expert discussions lasted 160–180 minutes, expert discussions 105–125 minutes. All discussions were transcribed, anonymized, and analysed in MAXQDA24 using thematic content analysis, combining deductive UTAUT2-based coding with inductive identification of additional constructs. In total, 748 coded references were identified.

The analysis of the focus group discussions revealed that acceptance of SDR follow seems to be influenced by nine key factors: (1) product features, (2) facilitating conditions, (3) performance and (4) effort expectancy, (5) perceived risk, (6) service availability, (7) perceived reliability, (8) hedonic motivation and (9) price value.

Regarding (1) product features, participants emphasized that the robot should accommodate everyday mobility and shopping needs. Participants highlighted the importance of size, load capacity, and practical loading-surface design. Terrain adaptability was considered essential, with the expectation that the SDR follow can operate on various surfaces and under different weather conditions. A range of about 10–15 km, reliable battery life, and appropriate speed were considered necessary for daily use. Additional features such as thermal insulation, weather protection, active cooling, and anti-theft measures were viewed as factors that could further increase acceptance.

(2) Facilitating conditions were the most frequently mentioned construct of the original UTAUT2 framework. Participants emphasized that aspects of road and mobility infrastructure, including narrow paths, paving blocks, public transport connections, and bike-sharing co-location, influence acceptance. The type of sharing station was also seen as important, with distinctions between retailer-based and public models. Participants further mentioned the importance of assistance, particularly for older or less tech-savvy users, and raised concerns about unclear legal conditions. Urban areas were generally considered more suitable than rural ones due to distance and topography, and snow was noted as a potential limitation, underscoring the need for winter operability.

Moreover, the (3) performance expectancy was discussed as an influencing factor for acceptance. Participants highlighted increased independence, easier transport of heavy goods, everyday convenience, and greater efficiency in daily routines. Potential health benefits and shifts toward more active

lifestyles were noted. Experts further emphasized business advantages, including faster deliveries, increased sales through improved transport options, and the innovative appeal. Societal benefits, including reduced car traffic, calmer streets, better air quality, and more liveable urban spaces, were also seen as enhancing acceptance.

Participants also emphasized that the (4) effort expectancy, in terms of intuitive, low-effort operation, is important for acceptance, whereas concerns about tasks such as returning the SDR follow made the system seem potentially inconvenient. Learning barriers for older adults were highlighted while participants stressed a low usage threshold and complementary support services as well as multilingual interfaces to accommodate tourists and linguistically diverse users.

Focus group participants further highlighted several (5) risks that appeared to affect their willingness to adopt SDR follow. Key concerns centred on potential misuse, vandalism, and theft. Additionally, the risk of accidents, including property damage and injuries to users or others, was frequently mentioned. Urban environments were considered particularly risky due to complex traffic conditions and crowded areas. In response to these concerns, many participants called for clear regulations and comprehensive insurance policies to mitigate risk and enhance trust.

Experts and non-experts agreed that acceptance of SDR follow may also depend on its reliable and convenient (6) service availability via a well-designed sharing infrastructure. Crucial factors included on-demand accessibility without requiring detours. High usage potential was expected in densely populated residential areas and pedestrian-heavy zones. Suggestions also included integration with existing sharing systems and placement at Park & Ride facilities. The option to reserve robots in advance was seen as an important feature to enhance user convenience.

Acceptance of the SDR follow was further linked to its technical reliability (7), particularly regarding the follow-me function and smooth operation in real-world environments. Participants expressed expectations of consistency and dependability, including regular maintenance and cleanliness. Availability was considered a key aspect of reliability, with participants emphasizing the need for multiple robots to be accessible simultaneously and for shared stations to be easy to locate and clearly marked.

Participants moreover highlighted that (8) hedonic motivation, including pleasure, enjoyment, curiosity, and interest, could positively influence

acceptance of the SDR. Some specifically described positive emotional experiences as important for user engagement.

Finally, (9) price-value was perceived as a critical factor influencing the acceptance of SDR follow. compared it to the costs and effort of private cars, cargo bikes, or delivery services, noting that acceptance would be higher if SDR follow were cheaper and more convenient. Many suggested that offering the service free of charge could further support acceptance.

This study identified nine key factors shaping the acceptance of SDR follow. While the UTAUT2 model provides a solid starting point for understanding the acceptance in this context, it requires additional extended constructs and contextual adaptations. Since SDR follow has not yet been introduced into everyday life, participants largely referred to anticipated functions and contextual fit rather than established habits or social influences.

Future research might seek to validate the findings using survey-based and experimental approaches with larger sample sizes, ideally incorporating real-world applications of functional SDR prototypes to capture actual user behaviour.

Overall, the findings in this study offers a nuanced and context-sensitive framework for understanding how individuals form intentions to adopt SDR follow.

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Discrete choice analysis of travel behaviour in Austria

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ABSTRACT

The transport sector significantly contributes to environmental impacts, making its decarbonisation essential for meeting Europe's 1.5°C climate goal. This requires both technological improvements and shifts in travel behaviour. To support the latter, understanding current determinants of mode choice is crucial. This study uses a nested logit model calibrated with data from Austria's national mobility survey "Österreich Unterwegs" to examine how socio-demographic and infrastructure-related factors influence the likelihood of choosing public transport, cycling, or walking over car use. Results show that proximity to public transport and household income are key predictors. The findings also underscore car dependency in rural areas and reveal the inelasticity of car use with respect to travel time, suggesting strong behavioural lock-in.

1. INTRODUCTION

This study aims to analyse travel behaviour in Austria using a nested multinomial logit (MNL) model and find factors which help determine travel mode choice between walking, cycling, driving or taking public transportation. Such an endeavour can help with guiding transport planning towards a more sustainable path and assist the government's efforts to decarbonize this sector (BMK, 2021). The transport sector is one of the leading emitters in the world. It accounts for almost 21% of all GHG emissions and 24% of CO₂ emissions worldwide (Ritchie & Roser, 2023). Within Austria, the transport sector accounts for the highest CO₂ emissions out of all sectors at 37% and has contributed the most to the overall increase in emissions since 2015 (IEA, 2022). Not only is this sector's impact on the environment tremendous but there is

also harsh inequity in emissions versus exposure, as poor households relying more on walking or public transportation bear the brunt of vehicular emissions higher than affluent households (Breffle et al., 2015). Therefore, there is a strong need for sustainable transport systems and decarbonisation. In its Mobility Master Plan, Austria signifies the importance of decarbonizing the transport sector to meet its carbon neutrality goals by 2040 (BMK, 2021). The country aims to utilize the Avoid-Shift-Improve Strategy, targeting I) mobility behaviour from the usage of private vehicles to using more public transportation and active mobility, II) elimination of combustion engine transport technology by ensuring that all cars and two-wheelers are electric, and III) a shift from commercial vehicles to carbon-neutrality via electrification and eliminate fuel export by 2040. Changing mobility behaviour alone can help reduce at least 3 million tonnes of CO₂ equivalent emissions in the country (BMK, 2021). This means there is a dire need to analyse people's mobility behaviours and identify factors which shape them in order to shape policies that can aid in changing people's travel behaviours in Austria. For this study, the focus will be on the province of Styria or originally called Steiermark. This brings us to the research questions being answered in this study: What are the significant socio-demographic and transport infrastructure-related determinants of mode choice within Austria?

1. People from which background are more likely to use cars over public transportation (PT), biking, and walking?
2. How does a shift in travel time and the distance to public transportation influence people's adoption of cars, public transportation, biking, and walking?

2. METHODOLOGY

This study used the nested MNL method to try and build a mode choice model for Austria. Three sample districts were chosen within the Austrian province of Styria- Graz, Graz Surroundings and Deutschlandsberg. Each representing urban, semi-peripheral and rural area respectively (see Fig. 1). The sample size comprised of 12,541 observations from these districts all of which were used in the study.

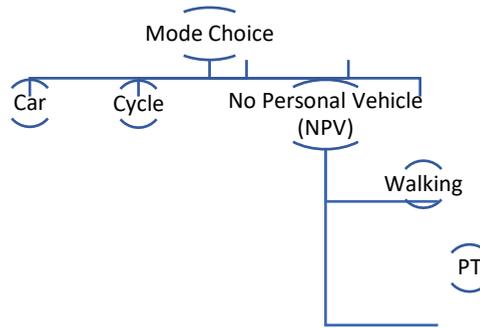


Figure 1: Visualisation of the nested alternatives

A nested model was chosen because the data showed roughly 46% of public transportation users stating ‘walking’ as an accompaniment. This implies that walking and PT are not mutually exclusive and therefore needed to be nested for this study under ‘no personal vehicles’ or NPV. The model was run on N-logit. The chart below summarizes the data processing:

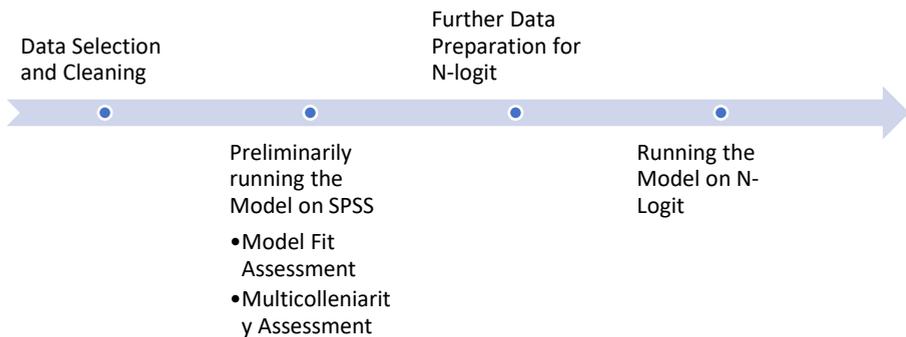


Figure 2: Steps for processing data within this study

2.1 DATA SOURCE

The data was obtained from Austria’s Ministry of Climate Action and Energy (BMK) via the nationwide survey *Österreich Unterwegs* (2013–14) (BMIMI, 2014). It includes 96 variables on socio-economic background, travel behavior, and travel environment. For this study, 14 key variables were selected—such as distance, travel time, urbanity, household size, proximity to public

transport, income, age, education, travel purpose, occupation, and gender—this was done by scanning the literature for relevant variables (Sadhu, 2023). Some variables were recategorized to improve model predictiveness and minimize the number of dummy variables.

2.2 UTILITY FUNCTION AND MODEL BUILDING

A utility function forms the basis for a logistic regression model (Christensen, 2006). It describes the pleasure or utility derived by an individual from using a given alternative (in this study- a particular mode of transportation) and presents the influence of different factors (explanatory variables) in the utility generation. left.

A general form of a utility function is as follows (Hensher et al., 2005):

$$U_{ij} = V_{ij} + \epsilon_{ij} \quad (1)$$

Where V_{ij} is the utility derived from alternative j (which is a sum of all the explanatory variables multiplied by their parameter values or Beta) by individual i and ϵ_{ij} is the error term associated with the unobserved factors affecting people's choices, such as social norms, personal biases etc. (Hensher et al., 2005).

To run the nested logit model on N-logit, utility functions needed to be built and added to the commands. N-logit then uses these functions and estimates the parameter values. This model considered 'car' as the pivot alternative; therefore, its utility function only has the scalar variable time in it and its alternative specific constant is 0. Car was chosen as the pivot because it is the least sustainable of the four transport options and the mode aim to avoid. By identifying factors that increase the likelihood of choosing walking, cycling, or public transport over cars, policies which promote these greener alternatives can be formulated.

2.3 MODEL FIT

In linear regression, model fit is assessed using R^2 value, which indicates the proportion of variance explained by the independent variables (Helland, 1987). For logit models where the variables are not scalar, model fit is assessed by the McFadden pseudo- R^2 (Hensher et al., 2005). The McFadden pseudo- R^2 value of 0.384 derived in this study roughly equates to an R^2 value

between 76-78% which means that within the model, the independent variables can help predict around 76-78% of the dependent variables which is indicative of a good model fit.

2.4 MULTICOLLINEARITY

In order to combat the issue of multicollinearity, this study computed a correlation matrix between all the explanatory variables. Only one pair of variables showed a high correlation of 0.7. This strong correlation was seen between the dummy variables of distance categories to the nearest bus stop 1 and 2. However, for the sake of isolating the impact that different distances to PT have on mode choice and PT adoption, this study retained the variables intact.

3. RESULTS & DISCUSSION

A descriptive modal split of the study area yields 65% car users, 13% pedestrians, 12% PT users and 10% cyclists (see Fig. 3).

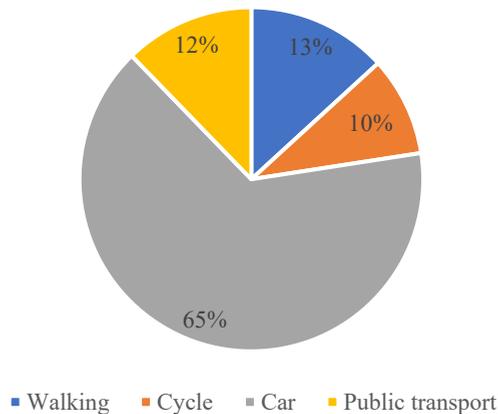


Figure 3: Modal split in Graz, Graz surroundings and Deutschlandsberg

The model ran logistic regression to test relations between 46 sets of explanatory variables and mode choices. Of these, 40 relations were significant at a confidence interval of 95% with a p-value lesser than 0.05. The nested logit model was built keeping the alternative 'car' as the pivot and then comparing

the likelihood of using the other alternatives against it. The parameter estimates derived are shown in Table 1 below.

Table 1: Nested Logit Model results, showing parameter estimates (β) and p-values for each mode and variable. Most relationships are highly significant; insignificant ones are bolded and italicised.

Nested Logit Model- With 2 levels (Car as the 'pivot')						
Variable (PT)	PT		Cycle		Walking	
	(β) Val- ues	Inverse Odds Ratio*	(β) Val- ues	Inverse Odds Ratio	(β) Val- ues	Inverse Odds Ratio
Alternate Specific Con- stant	6.84		6.01		8.76	
Urban**						
Semi-periphery	- 1.24	3.5	-1.39	4	- 0.75	2.1
Rural	- 2.35	10.5	-1.62	5.1	- 0.41	1.5
Single-person HH**						
HH with 2 people	- 0.96	2.6			- 0.71	2
HH with more than 3 people	- 1.51	4.5			-1.3	3.7
PT Stop within 5 mins on foot**						
PT stop 6-15 minutes on foot	-0.3	1.3	-0.54	1.7	- 0.58	1.8
PT stop above 15 minutes on foot	- 0.68	2	-0.12	1.1	-1	2.7
Lower-income HH**						
Middle-income HH	- 2.81	16.6	-5.49	242.3	- 6.01	407.5
Upper-income HH	- 4.37	79	-6.08	437	- 7.34	1540.7
Student**						
Employed	- 0.71	2	-0.89	2.4	- 0.82	2.3
Pensioners	- 0.28	1.3	-1.03	2.8	- 0.48	1.6
Other occupations	- 0.61	1.8	-1.14	3.1	- 0.34	1.4

Purpose- working**						
Purpose-education	2.06	0.1	0.69	0.5	1.52	0.2
Purpose-shopping	- 1.28	3.6	-0.76	2.1	- 0.06	1.1
Purpose- Others	- 0.87	2.4	- 0.45s	1.6	0.53	0.6
Gender (Female)**						
Gender (Male)	- 0.41	1.5				
Age Group below 19 years**						
Age group 20-54 years	- 1.34	3.8				
Age group above 55 years	- 1.35	3.9				
Uneducated/Un-trained**						
Education- School/trained			0.77	0.5		
Education- University and above			1.25	0.3		

*An inverse odds ratio is the ratio between the log odds of the reference variable divided by the log odds of the comparison variable

** reference variable

3.1 DETERMINANTS OF MODE CHOICE

The model also showed that the degree of urbanity affects people's mode choices. Urban households were 3.5 times more likely to use PT than semi-peripheral households and 10.5 times more likely than rural households. They were also four times more likely to cycle and five times more likely to walk than rural households. Interestingly, rural residents were more likely to walk than semi-peripheral ones, likely due to shorter local trip distances and fewer traffic-related barriers, echoing infrastructure and comfort-based factors cited in Alfonzo (2005) and Carlson et al. (2018).

Household income emerged as a key determinant in the model. Compared to upper-income households, lower-income households were 79 times more likely to use PT, 437 times more likely to cycle, and 1,541 times more likely to walk than to drive. Similarly, compared to middle-income households,

lower-income households were 242 times more likely to cycle and 408 times more likely to walk. These results align with the modal split by income, which shows a greater reliance on non-car modes among lower-income households as shown in Figure 4. This supports Pucher & Buehler (2006) and Plaut (2005), and contradicts earlier claims of rising active mobility among higher-income groups (Dill & Voros, 2007). In Styria's case, lower income households were most likely to rely on public transportation.

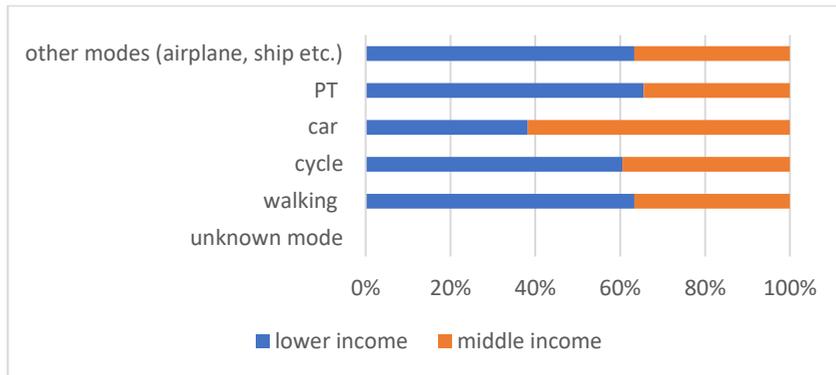


Figure 4: Modal-split based on income-levels

Distance to PT was critical. Having a stop within 5 minutes' walking distance increased the likelihood of choosing PT or walking. For instance, moving a stop from over 15 mins to within 5 minutes doubled the chances of PT use. These results support Buehler (2011), emphasizing infrastructure's role in facilitating sustainable mobility.

Upon examining the effect of occupation on mode choice, it was found that the students were the most likely to use sustainable modes over cars. They were twice as likely to use PT, 2.4 times more likely to cycle, and 2.3 times more likely to walk than employed individuals.

It was also found that larger households demonstrated a higher propensity for car use. Single-person households were 2.6–4.5 times more likely to choose public transport (PT) or walking over cars compared to households with 2 or more people. Larger households, especially those with 3+ members, tended to prefer cars, possibly due to the presence of children or coordination needs. This aligns with previous findings linking household size with higher car ownership (Gardenhire & Sermons, 2001; Holtzclaw et al., 2002).

The model also showed that women were 1.5 times more likely to opt for PT over cars compared to men. This aligns with Simma & Axhausen (2003) and

Scheiner & Holz-Rau (2012), who suggest that men's higher access to cars and work responsibilities influences this difference between genders

Another very interesting finding was the impact of education levels on people's propensity to cycle. The study showed that as people got more educated, their likelihood to cycle increased. When compared with uneducated and untrained individuals, those who went to school or university were 2-3.5 times more likely to opt for cycling. This supplements the research by Balsas (2003) who found a higher share of active mobility on campuses. The average education level of cyclists was also found to be higher than that of users of other modes.

3.2 ELASTICITIES OF TRAVEL TIME FOR VARIOUS MODES

To understand how travel time impacts mode choice, this study examines the direct and cross elasticities of travel time and how changes in travel time can lead to changes in people's travel preferences (Louviere et al., 2000). Table 2 presents the direct and cross-elasticity values derived from the model, quantifying the sensitivity of mode choice to a 1% change in travel time. Direct elasticities (marked with an asterisk*) refer to changes in the likelihood of choosing the same mode, while cross-elasticities indicate shifts toward alternative modes. Walking and PT are grouped within the same nest, leading to similar elasticity values. For instance, 1% increase in walking time reduces its walking 0.4% and PT use by 0.4%, while slightly increasing the likelihood of cycling and car use (both by 0.1%). A 1% increase in PT travel time reduces its own use by 0.67%, and also decreases walking by 0.67% due to nesting. The direct elasticity of travel time on car choice was -0.04%, indicating that a 1% increase in car travel time leads to only a 0.04% decrease in the likelihood of choosing a car. This highly inelastic response—the lowest among all modes—reflects a strong behavioural lock-in among car users. Despite the costs and known environmental impacts, many continue to rely on cars due to these 'locked-in' effects (Bamberg et al., 2003). Contrasting to cars were bicycles which showed a significantly elastic response to travel time. Increase in travel time by cycling by 1% led to a decrease in its usage by 1.8%. This result aligns with a previous study by Frank et al. (2008) and is testament to how people are easily dissuaded from using cycles if the infrastructure does not guarantee a timely commute, good cycling infrastructure and safety (Puello et al., 2020).

Table 2: Direct and cross-elasticity values of travel time on mode choice

Mode Choice (with travel time as the attribute)	Elasticity Value (Nested)- Impacted Choice Probability			
	Walking	PT	Cycle	Cars
Walking	*-0.4	-0.4	0.1	0.1
PT	-0.67	*-0.67	0.06	0.06
Cycle	0.6	0.6	*-1.8	0.6
Cars	0.17	0.17	0.17	*-0.04

3.3 POLICY IMPLICATIONS

This study identifies four key barriers to sustainable transport in the study region. First, rural dependence on cars stems from poor last-mile connectivity, with PT stops three times farther than in urban areas. Short-term solutions include introducing e-car or bike-sharing services in rural areas (Shergold et al., 2012), while long-term strategies involve expanding PT infrastructure by increasing PT stops, and optimizing routes in rural areas. Second, high travel time elasticity for biking indicates people are easily deterred from cycling. Addressing safety and perception through increasing the no. of segregated bike lanes, training programs, and better bike parking can improve adoption (Ajzen, 1991; Puello et al., 2020).

Third, higher- and middle-income households prefer private cars, unlike lower-income groups. Income-targeted policies such as taxing additional household vehicles and adjusting fuel taxes with income-based subsidies can help shift these preferences. Fourth, larger households (3+ members) also rely heavily on cars likely due to family responsibilities. Soft measures like personalized travel planning and targeted messaging (e.g., emphasizing climate impacts on children) can nudge these households toward greener modes (Pelletier & Sharp, 2008; Riggs & Kuo, 2015). Finally, since higher education levels correlate with increased bike use, integrating traffic education in elementary schools may further support modal shift.

4. LIMITATIONS AND EXTERNAL VALIDITY

The findings of this study are based on an Austrian national survey which was calibrated with data from Styria. Due to Austria's socio-demographic and infrastructural comparability, the results are regionally valid and broadly indicative of national trends. While the model offers useful insights for other developed EU countries, differences in factors like population density and living standards limit its external validity. However, the model itself includes several significant mode choice determinants and can be adapted for use in other regions with local data. This study has some limitations. First, income data was self-reported, introducing potential bias. Second, like many trip-based transport research, access trips (e.g., walking to PT stops) are included within PT trips, based on walking time—a common approach in the literature (Chen & Li, 2017; Ding & Zhang, 2016). More precise modelling, such as activity-based approaches, was beyond this study's scope. Lastly, key behavioural factors like norms and attitudes, which have proven to be important (Ajzen, 1991; Bamberg & Möser, 2007) were not assessed due to data constraints. Future research should explore these social and behavioural aspects to better understand and influence mode choice.

5. CONCLUSION

This study highlights key socio-demographic and infrastructural determinants of sustainable mobility choices. Higher-income households were significantly more likely to choose cars over other more sustainable modes, confirming a strong negative correlation between income and active or public transport use. Closer proximity to public transport stops—especially within 5 minutes—can double the likelihood of choosing PT over cars. Students, women, and highly educated people less inclined to using cars. Also, the rural-urban discrepancy in the usage of cars was also seen to be quite high. Policy recommendations include expanding PT access in rural and semi-peripheral areas by the way of increasing PT stops, improving last-mile connectivity, increasing, expanding bike lanes, and employing behavioural nudges to reduce car dependence. These findings reinforce the need to shift from auto-centric policies to planning approaches that enable and encourage public and active transport.

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Day 2 Session: Bridging Sustainability and Design II

Leveraging driving simulator advances in early phase vehicle development - Partitioning of vehicle states for enhanced motion feedback

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ABSTRACT

This paper presents a novel approach to motion cueing in moving base driving simulators (MBDS) for early-phase vehicle development. Traditional motion cueing algorithms (MCAs) rely on high-pass filtering of global vehicle states, which can reduce realism and limit the effectiveness of simulation-based subjective evaluations. The proposed method partitions vehicle motion into two components: terrain-induced (global) and vehicle-induced (local) motion. This allows for selective filtering, preserving low-amplitude high frequency vehicle responses while attenuating low frequency high amplitude terrain effects which does not fit in simulator workspaces. Two partitioning strategies are explored: a velocity-based method for pitch motion and a more general ground-plane estimation using tyre contact points. Simulation results demonstrate improved correspondence between actual and simulated pitch and roll motion, particularly in vehicle-induced motion such as braking or turning. The approach shows potential to enhance motion feedback without exceeding platform limits, enabling more effective virtual prototyping and subjective driver feedback early in the design process. Future work includes implementation in real simulators. The method supports sustainable vehicle development by reducing reliance on physical prototypes and accelerating iterative design.

1. INTRODUCTION

Sustainable vehicle development must balance environmental, economic, and social objectives while ensuring technological feasibility and competitiveness. The concept phase is critical for embedding sustainability, yet development often relies on incremental improvements rather than transformative changes. A key challenge is the reliance on subjective assessment for evaluating vehicle dynamics and comfort, which traditionally requires physical prototypes, limiting rapid prototyping [1].

Moving base driving simulators (MBDS) address this challenge by enabling early phase virtual testing and validation [2]. MBDS allow for evaluation of new concepts before physical prototypes are built [3]. This enhances resource efficiency, shortens development cycles, and facilitates early subjective evaluation of sustainability-driven designs.

A limitation of simulation-driven development is the subjective validation of motion cueing algorithms (MCAs), which rely on physical prototypes for tuning, hindering virtual-first development [1]. To close the loop on virtual prototyping, an objective MCA approach is needed, enabling early-stage assessments without physical testing and ensuring correlation between simulator and vehicle. By integrating virtual development and sustainability-driven design, objective MCA validation could accelerate the development of resource-efficient vehicles.

2. MOTION CUEING

Motion cueing is necessary in MBDS due to limited workspaces [4,5]. To handle the limitations, high-pass filters are used to remove large vehicle motions, which are on a global scale, while preserving smaller amplitude high-frequency content for driver perception [6]. A major challenge is maximising motion fidelity while avoiding simulator constraints when undergoing filtering [7].

A novel method to retain important motion for vehicle dynamics cueing was presented by Bruschetta et al. [8] where the vehicle yaw rate $\dot{\psi}$ was partitioned into the path yaw rate $\dot{\gamma}$ and the slip angle rate $\dot{\beta}$. Since γ represents the global motion, it requires filtering to avoid workspace limitations, whereas β , normally confined within $\pm 10^\circ$, can be directly fed to the simulator without filtering, improving motion quality and simulator-vehicle motion correlation [9][10]. By avoiding filtering, low-frequency content of β is kept

intact for the driver in the simulator to experience. This low-frequency content has a significant effect on the perceived fidelity and motion quality [10].

In this work, an effort is made to extend this approach to several DOFs. The motivation to extend this methodology to more DOFs is straight forward. By partitioning the states into quantities that are related to the global motion of the vehicle, which is only path dependent, and quantities that are related to the vehicle's states, which are dependent on the driver's input, improvements are possible: Ground vehicles motions are in general limited in relation to the local path. As mentioned, lateral slip is commonly limited, and so are roll motion relative to ground, pitch motion relative to ground and the centre of gravity height relative to ground.

To estimate pitch angle relative to ground during straight ahead driving, a naïve approach is to use the vehicles vertical heading as a proxy for ground heading. Thus, a vertical body slip angle ϕ can be defined by vehicle's z-velocity v_z and x-velocity v_x :

$$\tan \phi = \frac{v_z}{v_x} \quad (1)$$

This would be defined as the body angle of attack in aviation terms. Thus, pitch angle can be partitioned into:

$$\theta = \alpha + \phi \quad (2)$$

where α represents pitch angle of the terrain, while ϕ captures vehicle pitch motion relative to local terrain. Filtering α while preserving ϕ allows for realistic simulation of local pitch dynamics:

$$\theta_s = G(s)\alpha + \phi \quad (3)$$

where θ_s is the pitch angle of the simulator, $G(s)$ is a high-pass filter where s is the Laplace operator. This is compared to the industry standard approach of filtering $\dot{\theta}$ directly:

$$\theta_s = G(s)\theta \quad (4)$$

To illustrate this strategy, a simulated vehicle was tested on a track with a crest into a 5% slope. At 550-630 meters, the driver applied 0.6 G braking (Figure 1).

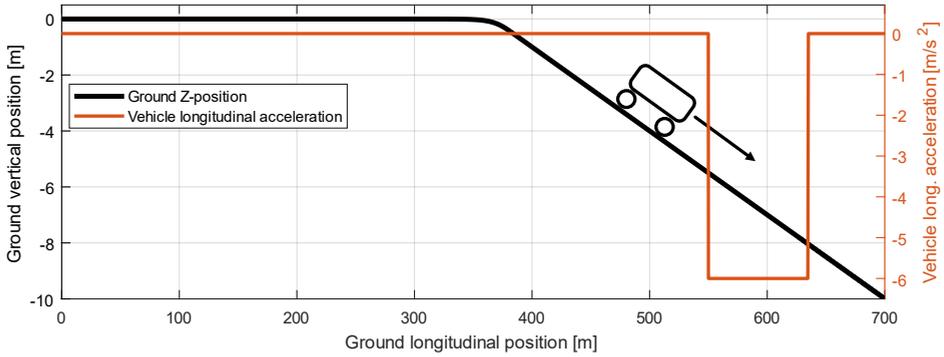


Figure 1: Track and acceleration input for pitch simulation

The results (Figure 2) show that between 6–10 seconds, both partitioning and standard filtering methods performed similarly, with an initial pitch onset followed by washout. However, between 11–14.5 seconds, when braking occurs, the partitioning method retained pitch cues 1:1, whereas the standard method washed out pitch, reducing realism. The bottom right graph highlights how the partitioning method preserves vehicle pitch relative to the ground, improving driver perception of longitudinal dynamics demonstrating its advantage for early-phase evaluation.

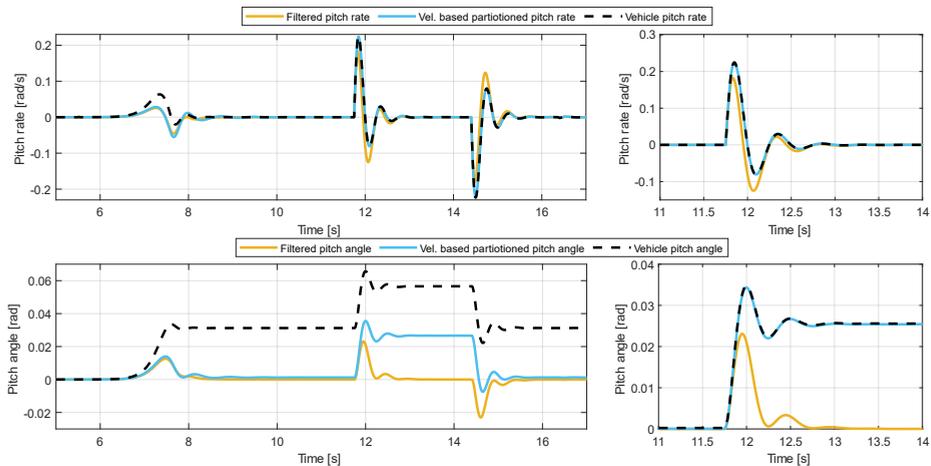


Figure 2: Results of simulation with pitch rate (top) and pitch angle (bottom). Note that bottom right plot illustrates vehicle pitch angle relative ground.

The scope of the velocity-based method is limited to pitch, as it does not allow for estimation of vehicle roll angle relative to ground nor vehicle vertical

motion relative to ground. For vehicle roll relative to ground, a velocity-based method is difficult to obtain as vehicle to ground roll is not necessarily observable, as it requires v_y to obtain how the vehicle slides on the ground surface in the global frame of reference. Lateral velocity v_y is a state that is rapidly changing, and for a neutral steer car it is zero (or close to zero) in steady state and hence the direction of $V = [v_x, v_y, v_z]^T$ is not suitable to be used to find a proxy for ground roll. It is thus necessary to find another method to estimate the ground plane.

One possible method is to use the tyre-ground contact points as ground probes, to estimate the local ground states. The methodology is illustrated in Figure 3, with a four wheeled vehicle rolling over uneven ground.

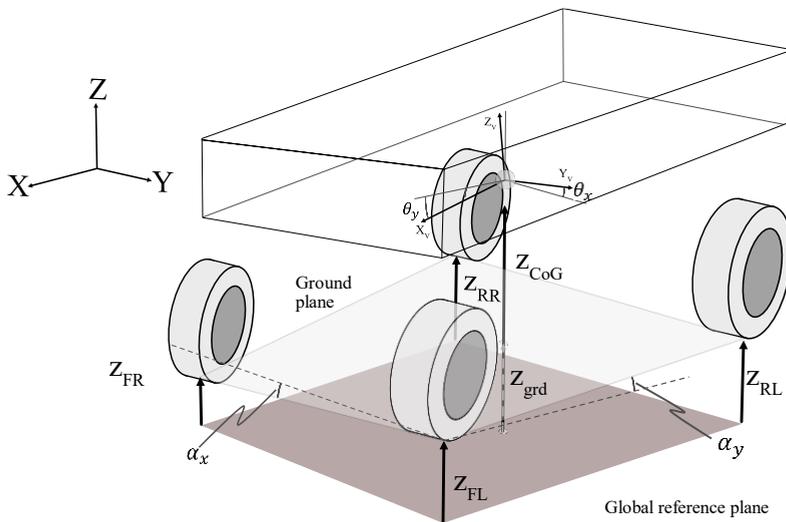


Figure 3: Illustration of a four wheeled vehicle rolling on a road with road roll-angle α_x , and road pitch-angle α_y and height z_{grd} at the point of interest (in this case CoG).

The ground is assumed to be a flat plane with the equation based on the wheel x_{ij} and y_{ij} positions relative to the point of interest:

$$z_{ij} = x_{ij} \tan \alpha_x + y_{ij} \tan \alpha_y + z_{grd} \quad (5)$$

The vehicle in this case has four wheels, and hence the wheel contact points overdetermine the plane. A least square approach to estimate the plane states is therefore used. The problem can be formulated as:

$$A_{whl} \begin{bmatrix} \tan \alpha_x \\ \tan \alpha_y \\ z_{grd} \end{bmatrix} = [z_{FL} \quad z_{FR} \quad z_{RL} \quad z_{RR}]^T = z_{whl}$$

where z_{whl} is the wheel z-coordinates and A_{whl} is the coefficient-matrix:

$$A_{whl} = \begin{bmatrix} x_{FL} & y_{FL} & 1 \\ \vdots & \vdots & \vdots \\ x_{RR} & y_{RR} & 1 \end{bmatrix} \quad (7)$$

The least square involves a pseudo inverse of the A_{whl} matrix. The matrix is static and hence the pseudo-inverse can be calculated offline. The least square approach is therefore suitable for real-time calculations and the ground plane states can be solved as:

$$\begin{bmatrix} \tan \alpha_x \\ \tan \alpha_y \\ z_{grd} \end{bmatrix} = (A_{whl}^T A_{whl})^{-1} A_{whl}^T z_{whl}$$

Even though the ground states are filtered due to the least square fitting, the ground states are inherently carrying noise, as the ground coordinates can change in vertical direction without any limit. The idea of partitioning the states is to filter out low frequency content that is contained in the global motion of the vehicle, Thus, before calculating the vehicle relative to ground states, the ground states are low-pass filtered.

The low-pass filter used in this work was calculated to be a first order filter based on the kinematics of a rolling vehicle, on uneven ground. The assumption is that any ground state will change fully over the length of the wheel base, denoted L , given a step input. Thus, the following first order filter is used and an example for pitch is presented below and illustrated in Figure 4:

$$\alpha_{y,0} + \dot{\alpha}_y dt = \alpha_{y,1} \rightarrow dt = \frac{L}{v_x}$$

$$\dot{\alpha}_y = \frac{v_x}{L} (\alpha_{y,1} - \alpha_{y,0}) \tag{9}$$

$$\alpha_{y,0} = \frac{\frac{v_x}{L}}{s + \frac{v_x}{L}} \alpha_{y,1} = LP_y \alpha_{y,1} \tag{10}$$

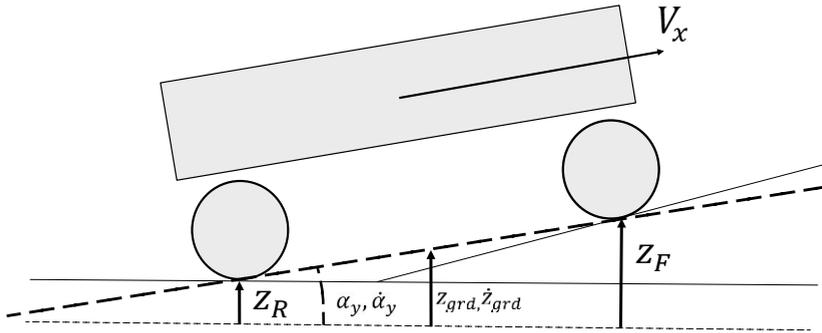


Figure 4: Illustration of a two-axle vehicle rolling on an undulated road, highlighting the spatial filtering of the ground due to the wheel base.

where LP_y denotes the resulting low pass filter. Now the estimated vehicle roll angle φ , vehicle pitch angle ϕ and vehicle CoG height relative to ground h_{grd} can be estimated:

$$\begin{aligned} \theta_x - LP_x \alpha_x &= \varphi \\ \theta_y - LP_y \alpha_y &= \phi \\ z_{CoG} - LP_z z_{grd} &= h_{grd} \end{aligned} \tag{11}$$

The roll, pitch and vehicle vertical states have now been partitioned into a ground state which is related to the local terrain, and a vehicle state relative to this local terrain.

The terrain related states are then high-pass filtered to filter out the global motion, and the simulator states can now be calculated as:

$$\begin{aligned}\theta_x^s &= \varphi + G(s)_x LP_x \alpha_x \\ \theta_y^s &= \phi + G(s)_y LP_y \alpha_y \\ z^s &= \Delta h_{grd} + G(s)_z LP_z z_{grd}\end{aligned}\tag{12}$$

where $G(s)$ is a high-pass filter. In this work a second order high-pass is used with a frequency of 0.65 Hz and a gain of 1. $\Delta h_{grd} = h_{grd} - h_{grd}^{static}$, i.e. how much the CoG (or the point of interest) is moved relative to ground compared to when the vehicle is static in stand-still.

Ideally, the filtered quantities are only related to the terrain, the velocity the vehicle has been driven with over the terrain, and the dimensions of the vehicle. The configuration of the vehicle should ideally only affect the parts which are not high-pass filtered: e.g., with softer springs, the vehicle will have a larger roll and pitch angle relative to ground, however the ground roll and pitch angle will not change. Hence, by partitioning the states and avoid high-pass filtering the vehicle related states, the possibility to test vehicles in the simulator should be enhanced, even when driving on tracks which has terrain which is significant to the workspace of the simulator (i.e. test tracks which are not flat).

For reference, $G(s)$ is applied to the total roll and pitch state according to equation (4).

3. RESULTS

A full car was used to test the outlined methodology, using tyre contact points to probe the ground. The same manoeuvre as illustrated in Figure 1 was applied to validate the method in comparison with the velocity-based method.

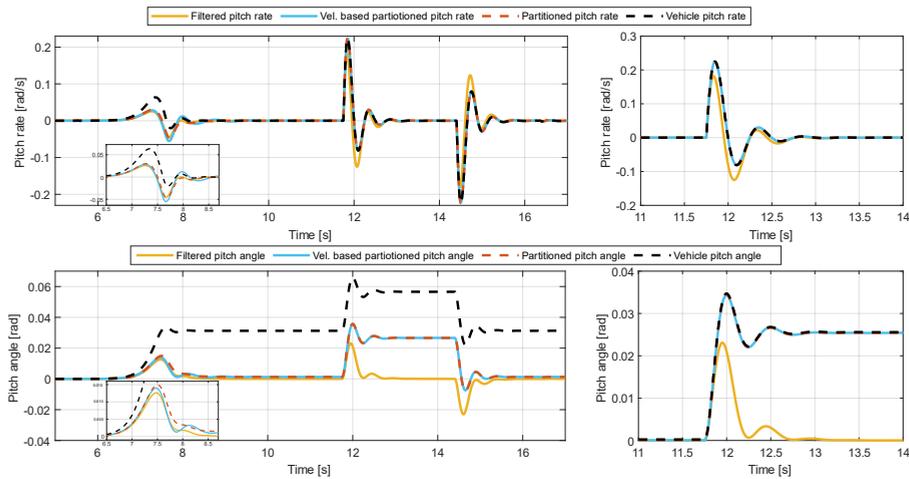


Figure 5: Pitch feedback for a full-car running down a hill and subsequent braking at 6 m/s^2

The results shows that probing using the tyres produced similar performance as with using the velocity-based method, showing the same enhancements especially regarding vehicle motion which is independent of ground (pitch due to acceleration) showing one-to-one correlation in this case. A significant improvement compared to classic high-pass filtering.

To showcase the method for more degrees of freedom, a manoeuvre using a road-step on the left side was used, followed by a right turn at 6 m/s^2 . The rational for this manoeuvre was to trigger both roll, pitch and vertical motion of the vehicle. The manoeuvre was conducted at highway speed at 30 m/s .

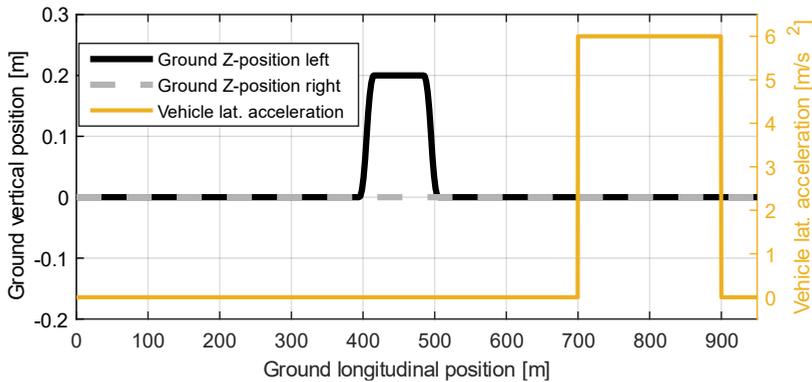


Figure 6: Manoeuvre with a road-step on the left side of the car, followed by a right turn at 6 m/s^2

The results from the road-step manoeuvre are presented for pitch and roll in Figure 7 and Figure 8 respectively. The road-step does not contain any steady state pitch, but rather creates a transient manoeuvre with subsequent oscillations due to a slightly underdamped vehicle. For pitch, it is clear that partitioning the state has possible advantages even during transient events, as it can follow the vehicles oscillations close to 1-to-1 in such an event. The reason for this behaviour is that with the use of a low-pass filter according to equation (11), highly transient events will be attributed to the vehicle state (φ, ϕ and h_{grad}), as only the low frequency content of the ground state ($\alpha_y, \alpha_x, z_{grad}$) is deducted from the global vehicle motion ($\theta_y, \theta_x, z_{COG}$). This highlights one key benefit of the method.

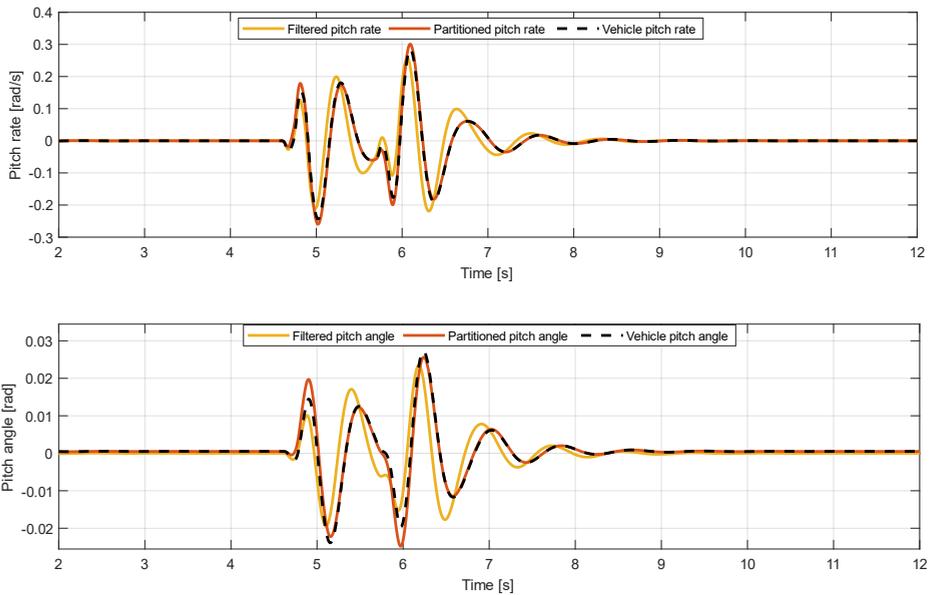


Figure 7: Pitch rate and pitch angle during road-step manoeuvre

For roll, there is a steady state roll angle when the vehicle is driving on the road-step on the left side. The results show once again that portioned roll states stay closer to the actual vehicle roll states compared to the filtered reference. Specifically, the roll state has a smaller false roll angle cue at ~5.5 seconds, as it contains some of the vehicle roll angle (which is slightly positive due to the incline from the road-step). Further, it follows the roll rate to a higher degree around 5.5 seconds, as well as around 6.5-7 seconds, when oscillations from the vehicle itself is the dominant roll cue after going down the road-step.

At 8 to 11 seconds, when the vehicle is undergoing cornering, and the roll angle is acceleration induced, the partitioned roll states follow the vehicle roll states exactly, highlighting the advantage of partitioning of states to improve simulator motion. The added benefit of tilting the simulator in steady state during cornering is also to be mentioned, giving a steady state lateral acceleration of the driver, in this case of about 0.6 m/s^2 , which is not insignificant (not shown, but can be deduced from the roll angle).

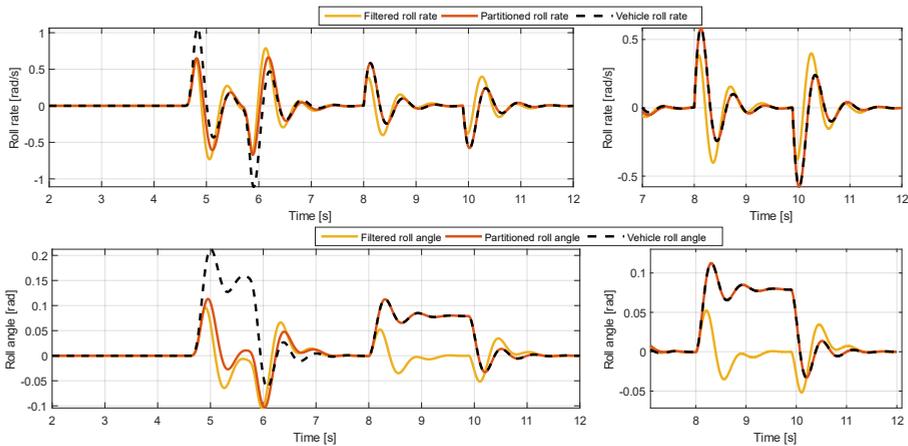


Figure 8: Roll rate and roll angle during road-step manoeuvre

4. DISCUSSION AND CONCLUSION

Simulators are a key element in resource efficient vehicle development, as it allows for a faster rate of development while it reduces resource heavy physical testing. For simulators to be a good complement and in some cases a successful substitute to physical testing, the motion cueing must represent the actual vehicle motion well. This is one of the challenges of simulators which has limited their use.

In this work, a novel methodology for motion cueing is presented which is based on partitioning global vehicle states in ground states and vehicle relative-to-ground states. The fundamental idea is to filter out the ground states which can be large, while retaining vehicle-to-ground states which are small enough to fit in the workspace of a simulator.

Two methodologies to partitioning the states are presented in this work, the first using velocity-based partitioning, inspired by the work of Bruschetta et al. [1], which is limited to pitch only. A further development of the methodology is also presented, using tyre contact point probing to estimate ground states which then is used for partitioning of pitch, roll and vertical motion.

Both methodologies show promising results. The velocity-based method has similar performance as the classic filtered method for pitch induced by ground and improves the performance significantly with pitch induced by acceleration. The ground state methodology indicate that it can improve cueing for pitch feedback compared to classic filtered cueing, both illustrated during a

slope and brake manoeuvre, as well when running over a road-step where the cueing allows close to 1-to-1 feedback in the simulator. For roll, the methodology shows significant improvements both during ground-induced motion as well as vehicle induced (turning) motion.

Future work should be to implement the strategy in a driving simulator to be evaluated by professional test drivers. Further, partitioning could possibly be extended to aviation as well, e.g. separating angle of attack from airplane pitch, and separate a turn into a coordinated turn and a relative roll angle.

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Towards an approach to road cargo system-of-systems modelling

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ABSTRACT

The transition from internal combustion engines to electric propulsion for road-cargo systems is on-going and faces multiple challenges for the involved actors and affected stakeholders. The product development of, for example, future battery electric heavy trucks for long distance hauling requires new perspectives on concept evaluation and selection due to high data uncertainty. These new perspectives are needed to satisfy the business objectives of both OEMs and transport providers, while also fulfilling an overall set of requirements, including environment-related ones. From a society point of view, public investments in electric power generation and distribution grids will be needed as use of electric energy will increase. These public investments need to be balanced and prioritized with other expenses. The investments in new technology in terms of battery electric haulers made by the transport providers need to be profitable and competitive with respect to utilization rate and cargo transport efficiency. The time duration of the mentioned activities is significantly different, which adds more complexity. The complexity of the road cargo system as a whole can be modelled as a system-of-systems, as the constituent systems like truck, transport and energy providers as well as energy and road infrastructure are independent managerially and/or operationally systems themselves. This paper describes the state and outlook of the conceptual modelling of key components in a general road cargo system of systems framework.

1. INTRODUCTION

The ongoing global climate change driven by greenhouse gas emissions from fossil fuels, where the ground transportations, i.e. road transportation, accounts for 16% of the total CO₂ emissions, is a challenge to mitigate (Ritchie, 2020, IEA, 2022). Road transportation accounts for three-quarters of the transport emissions, where most of this originates from passenger transportation, around 45% while 30% is from road cargo transports. Reduction of greenhouse gas emission may be undertaken through a combination of reducing emissions at the vehicle source, change in fleet configuration and the total transportation demand. The demand for ground transportation is however increasing due to an increase in regional and global economic growth and trade. This implies that CO₂ emission reduction is a multi-objective problem, consideration to both environment and economics are needed when countermeasures are to be researched, developed and implemented.

The efforts to reduce CO₂ emissions at the source focus on optimization of the internal combustion engine, transition to other energy sources like hydrogen or electricity as well as minimizing road load, i.e. mainly aerodynamic drag and rolling resistance. The former efforts are likely to result in marginal improvements in efficiency compared to the emission reduction needed and the fact that the internal combustion engine has been available on the market for more than a century while transition to hydrogen and electricity yields in larger emission reduction possibilities. Using well-to-wheel perspective it is evident that transition to either hydrogen or electricity also requires focus on emission reduction on the energy production system.

The transition to electric as well as hydrogen propulsion systems for road cargo system is evolving. Standard purpose zero-emission heavy trucks, which mainly have a battery-electric propulsion system, have been on sale on the Chinese and European markets for more than half a decade. The sales numbers in Europe at present are small, the market share is less than 2% indicating that a possible major market break through still lies in the future (ICCT, 2025a). The sales of zero-emission heavy truck by configuration are different, more evenly distributed between tractor-semitrailers (long haulers) and rigid trucks compared to conventional heavy trucks, where tractor-semitrailers hold slightly more than half of share. On the Chinese market the sales of zero-emission heavy trucks reached a share of slightly less than 21% by the end of year 2024 (ICCT, 2025b). The overall share for whole year 2024 were 13%, indicating a market break through. Battery swapping techniques, allowing for smaller batteries in terms of energy storage, mass and vehicle

investments, together with national subsidies have paved the way for the increase in sales.

Traditionally, the product development in the heavy truck industry as well as in the automotive industry is by its nature evolutionary, innovative in small increments while minimizing development risk. The introduction of new innovative technologies such as electrification of the propulsion system is challenging as a high degree of uncertainty is present in the concept phase, where the vehicle architecture is defined. The decisions concerning definition of product capabilities balanced to product cost and investments to meet requirements from stakeholders and customers are strongly affected. Reuse of system and system elements as well as investments, i.e. legacy, minimizes product development risk but may be a constraint for innovation. Dependency and effects of capabilities and business objectives may be complex but are important to consider. As an example, the energy storage concept, e.g. type, sizing and packaging constraints, relation to payload penalty may affect the contribution margin for transport mission, which may be offset by lower cost of energy. The truck, abstracted as a system, has interfaces to other systems, see Figure 1, which need to be considered in the management of the product life cycles (Walden et al, 2023). The increasing complexity with respect to endo- and exogenous system and system elements including interfaces over the whole product life together with sustainability regulations yields in additional challenges during the concept definition and selection phase. As an example, the infrastructure investments in energy distribution to a network of point-based charging stations or semi-continuous charging while driving may also be needed. The product life and residual value are also important factors to consider. The time lag and inertia of infrastructure investments differs geographically and feature differences to product development rate in the heavy truck industry. This means that the conceptual sweet spot for a single global configuration for e.g. long hauling may be difficult to find. Modelling and analysis of system interactions to support decision making in the conceptual phase may be a key factor to minimize risk.

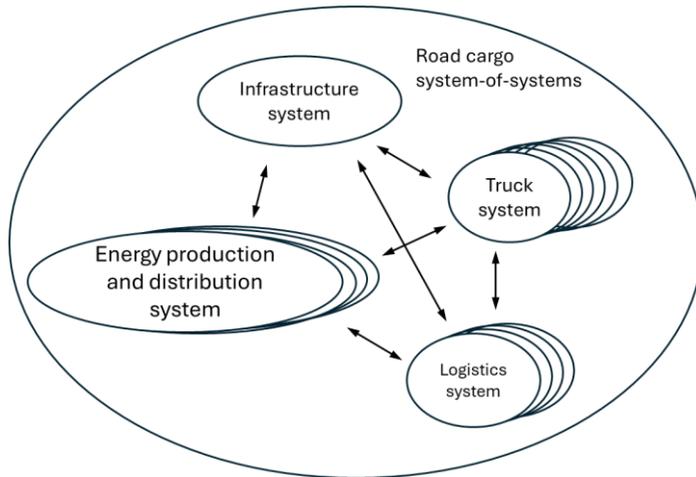


Figure 1: Modelling approach of road cargo system-of-systems.

Systems Dynamics methodology offers opportunities to model and analyse complex systems using a trade-off between simplicity/high abstraction level versus complexity/high detail fidelity and has been applied to transport system for several decades (Shepherd, 2014). The advantage with System Dynamics approach is that both qualitative and quantitative entities may be included using, for example, a causal loop diagram but a too complex model can be difficult to understand and lack rigour. For decision making quantitative metrics may be requested resulting in a need of mathematical representation of the system input and output relationships build on empirical and/or physical relations including feedback loops with time lag and gain.

Application of System Dynamics to model and analyse transportation systems is often limited in consideration to one of the systems shown in Figure 1 and sometimes only statically in the meaning that the critical dynamic interaction or feedback between systems and system elements are not included (Ghandriz, 2018). When optimisation of vehicle concepts with respect to mainly total cost of ownership have been done considering interaction to road infrastructure for different propulsion concepts and truck configurations the problem quickly gets very large as the number of vehicle configurations is substantial (Ghandriz, 2018). Finding the global optimality may then be hard.

In (Raofi et al, 2024), key entities are identified together with their interactions using reinforcing or balancing loop. Grouping of entities to facilitate system dynamics is found to be useful. In (Andruetto, 2024) a System Dynamics approach to model and analyse different policy scenarios for the road

cargo transport has been conducted starting with the establishment of causal loop diagrams. The model has been decomposed into different sectors where stock and flow equations have been formulated. Metrics for emissions and a proposed transport efficiency metric have been evaluated. Consideration to charging of electric trucks and infrastructure has been included by means of different policies. In (Fehler! Verweisquelle konnte nicht gefunden werden.r, 2023) a system-of-systems modelling approach have been applied to study different scenarios for infrastructure in the Netherlands considering passenger transportation by road and rail as well as cargo transport on rail, road and seaways. Interaction for demand and choice of transportation mode (e.g. rail or road) has been modelled.

Within the Centre for ECO² Vehicle Design at KTH Royal Institute of Technology a general framework for modelling road cargo systems featuring interactions to be modelled using system dynamics approach has been developed with purpose to support conceptual decision making (Fehler! Verweisquelle konnte nicht gefunden werden.et al, 2021). The framework includes system context, characteristics and performance for each constituent system. A step-by-step development of configurable vehicle models or agents balancing accuracy of underlying physics to computational effort has been done (Fehler! Verweisquelle konnte nicht gefunden werden.2022, Wu, 2023) to support the modelling and analysis of road cargo system-of-systems.

The overall research questions for the ongoing project are:

1. How to model the system-of-systems that make up road-cargo transport considering its constituent systems and technologies and their relevant interdependencies and dynamics for a class of transport missions and conditions?
2. What are the relevant category elements (e.g. society and planning, infrastructure and energy provision, haulage operators, vehicle manufacturers, etc.) and their interdependencies?
3. What are the emergent phenomena and behaviours that characterise the constituent systems at different scales (e.g. coarse and fine) and what are the underlying mechanisms, variables and connections to be included in a valid model?
4. How can the scale resolution be extended from early coarse indicative simulations to more advanced resolution while retaining category element interfaces, handling increased uncertainties, and maintaining verification and validation capabilities?

5. Strategies for systems of system model verification and validation and critical metric development and cascading to constituent systems.

This paper focusses on describing the architecture, the early phase of definition, abstraction and partly the implementation of some key system elements of the road cargo system-of-systems.

2. METHODS

While Systems Engineering is traditionally focused on the development and life management of monolithic systems with well-defined boundaries System-of-Systems Engineering is focused on the assembly of a mix of possibly already existing and new systems into a new whole where the capability is greater of its constituent parts (DeLaurentis et al, 2023). In Systems Engineering the basic assumption is that a given set of requirements based on input from customers and stakeholders yield into that the system can be built to meet those requirements. This assumption does not hold if the boundaries interfaces are open or ill-defined resulting in unpredictable behaviour of system elements and unclearly defined requirements, which make the verification and validation challenging.

The term system is old and may be attributed all the way back to Aristotle: “The whole is more than the sum of its parts. The part is more than a fraction of the whole.” This abstraction is called systems thinking defining a system as an integrated set of elements, subsystems, or assemblies that accomplish a defined objective (Walden et al, 2023). The term system-of-systems is defined as a set of systems or system elements that interact to provide a unique capability that none of the constituent systems can accomplish on its own (ISO 2019). Classification is applied in both Systems and System-of-Systems Engineering. The term complex system is defined as a system composed of multiple interacting elements, which collective behaviour does not yield trivially from the behaviour of individual elements (DeLaurentis et al, 2023). Classification may also be based on the level of control authority (DeLaurentis et al, 2023). A system-of-systems where the participation is voluntary and feature no central objective, management, authority or funding is denoted collaborative system-of-systems. This means that the constituent systems have a high degree of autonomy in its operation. The road cargo system clearly fulfils these two definitions and can be defined as a complex, collaborative system-of-systems.

assumed to be users or operators, system-of-systems engineering often exhibits its modelling challenges of humans due to their socio-technical character. Operations are the processes and procedures that contribute to the dynamics of the system-of-systems like a transport mission or a charging operation. Policies are the regulations and rules that govern management and operations like truck driver working hours or emission taxation and regulations. Finally, the Economics are e.g. revenue, interests, investments, operational cost and taxes for the different stakeholders. Introducing hierarchy levels as the second dimension of system-of-system categorization yields in sorting of elements with interdependence and autonomy where lowest level, the α -level, manifests in no further decomposition and may be thought as building blocks (DeLaurentis et al, 2023). The next levels, β , γ and so on, are the collections of elements from the immediate lower level. Depending on the size and complexity of the system-of-systems the number of hierarchy levels may vary. In Figure 3 a system-of-systems a generic model abstraction using ROPE categories and hierarchy levels is shown.

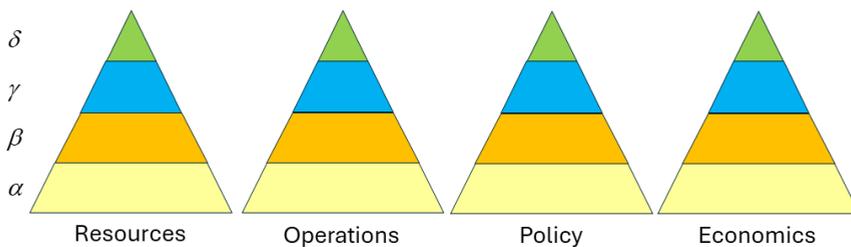


Figure 3: The ROPE categories and levels of hierarchy after (DeLaurentis et al, 2023).

The Abstraction phase focusses on the defining the actors, effectors, disturbances and the interdependency networks using e.g. the categorized entities from e.g. a table shown in Figure 3. The big picture dynamics is encapsulated. The outcome of the abstraction are the modelling variables as inputs, outputs and metrics at each level of the system-of-systems (DeLaurentis et al, 2023). The emphasis is on building the highest possible level of abstraction, to move away from details. Three classes of design variables in the abstraction process are in focus: composition (which systems, functions and resources), configuration (which operational interdependencies and constraints) and control (what autonomy, which incentives). Composition relates to topics like which systems are present, the interface requirements, cost and risk while configuration relates to topology of the system-of-systems and which information is

passed on the links and control address how and who controls the effectors. In a product development context consideration to time scale for the system-of systems is also carried out. Finally, identification of stakeholders and their needs, the tangible systems of resources, the drivers, which are the forcing functions that drive the stakeholder network, the disrupters, which are the exogenous entities that affect the network and the network itself are done.

3. RESULTS

An initial road cargo system-of-systems model has been developed where the Definition, Abstraction and partly the Implementation phases have been performed. Results from the Definition phase in terms of ROPE-table as shown in Table 1. Quantitative characteristics can then be identified and assigned to the resources and economic categories in the ROPE table at α -level for modelling purpose in the Implementation phase. The dynamics of the operations with exciters, both exo- or endogenous, and constraints may then also be formulated by means the operations and policy categories in ROPE table during the Abstraction phase. Model requirements and simplification criteria and the impact on modelling and accuracy of analysis results are also important outcome, see Figure 4. Objective data (Transport Analysis, 2024) has been input to simplifications done, which are valid for a Swedish transport system context and obviously the simplifications may be different for another context yielding in different simulation outcome.

Table 1: ROPE table for road cargo system-of-systems.

	Resource	Operations	Policy	Economics
α	Vehicle, road, energy production unit, energy distribution hub, logistic hub,	Vehicle operation, road infrastructure operations, energy production unit operation, energy distribution hub operation, logistic hub operation	Vehicle policies Road policies, Working hour regulations, Energy production regulations and policies Energy distribution regulation and policies logistics hub policies,	Vehicle operating costs, road operating costs, energy production unit operating costs, energy distribution operating costs, logistics hub operating costs
β	Transport provider vehicle fleet, energy production plant, energy distribution network, B2B logistic provider network	Transport provider operations, road network operations Energy production plant operations, energy distribution operations, logistics provider operations,	Policies concerning network operation	Operating cost for a resource network
γ	Collection of national resources in a road transportation system	Collection of national operations in a road transportation system	Policies for national road transportation system	Forecast of national road transportation market

During the Implementation phase modelling and analysis take place generating data for model verification and validation as well as project decision

making. Depending on complexity of the system-of-systems of interest it may be useful to make a graphical representation of the implementation to visualise the interactions by the different systems. In Figure 5 a conceptual representation using a causal loop diagram of the road cargo system-of-systems is shown in where equations of motions for vehicle system are incorporated in order to derive metrics like energy consumption and CO₂ emissions (Hayes et al, 2018, Wu, 2022, Rill et al , 2020, Wu, 2023). Complexity may be added gradually by means of iterations of model abstraction, simplification and re-modelling depending on outcome of model verification and validation tasks.

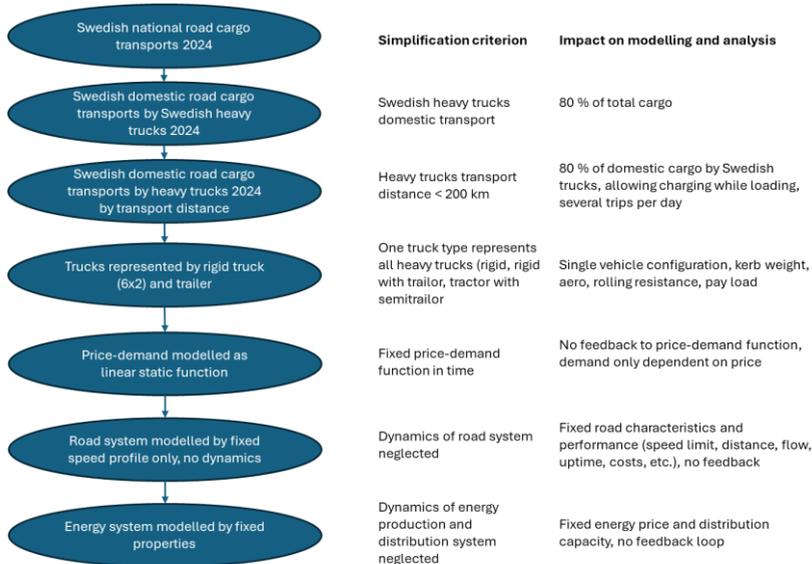


Figure 4: Model abstraction for road cargo system-of-systems.

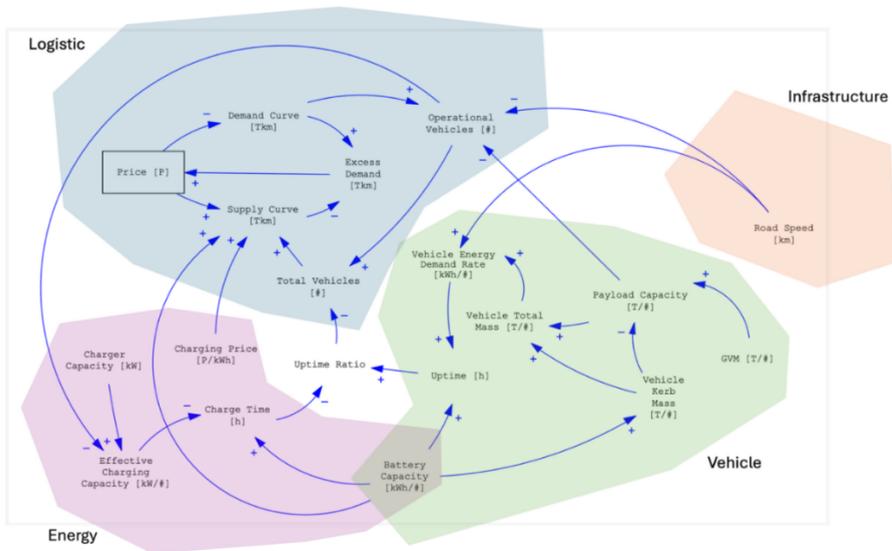


Figure 5: Conceptual representation of the system-of-systems model.

4. DISCUSSION

An initial conceptual road cargo system-of-systems model for a Swedish context has been developed using System-of-Systems Engineering approach. By means of categorisation of the constituent systems and their elements and model simplification the system dynamics of conceptual model could be established. The simplifications applied will influence simulation outcome, other contexts require other simplifications. The underlying fundamental equations for different metrics like energy consumption and CO₂ emissions have been implemented separately and will be integrated in model in the future. Policies can be implemented as model constraints or exogenous exciters. The next steps focus on model verification and validation followed by remodelling iterations where increasing modelling complexity may be a key until sufficient accuracy is achieved. The famous quote by G.E.P Box “All models are wrong, but some are still useful” may be used as guideline in the verification and validation task emphasising on a “useful” model as end outcome. Inclusion of the dynamics of energy production and distribution system and road system may be studied in future work and also more complex modelling such as socio-technical parameters and parameter sensitivity and uncertainty propagation to model response. Interactions with additional systems like

macro-economics to study and understand balancing economic and ecological performance are also planned.

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Optimising the configuration of a double-decker sleeping car from Germany to the Mediterranean – squaring the circle

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ABSTRACT

The revitalisation of night train services aims to offer a sustainable alternative to air travel on routes between 500 and 2000 km. However, high operating costs make ticket prices uncompetitive compared to low-cost airlines and high-speed day trains, resulting in the discontinuation of several services in Europe over the past 15 years. Challenges persist, including limited passenger capacity, large space requirements per passenger, and lack of seat turnover. Furthermore, the constraints of the G1 gauge limit international services, putting night trains in central Europe at a disadvantage compared to the American Superliner or the Finnish VR Ny, as well as other modes of transportation. This paper explores early-stage design strategies to improve the economic viability and efficiency of double-decker sleeping cars. Findings from Project “AliSa” identify critical design trade-offs and technical constraints. Desk research and CAD analyses reveal that accommodating two double cabins on both the upper and lower decks within the G1-profile is not feasible, as seen with the Superliner model. One alternative is to emphasise reclining armchair seating, which is less affected by height restrictions and offers greater flexibility. Norske tog’s survey indicates positive passenger attitudes towards this option, particularly when paired with private cabins to enhance privacy. Additionally, shorter but wider carriages improve spatial efficiency and comfort. A novel configuration is proposed to maximise capacity while adapting to demand variations. Some armchairs are reserved for the entire journey, while

others allow seat turnover. This setup incorporates adaptive lighting and modular partitions to balance privacy with occupancy efficiency. A linear programming simulation using demand scenarios and different ticket prices optimises the upper deck configuration, combining two-person cabins, overnight armchairs, and turnover armchairs. Results indicate that turnover armchairs are more profitable in high-demand scenarios, while night armchairs gain relevance in lower-demand situations.

1. INTRODUCTION

The revival of night train services offers a low-carbon alternative for mid-range travel. However, high operating costs and limited passenger capacity often make them less competitive compared to air travel and high-speed day trains (HST). This paper presents evaluation and early-stage design insights from the AliSa project (from the German *Angebotsdifferenzierter, leichter und innovativer Schlafwagen* – “offer-differentiated, lightweight and innovative sleeping car concept”), funded by the Federal Ministry for Economic Affairs and Energy of the Federal Republic of Germany. This project aims to improve the economic viability, operational efficiency and affordability of night train services across all social groups.

Previous studies and surveys have identified key factors influencing passengers’ choices for night train services - namely travel time, cost and comfort, with the latter closely linked to privacy considerations (Kantelaar et al., 2022). These factors strongly shape passenger preferences and often deter them from choosing rail over other modes of transport (Rüger & Mailer, 2020). A TU Dresden study found that 80% of participants prefer a lying position, and 50% prioritize privacy (Bellmann & Bauer, 2019). Furthermore, passengers also emphasise the need for adequate luggage space and the importance of maintaining visual contact with it (Rüger, 2021). Nonetheless, most existing research primarily relies on feedback from current night train users, resulting in a somewhat biased sample and providing limited insight into the broader potential market. Recent research work by Ramboll (2024), which confirms the lack of demand data for night trains, helps address this gap by estimating modal shift potential from air and car travel under various demand scenarios. Additionally, the literature points to an inherent disadvantage in the productivity of current sleeping and couchette carriages which, while essential for overnight services, remain unused during the day, reducing productivity. Troche et al. (2007) suggest that enabling day and night use could more than double their economic efficiency. Concepts such as the

EuroDayNiter (Manthei, 2005) and the TANA project (Rüger et al., 2024), designed for full day/night operation, provide potential solutions to this challenge. However, no vehicle has yet reached full realization in this area.

Combining literature data, CAD analysis, and a simulation model, this study proposes an innovative strategy to optimise space while maintaining a sufficient degree of passenger comfort and adapt to fluctuating demand. It also addresses design constraints and trade-offs. The paper proceeds in two main phases: first, an **evaluation** of current and former night train services is conducted to define benchmarks, requirements and early-stage design decisions for the AliSa concept, with a focus on economic viability. The upper deck is identified as a key area for revenue generation, due to its potential capacity and homogeneity. In the second phase, a linear programming model is used for the **optimisation** of the proposed upper deck configuration, aiming to maximise profit through the allocation of night and turnover armchairs, while keeping a small number of fixed private cabins.

2. METHODOLOGY

During the evaluation phase, existing and discontinued sleeper car concepts from various regions (Europe, America, Asia) were explored to derive insights relevant to the AliSa concept. Thereafter, an optimization of the upper-deck was conducted. The research was structured as follows:

1. Evaluation of existing and former night train services:

- **Literature review and data collection:** A total of 18 sleeping car concepts were surveyed, spanning various regions, and characterised based on the following criteria: general and operational features, service routes, wagon type and length, passenger capacity, amount and layout of seating / couchette and sleeping cars, cabin quality levels, presence of WC and PRM-cabins where applicable, etc. Additionally, 10 related vehicle concepts were documented, which were either already represented by one of the previously surveyed models or lacked sufficient data for inclusion in the broader analysis.
- **Benchmarking:** A structured benchmarking approach was applied to systematically compare the surveyed night train concepts. This involved the development of a matrix-based tool to evaluate key parameters such as spatial efficiency, modularity, passenger comfort features, and suitability for day/night use. By analysing these criteria across the mentioned concepts, common patterns, best practices as

well as critical trade-offs between comfort, capacity and flexibility were identified.

- **Early design decisions:** Based on the benchmarking results, a set of requirements was iteratively formulated through a qualitative synthesis approach: key findings from the literature and benchmarking were evaluated for their relevance to improving capacity, modularity and cost-efficiency within the constraints of different loading gauge profiles. The latter were identified and discussed through a detailed CAD analysis.
2. **Linear programming simulation:** The optimization of the upper deck configuration was carried out using a linear programming model developed with Python’s PuLP library (Mitchell, 2004). The model aims to **maximise profit** while dynamically adjusting the allocation between night recliners (NRA) and turnover recliners (TRA) in response to pricing and demand constraints. NRA are intended for full-route bookings, whereas TRA, similar to first-class quiet zone seats with dimmed lighting, are available for shorter segments (approximately one-third of the route). This novel, flexible configuration scheme improves occupancy efficiency by better aligning with varying demand. It also facilitates the day/night use of the reclining armchairs and incorporates adaptive lighting and adjustable cabin dividers to balance privacy with occupancy efficiency.

FORMULATION OF THE OPTIMIZATION PROBLEM

For the simulation, reference values were initially defined for key parameters, which can later be varied. Initial simulations revealed a model tendency to select TRA, so a business rule requiring a minimum of 4 NRA in high demand was introduced. In high demand scenarios, base demand is set at 40 for TRA and 15 for NRA. In low demand scenarios, the base demand is set at 15 for TRA and 5 for NRA. These demand levels are dynamically adjusted based on ticket price elasticity. The model uses a base price of €85 for TRA – reflecting an average fare of 5-hour 1st-class ICE routes – and €130 for NRA, based on full-night fares of upper-segment night trains in Central Europe, with elasticity factors (*elast*) of 0.6 and 0.2 respectively, reflecting differing demand sensitivities.

$$\max_{TRA} = \max (0, \text{base_demand}_{TRA} - \text{elast}_{TRA} \times (\text{t_price}_{TRA} - 85)) \quad (1)$$

$$\max_{NRA} = \max (0, \text{base_demand}_{NRA} - \text{elast}_{NRA} \times (t_price_{NRA} - 130)) \quad (2)$$

The objective function maximises profit by balancing revenues from each type of booking against costs, where the total seats constraint is: $\text{TRA} + \text{NRA} = \text{fixed_total_seats} = 23$. The revenue_{NRA} is t_price_{NRA} , while it is assumed that the TRA is booked in two thirds of the route, so that the $\text{revenue}_{TRA} = 2 \times t_price_{TRA}$. Cabins are considered fixed with two units with two berths each, and an occupancy fixed at 75%. The fixed costs of the entire waggon are estimated at approximately €4,000, with an additionally €10 in operating costs applied per occupied seat. The profit calculation of the upper deck is evaluated in relation to the total costs of the waggon:

$$\begin{aligned} \max\text{Profit} = & (\text{revenue}_{TRA} \times \text{TRA}) + (\text{revenue}_{NRA} \times \text{NRA}) + (\text{revenue}_{cabin} \times \text{fixed_cabins}) - ((\text{operating_cost} \times (\text{TRA} + \text{NRA} + \text{fixed_cabins})) + \text{fixed_cost}) \end{aligned} \quad (3)$$

3. RESULTS

3.1 RESULTS OF THE EVALUATION AND PROPOSED ALISA CONCEPT

The following **findings** emerged from the literature review:

- Following the financial and debt crisis and the emergence of low-cost airlines, there was a **wave of major discontinuations** of night train services in Europe between 2015 and 2021 (see Figure 1). This highlights that the economic viability of some night trains remains uncertain and vulnerable to external economic pressures, even after the proliferation of new concepts post-Corona.

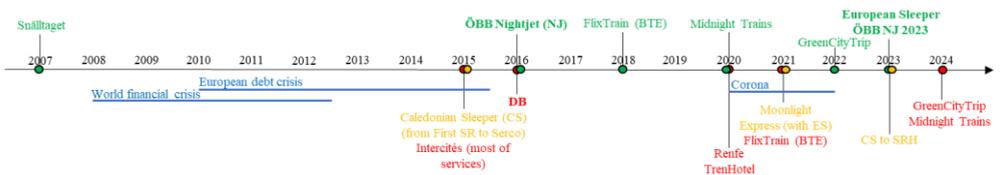


Figure 1: Timeline of the start and discontinuation of night train services in Europe from 2007 to 2024: green for starts, orange for mergers, red for discontinuations, and blue for external events.

- Up until recently, night train services were national initiatives. New developments by ÖBB and European Sleeper (ES) reflect a new trend in the **international positioning** of operators.
- A **variety of sleeper wagon concepts** have emerged across different market segments. These concepts vary significantly in terms of service and design quality (see Table 1).

Table 1: Spectrum of identified train concepts and their corresponding market segments.

Segments	Examples	Defining attributes
Budget	PKP, ČD, ES, TransSib	Older or refurbished 2 nd - and 3 rd -class rolling stock with limited comfort and sleep quality; often not price competitive with HST or low-cost airlines.
Mid-to-Upper	ÖBB NJ, CS, VR, SJ, FLEX	Upgraded wagons facing strong competition from HST and air travel; some heavily subsidized (e.g. CS), others discontinued (e.g. Renfe TrenHotel).
High-Density	Škoda (2024), Luna Rail	New double-decker concepts with high passenger density and modular layouts. Luna Rail’s (Dubrau, 2024) concept allows for day/night use.
Premium	TANA, Luxon	High-end sleeper prototypes seeking greater comfort and exclusivity.
Non-EU	Amtrak, CRRC	Fewer constraints on loading gauge and interoperability.

- Despite the variety of night train concepts, **no lightweight design** is on the market yet.
- Nearly all of the characterised concepts incorporate at least one **modular solution**, such as interconnected compartments, folding couches that convert into seats, folding table tops that cover washbasins, or folding backrests transforming into small tables. The modular design of the **Amtrak Superliner Roomettes** (National Railroad Passenger Corporation, n.d.) serves as a benchmark for the AliSa project due to its high passenger density - up to 4 passengers every 2 meters of deck length – enabled by the vehicle width accommodating two parallel Roomettes and sufficient height for its duplication across both decks. Each Roomette consists of two wide seats facing each other during

the day, which convert into a long couchette at night, in addition to an overhead couchette folded up during the day.

- **Reclining armchairs are gaining popularity**, being included in both the TANA project and in Norske tog's new order (successor to the Norwegian national railways (NSB) for rolling stock) for night trains entering service in 2028 for the Norwegian operator Vy. Following a survey by Norske tog and a study of its sleeper train service, the new Type 79 (**Stadler FLEX**) night trains will have carriages with recliners, alongside others offering seats and convertible berths. However, Norske tog is not waiting for 2028 and has already decided to refurbish its current night trains with reclining armchairs (Railway Public s.r.o., 2023).

The following relevant implications and **requirements** were derived for the AliSa concept:

- **Dimensional optimisation and modularity**: The car body should be as wide as technically and legally possible to accommodate larger modules and improve sleep comfort. Vehicles like Amtrak's Superliner, the Finnish VR Ny and Stadler FLEX exploit larger loading gauges in their networks and serve as benchmarks for AliSa. Despite more restrictive Central European loading gauges, the project aims for an optimized width by designing shorter, wider wagons: a formation of two 14.900 m end wagons and a 14.500 m middle wagon, all with single-axle bogies is proposed (see Figure). This results in approximately 90% the length of the usual 2 x 25 m wagons, but 2.960 m width, about 10% wider than conventional concepts like the Nightjet or ES.

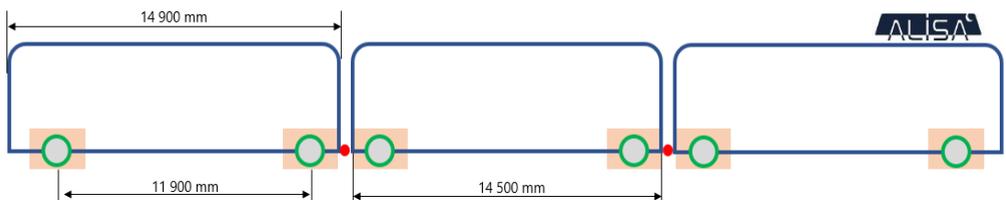


Figure 2: Sketch of the AliSa three-wagon formation of shorter but wider wagons.

- **Interoperability**: A double-deck design is confirmed, that should be capable of travelling across multiple European countries. Initially, a **G1-profile** was considered for interoperability on routes from

Germany to the Mediterranean, including France and Italy. However, it was found out, that this low gauge severely limits passenger density, impacting economic viability, and prevents the intended double gangway on both the upper and lower decks. As a result, a decision was made to adopt the larger **GC-profile**, which is closer to the Amtrak benchmark and is intended to be available for high-speed tracks connecting European capitals by 2030. This profile also enables a double gangway between the carriages of the AliSa three-car formation (see Figure 3)

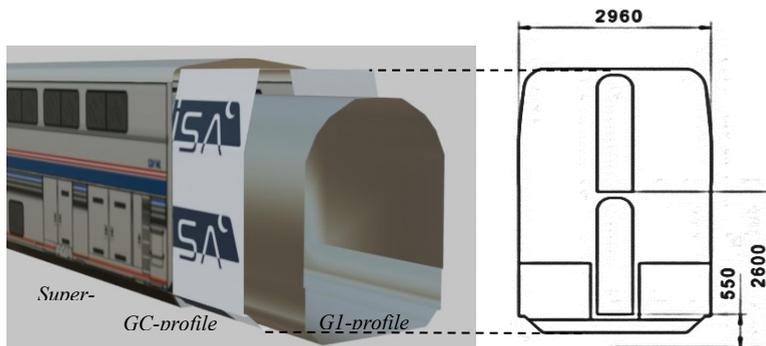


Figure 3: Left: AliSa cross-section with GC profile (4.650 m height) between a G1 profile (4.310 m) and the projected Superliner (4.930 m) for reference. Right: Final AliSa GC profile with its double gangway and optimised width (2.960 m). *Source of Superliner illustration: trainweb.org*

- **Ticket price and space efficiency:** It was found out that concepts with premium sleeping compartments typically charge three times the price of a seat for them, while long-haul aircraft "First Class" fares are around eight to ten times the price of a standard seat. The relatively low willingness to pay for a premium bed in a sleeping compartment does not justify the space it occupies in an optimised concept. The AliSa concept will include space-optimised compartments.
- **Economic efficiency and passenger density:** The AliSa concept will feature an optimised arrangement of sleeping berths and sanitary facilities, along with a PRM cabin and technical space on the lower deck. To improve economic viability, enhancing seat turnover and allowing for day/night use is essential. In response, a novel upper-deck configuration has been proposed, incorporating **dual-use reclining armchairs**, addressing both sleeping arrangements and seating turnover, while moderately impacting privacy.

Table 2: Comparison of key dimensional features of representative night trains and positioning of the AliSa system after the optimization.

Model	Wagon width	Wagon height	Wagon length	Volume comparison (Superliner 100%)	Max. passenger density (pax/m) in couchette / recliners wagon
ÖBB NJ (2023)	2.825 m	4.050 m	26.500 m	ca. 74%	ca. 2
ES (Schmid, n.d.)	2.825 m	4.050 m	26.000 m	ca. 74%	ca. 2.5 (5 persons compartment considered)
Caledonian Sleeper (n.d.)	2.750 m	ca. 4.000 m	22.200 m	ca. 71%	ca. 1.5
Norske tog Type 79	3.200 m	4.360 m	ca. 26.000 m	ca. 91%	ca. 1.8
Amtrak Superliner	3.100 m	4.930 m (double decker)	25.900 m	100%	4 (4 pax. every 2 m per deck)
AliSa (GC-profile)	2.960 m	4.650 m (double decker)	14.500 / 14.900 m	ca. 88%	ca. 3 2.1 alone at upper deck

3.2 RESULTS AND DISCUSSION OF THE UPPER DECK OPTIMISATION

The AliSa concept aims to integrate various types of cabins and seats within a modular architecture. Each upper-deck consists of five 2.550 m segments (excluding staircase space), enabling multiple layouts. One such configuration is the object of this optimisation study: Based on an initial configuration of the upper deck with 2 double cabins and 23 reclining armchairs (RA) within an available inner surface of 14.025 m length and 2.860 m width (Figure 4), the linear optimisation problem was formulated as described in chapter 2.1.

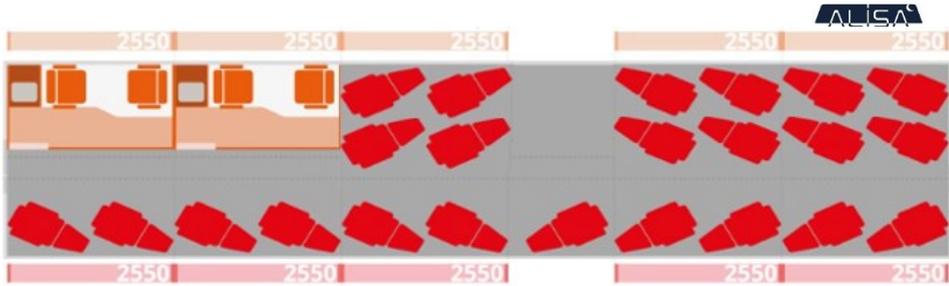


Figure 4: Upper deck layout with two fixed double cabins (upper left) and 23 dual-use recliner armchairs prior to their allocation as either turnover or night recliners (TRA-NRA).

4. OPTIMISATION RESULTS AND DISCUSSION

The optimisation results from the linear programming model for both high and low demand scenarios with varying price points are shown in Table 3. The profit values shall be taken just as an orientation, since they are based on the previously mentioned parameters and a rough cost estimation.

Table 3: Optimisation results allocation of TRA and NRA for different scenarios.

Demand scenario	t_price_{TRA} (€)	t_price_{NRA} (€)	TRA	NRA	Estimated profit (€)
1 - High demand	85	130	19	4	200
2 - High demand	95	150	19	4	760
3 - High demand	105	170	19	4	1320
4 - Low demand	85	130	15	5	-320
5 - Low demand	95	150	9	1	-1460
6 - Low demand	105	170	3	0	-2520

In high demand scenarios, the model consistently selects the minimum required number of NRA (4), favouring TRA due to their higher revenue potential, as they are assumed to be booked twice per night.

In contrast, **low demand scenarios** exhibit a different pattern: At moderate prices, the model still manages to fill most of the available seats, favouring TRA to optimise seat usage within the limited demand. However, as ticket prices increase, the demand sensitivity leads to a noticeable drop in seat allocation, specially of TRA (see Table 3 and Figure 5). NRA seem to fit better in a scenario with low demand and moderate ticket prices.

Overall, this adaptive upper deck configuration demonstrates its potential to cover the full cost of the wagon in all high demand cases, with Scenarios 1 and 4 representing near break-even points for high and low demand, respectively. In low demand situations, however, profitability cannot be guaranteed with the upper-deck alone, and a precise configuration strategy is required to minimise possible losses.

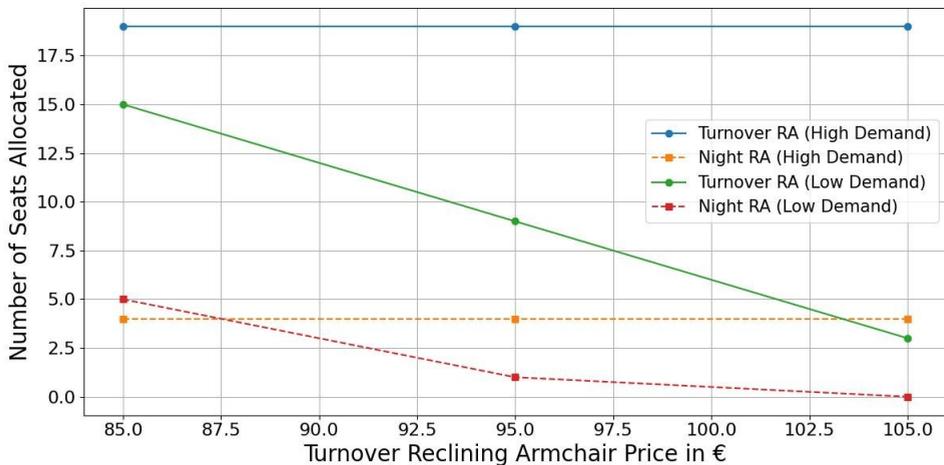


Figure 5: TRA and NRA allocation vs TRA price for different demand scenarios.

The physical separation between night and turnover areas is achieved using cabin dividers, similar to those found in commercial aircrafts, mounted on guides along the walls in longitudinal direction. This allows cabin dividers to be shifted row by row, enabling flexible proportions of TRA and NRA based on demand. However, the row-wise adjustment makes a direct translation of the optimisation results only approximately feasible, as each row contains either one or three recliners, which must be entirely assigned to either TRA or NRA (see Figure 6).

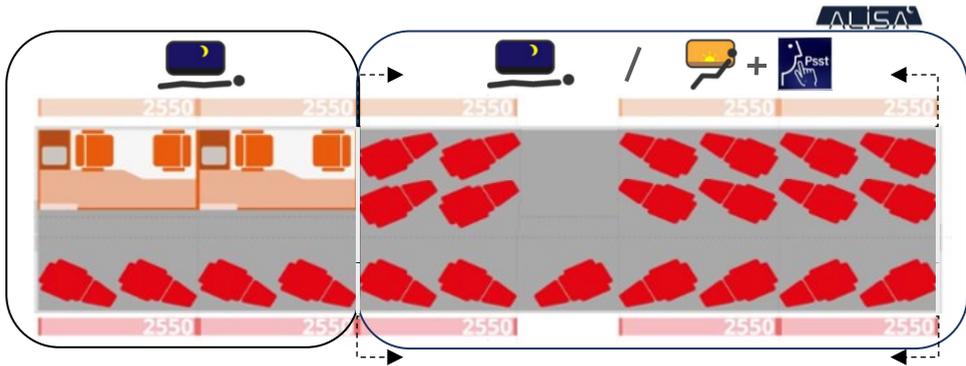


Figure 6: Proposed upper-deck configuration for high demand scenarios (1, 2, 3) and scenario 4 (low demand, moderate ticket price). The left cluster groups the cabins and NRA, while the right cluster is reserved for TRA. The left cabin divider is positioned between rows 4 and 5 but can be shifted rightward. The right divider remains in its default position. *Quiet area logo source: DB AG.*

5. CONCLUSION

This study has explored the potential of flexible configurations to improve the economic viability of night train services. By combining insights from the evaluation of current and discontinued sleeping cars, CAD-based design constraints and linear programming optimization, the early AliSa concept was developed with optimised geometrical features and a flexible, modular seating layout based on dual-use reclining armchairs. This layout supports both day and night use, with turnover recliners designed to be booked multiple times along a single night train journey.

The upper-deck optimization results show that, in high demand scenarios, profit-positive configurations are achievable, especially when turnover recliners are prioritised due to their higher revenue per seat. In low demand scenarios, however, targeted configuration adjustments are necessary to mitigate financial losses. Although the simulation is based on simplified cost assumptions, it provides a foundation for more detailed future planning. Further optimisation effort should focus on integrating the lower-deck layout and validating the results against broader passenger market data. In the coming months, the AliSa project will focus on optimizing structural lightweight design, achieving full vehicle integration, and developing a comprehensive cost model.

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AI was utilized as a programming tool during the optimisation process and for language polishing in the preparation of this paper.

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Sustainable product development framework: Early-stage integration from components to product sustainability – speed pedelec case study

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ABSTRACT

Integrating sustainability considerations into the early stages of the Product Development Process (PDP) is essential for designing environmentally, economically, and socially responsible products. This paper presents a structured and scalable methodology for sustainable product development, applied to the case of a speed-pedelec. The proposed framework introduces intermediate variables to bridge the gap between component-level design variables and product-level indicators. Moreover, a two-stage process for identifying Key Design Variables is also developed. The methodology is designed to integrate seamlessly into existing PDPs through standard evaluation gates and supports iterative refinement as more data becomes available. A case study illustrates the practical application of the framework, with the goal of extending its range. The analysis includes a reparability assessment based on a reduced-order Bill of Materials, validated against full-product calculations. Results not only demonstrate acceptable improvement in range and efficiency, but also a measurable improvement in reparability, confirming the effectiveness of the proposed early-stage methodology. The framework is adaptable to various product domains and supports companies in making informed trade-offs between sustainability, performance, and cost from the earliest stages of design.

1. INTRODUCTION

Reflecting environmental challenges, recent regulations and standards have introduced new sustainability requirements to many sectors in manufacturing (Regulation (EU) 2024/1781) and (International Organization for Standardization [ISO], 2025). Therefore, most of them face the need to estimate and compare relatively new environmental aspects of different product variants early in the Product Development Process (PDP). To enable a new kind of decision-making, conventional PDP must be analyzed, restructured, and extended to address sustainability issues and guiding design decisions (Gagnon et al., 2012) and (Delaney et al., 2022). A Sustainable Product Design (SPD) framework consists of several phases, each representing refined processes, choices, and decisions for developing a new product.

There is a vast number of environmental sustainability indicators that could be considered in SPD (Regulation (EU) 2024/1781), (International Organization for Standardization [ISO], 2025), (de Oliveira et al., 2021), and (Chrispim et al., 2023). While many of the indicators are related to materials constituting products (like environmental footprints and circularity of material flows), there are also indicators reflecting product lifetime extension like durability, and repairability (Regulation (EU) 2024/1781). Currently, there is no standard approach to integrate sustainability indicators into SPD (Kravchenko et al., 2021) and (Parolin et al., 2024). Our assumption is that at the very early stages of SPD a group of experts establishes a sustainability scope and main objectives for a new product.

How early in the SPD process different product design variants become comparable depends largely on the availability and reliability of design data, as well as the validity of any extrapolations derived from it. Several studies aim to shift sustainability decision-making toward earlier PDP phases (Hallstedt et al., 2023), while also addressing the challenges of trade-offs between conflicting objectives (Parolin et al., 2024). This paper takes repairability as a representative example to investigate which data are required to evaluate such a KPI and when this data becomes available during the design process. Using a selected benchmark case, new product design variants are quantitatively assessed across several PDP phases to observe how the availability and granularity of data evolve—and how these influence the development of a reliable repairability score. This process enables tracking of how design deviations impact final product-level KPIs, ultimately supporting the selection of the most suitable design variant.

Although recent regulations increasingly reference repairability, there remains no universal method for quantitatively expressing repairability across all product categories. Most current approaches define product-specific repairability metrics, such as those for washing machines, smartphones, or laptops (Bracquene et al., 2021), (Boix et al., 2024), and (Spiliotopoulos et al., 2019). Common frameworks—such as RSS (Sanfelix et al., 2019), AsMer (Bracquene et al., 2021), EN 45554 (CEN and CENELEC, 2020), and iFixit (Suovanen, 2023)—typically assess a combination of engineering design aspects, support services, and information availability. However, the present study focuses solely on the repairability aspects related to engineering design. Section 2 outlines the reference PDP; Section 3 introduces a generic methodology for integrating sustainability KPIs into PDPs via data tracking from Key Design Variables (KDV) through intermediate variables to product-level outcomes. Section 4 provides a case-based analysis of repairability evaluation across PDP stages for speed-pedelec variants. And finally, section 5 concludes with discussion and directions for future research.

2. SUSTAINABLE PDP (S-PDP) FRAMEWORK

The generic product design process (Zheng et al., 2014) and (Jiang et al., 2021) is typically structured into four main phases: the Exploration, the Conceptual Design, the Detailed Design, and the Testing and Validation Phase. Each phase builds upon the previous by refining requirements, narrowing down design options, and validating performance to reduce technical and commercial risks. The proposed SPD framework extends this structure by embedding sustainability considerations throughout the entire process. It encourages informed decision-making across disciplines to reduce environmental impact while maintaining economic and functional performance. Integrating sustainability KPIs in the early stages of PDP is essential to ensure that environmental considerations are embedded from the outset. To support this approach, evaluation gates are placed at key transition points—between exploration, conceptual, and detailed design phases—ensuring that sustainability KPIs are systematically reviewed and validated before advancing (Figure 1). Additionally, a robust data flow is also critical, enabling consistent tracking and exchange of environmental data, material properties, and performance metrics.

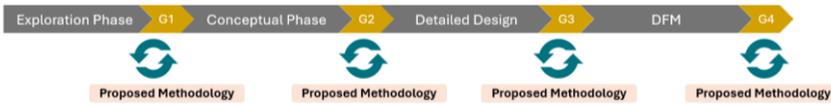


Figure 1. Gates between the phases of the generic PDP

3. METHODOLOGY

This section introduces a structured methodology to systematically translate component-level design variables (DV) into product-level sustainability KPIs, beginning from the earliest stages of the PDP. Central to this approach is the use of intermediate variables— (Component Performance Metrics (CPMs) and Environmental Variables (ENVs))—which serve as a bridge between design decisions and product KPIs (figure 2). This structure also supports the identification of KDVs (that can be defined as the most impactful design variables) from a broader set of variables, to focus efforts on the most impactful factors.



Figure 2. Component level and product level parameters

3.1 INTERMEDIATE VARIABLES (INV)

Establishing a direct relationship between specific component-level design variables and high-level product KPIs is often highly complex or even impractical. To address this challenge, the proposed methodology introduces intermediate variables (INVs)—quantifiable metrics at the component level categorized into two main groups:

- **Component Performance Metrics (CPMs):** capture the functional and non-environmental performance characteristics of individual components, such as efficiency, power density, and cost.
- **Environmental Variables (ENVs):** reflect environmental impacts, such as carbon footprint, material weight, energy consumption, depth of disassembly, or disassembly time of a component.

A structured scoring methodology is also developed to clarify the criteria when selecting a variable as INVs. (Figure 3).

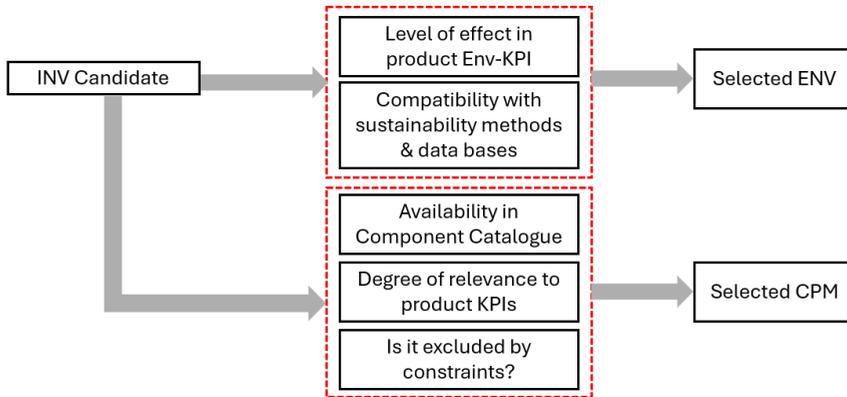


Figure 3. Flowchart of selecting Intermediate variables

3.2 KPI MAPPING PROCEDURE

Once potential INVs are defined, the next step is to establish how they relate to product KPIs. This methodology classifies these relationships into three types based on complexity and data sources:

- **Type 1-Additive (BOM-based):** Simple summation relations, such as component weight contributing to total product weight.
- **Type 2- Functional:** Analytical expressions combining multiple CPMs/ENVs, for example, overall product efficiency may depend on the efficiencies of several interacting components.
- **Type 3- Data-driven:** When additive or formulaic relations are not feasible, empirical models are used. This approach relies on data from simulations, tests, literature, or databases to create multi-dimensional lookup tables that relate IVs to KPIs.

3.3 FROM DESIGN VARIABLES TO INVS

Once the product-level KPIs are reliably linked to a set of intermediate variables, the next step is to establish how these INVs are influenced by

component-level design variables. Proposed methodology categorizes them into two groups based on the quantifiability of the design variables:

- **Design Effect Matrix (DEM):** For quantifiable DVs, the DEM serves as a structured, multi-dimensional lookup table that maps their influence—both direct and cross-effects—on specific IVs.
- **Type Selection Matrix (TSM):** For non-quantifiable or categorical DVs (e.g., motor type, battery cell chemistry), the TSM functions similarly to the DEM. It provides a rule-based or data-driven framework to estimate the influence of design choices that cannot be expressed through numeric scales.

3.4 KEY DESIGN VARIABLES IDENTIFICATION

In the development of complex products, the number of potential DVs can be vast—often in the thousands therefore, identifying a focused set of KDVs is essential. The KDV identification process consists of two stages (Figure 4):

Stage 1: Design-Level Evaluation: Each DV is scored based on four critical aspects:

- *Feasibility in Manufacturing*
- *Multi-KPI Effect*
- *Definability as the product KDVs*
- *Dependency Level to other KDVs*

Stage 2: KPI-Relevance Evaluation: DVs that pass the first stage are further assessed based on their relationship to INVs or to KPIs.

- *Breadth of Impact on INVs:* DVs with broader and more significant influence on multiple INVs (CPMs or ENVs), and thus on product KPIs, are prioritized.
- *Sensitivity:* DVs that exhibit high sensitivity—where small changes lead to significant effects on INVs or KPIs—are considered strong candidates for KDVs.

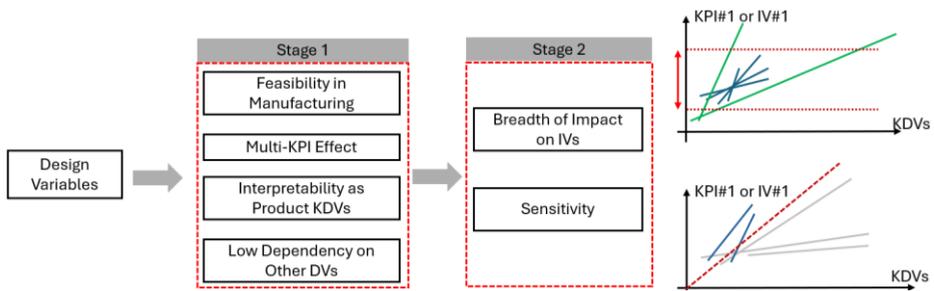


Figure 4. Flowchart of scoring of DVs to clarify K DVs. Stage 1, represents the first scoring stage. Stage 2 performs sensitivity analysis and impact analysis of each DV on the product KPIs.

3.5 INTERACTION OF PROPOSED METHODOLOGY WITH CURRENT PDP

Most companies operate with an established PDP that has evolved and proven effective over time. Therefore, it is essential to clarify how the proposed methodology integrates with the existing PDP without disrupting its core structure. To illustrate this interaction, the PDP is analysed in terms of its inputs and outputs, and its connection to the proposed methodology is visualized in Figure 5. The methodology interfaces seamlessly with the existing PDP, operating in parallel rather than requiring structural modifications. A key component is the iteration decision block, which evaluates whether a given combination of K DVs and the resulting product-level KPIs satisfies the design requirements. If not, the process allows for iterative refinement of K DVs.

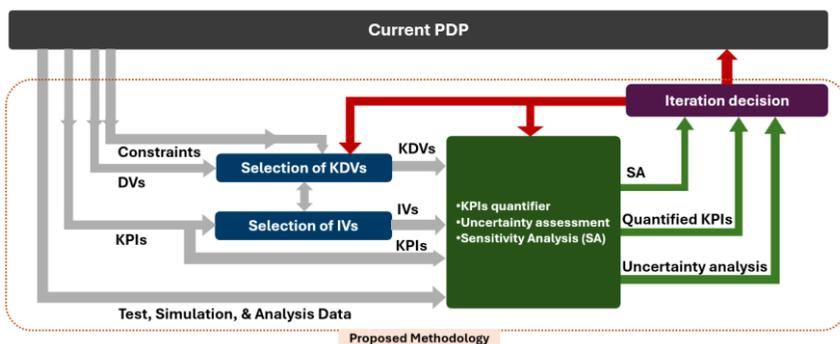


Figure 5. Interaction of the proposed methodology with the current PDP

3.6 DATA AVAILABILITY AND INTEGRATION GATES

Another key consideration is the identification of appropriate integration points—referred to as gates (Figure 1)—within the existing PDP. At each gate, the methodology can be activated to assess and quantify results, using available data at that stage. These results can then be evaluated not only through the standard PDP trade-off approach but also compared with outcomes from previous gates. This iterative comparison enables tracking of performance trends and, importantly, allows for the evaluation of uncertainty and sensitivity as the PDP progresses.

4. SPEED PEDELEC CASE STUDY & REPAIRABILITY ASSESSMENT

4.1 PRODUCT DESIGN SCENARIO

A Speed Pedelec has been selected as the case study for applying the proposed methodology. Rather than developing an entirely new design, the scenario begins with an existing product. Due to the limited availability of detailed design data for this product, a series of ad-hoc methodologies was employed to generate diverse yet coherent datasets, with careful attention to maintaining realism and consistency. The primary objective is to improve a KPI—the bike’s range—from 40.7 km to over 95 km. In addition to this KPI, a subset of K DVs has been identified for potential modification, based on the methodology outlined in the previous section. These K DVs include motor speed, motor type, motor location, number of batteries, and transmission type. Furthermore, the repairability of the redesigned product will be evaluated as a sustainability-related KPI to demonstrate the effectiveness of the proposed approach.

4.2 REPAIRABILITY ASSESSMENT OVERVIEW

Several reference methods assess repairability based on common aspects: *priority part selection*, *Depth of Disassembly (DoD)*, *Disassembly Time (DT)*, *Tools Score (TS)*, and *Fastener Score (FS)* (Wandji et al., 2023). Rather than calculating a single weighted score, these metrics are used as INVs within the PDP.

The priority parts are selected based on *functional importance* and the *failure frequency* of the components, not economic or environmental impact, they are motor, battery, and transmission.

The next metric to calculate is the DoD, which is defined as the number of steps to remove a part without damage. The level of detail depends on the PDP stage and available data. Early phases may only allow part removal counts; detailed design will include tool changes as the steps too.

The other metric (DT) is defined as the sum of four key components: fastener time, tool change time, handling time, and access time.

- *Fastener time* accounts for the number of joints and their associated disassembly durations, which may depend on joint type and length.
- *Tool change time* reflects the additional time required to switch between different tools during disassembly, including specific tools like torque wrenches.
- *Handling time* estimates the time needed to safely handle and remove the component, based on its size, shape, and complexity.
- *Access time* represents the cumulative time needed to remove other components that obstruct access to the target part. It aggregates the fastener, tool change, and handling times of those preceding components.

Tool Score (TS) is the other aspect in this methodology, and it takes the effect of tool complexity, availability, and changing penalties into account. Fastener Score (FS) is the final metric that considers the fastener reusability, their potential to cause damage, and the number of the fasteners.

After calculating all these previous metrics, they are normalized between 0-10. Thereafter, for each component in priority list, the i^{th} component repairability score can be calculated, based on the below equation:

$$RS_i = w_1 \times DoD_i + w_2 \times DT_i + w_3 \times FS_i + w_4 \times TS_i \quad (1)$$

Then using the weight factor for each component from the priority list the final product repairability score can be evaluated easily.

4.3 REPAIRABILITY RESULTS

Table 1 presents the calculated repairability scores for both individual priority components and the overall product, based on a Reduced-Order BOM. In this context, the reduced-order BOM refers to a subset of four critical components—selected from a total of approximately 20 in the S-Pedelec—for analysis under the range extension scenario. The overall repairability score of the product is, therefore, estimated by focusing solely on these four components as the priority list.

As the PDP advances from the Exploration (Exp.) to the Detailed Design phase (Det.), uncertainty in the design is reduced and the reliability of the data improves. The variation between the Reduced-Order BOM results in the Detailed Design phase with exploration and Conceptual phases (Con.) are 30% and 0.098% respectively. This trend highlights the increasing accuracy of repairability predictions as the PDP advances and as a result the data availability and reliability improve. To further assess the accuracy of the Reduced-Order approach, a full repairability analysis was conducted using the complete BOM, with results presented in the final row of Table 1. The deviation between the Reduced-Order and Complete BOM results across all PDP phases ranges between 3.8% and 22%, confirming that the proposed methodology can estimate repairability with acceptable precision even in the early design stages.

Table 1. Repairability score for product and priority list components in different PDP stages

Target view for Repairability Score	Repairability Score Value						
	Previous product	Mid motor Configuration			Hub motor Configuration		
	Exp.	Con.	Det.	Exp.	Con.	Det.	
Motor	7,68	7,41	7,33	7,32	8,00	8,01	8,01
Battery down	9,52	9,45	9,52	9,52	9,44	9,52	9,52
Battery Up	-	3,00	9,90	9,90	3,00	9,89	9,89
Transmission	8,56	5,24	8,56	8,54	5,40	8,57	8,54
Product Reduced BOM	8,58	6,13	8,79	8,78	6,31	8,93	8,93
Product Complete	8,42	7,94	8,47	8,46	7,98	8,50	8,50

To test the methodology under architectural variation, a second analysis was performed using a Hub Motor configuration. The results are shown in three

right hand side columns of Table 1 and are consistent with the previous findings: deviation from Detailed Design results is highest in the Exploration phase and decreases as the design matures. The deviations across all PDP phases for this configuration fall within 5% to 21%. Additionally, a comparison between the Hub and Mid motor configurations reveals that the Hub Motor setup offers a 1.6% higher repairability score, indicating a marginal advantage in this KPI. Finally, a comparison of the overall repairability scores of the new product (in both configurations) against the original product confirms an overall improvement in repairability—despite the inclusion of a second battery in the design.

Table 2. Final Product KPIs and KDVs Compared to Original Configuration

Previous Product			New Product		
KPI	Unit	Value	KPI	Unit	Value
Range	km	40.72	Range	km	107
Efficiency	%	62.9	Efficiency	%	85
Repairability		8.42	Repairability		8.50
KDV	Unit	Value	KDV	Unit	Value
Rated speed	kph	20	Rated speed	kph	30
Motor Type		SRM	Motor Type		PMSM
Motor Location		Mid	Motor Location		Hub
# of Batteries		1	# of Batteries		2
Battery #1 Capacity	Wh	500	Battery #1 Capacity	Wh	400
Battery #2 Capacity		-	Battery #2 Capacity	Wh	500
Transmission type		Chain	Transmission type		Belt

This suggests that the revised architecture not only enhances performance KPIs (e.g., range and efficiency) but also preserves or improves serviceability. Table 2 summarizes the KPIs of the final selected configuration compared to the original model, highlighting the tangible improvements achieved through the proposed design methodology. The range, which was the primary objective of the redesign, increased by approximately 162%, from 40.72 km to 107 km. In addition, the new configuration led to a 35% improvement in efficiency and a 1% increase in the repairability score, demonstrating that performance and serviceability were enhanced simultaneously.

5. CONCLUSION

This paper presented a structured methodology for integrating sustainability-focused KPIs into the early stages of the PDP, with a particular emphasis on the design of a speed pedelec. The proposed Sustainable PDP framework enables a systematic translation of component-level design variables into product-level sustainability outcomes using intermediate variables—specifically Component Performance Metrics and Environmental Variables.

A two-stage process for identifying K DVs was introduced, enabling design teams to focus on the most influential parameters across various KPIs. Additionally, the use of DEM and TSM matrices allowed for a traceable mapping of design decisions to sustainability and performance metrics. Integration points with existing PDP structures were clearly defined, and the methodology was shown to function effectively within standard gate-based development frameworks.

The case study on a speed pedelec demonstrated the practical application of the methodology, focusing on extending the vehicle's range while also evaluating improvements in repairability and efficiency. The results validated the accuracy of the reduced-order BOM approach and confirmed the convergence of early-phase estimates toward final design outcomes. Notably, a 162% increase in range, a 35% improvement in efficiency, and a measurable increase in repairability were achieved, demonstrating the strength of this early-stage sustainability-driven design process.

Future research can build on this methodology by extending it to full lifecycle assessments, incorporating end-of-life factors such as recyclability and disassembly. Further opportunities include integrating multi-objective optimization tools for automated trade-off analysis, adapting the framework to other product domains like electric vehicles or industrial systems, and leveraging digital twins and AI-based tools for real-time KPI estimation and design feedback. Overall, this research offers a scalable and practical foundation for embedding sustainability into early-stage product development, guiding companies toward more informed and responsible design decisions.

ACKNOWLEDGEMENTS

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The organizing committee of rev2025 extends its deepest gratitude to our financial supporters, whose contributions have been instrumental in making this event a success.



Programme overview

rev2025 took place over a span of 2.5 days comprising 11 sessions, 4 keynotes, an industry excursion, as well as a City of Graz tour. The programme overview is depicted in the table below.

Programme day 1 (September 23rd, 2025)			
from 8:30 onwards		Registration	
From	To		
09:00	09:30	Welcome to and opening of rev2025	
09:30	10:15	Keynote I Speaker: Johanna Nylander, GKN Aerospace	
10:15	10:30	Morning Coffee Break	
10:30	12:00	M1.1: Advancing Sustainable Battery Design: Materials, Circularity, and Environmental Impact	M1.2: Enhancing Resource Efficiency and Circularity in the Transport System
12:00	13:00	Lunch Break	
13:00	13:45	Keynote II Speaker: Matthias Asplund, Trafikverket	
13:45	14:00	Break	
14:00	15:30	A1.1: Life Cycle Management in early-vehicle design: Frameworks and Life Cycle Optimization approaches	A1.2: Digital Product Passports for Sustainable Mobility Solutions

15:30	16:00	Afternoon Coffee Break	
16:00	17:30	A2.1: Innovative Rail Vehicle Design: Lightweight Structures, Efficiency, and Integrated Functions	A2.2: Advancing Energy Efficiency and Sustainability in Mobility Systems
Programme day 2 (September 24th, 2025)			
from 8:30 onwards		Registration	
From	To		
09:00	09:45	Keynote III – Round Table	
09:45	10:00	Morning Coffee Break	
10:00	12:00	M1.1: Data-driven circular and sustainable vehicle management	M1.2: Innovations in Sustainable Transport
12:00	13:00	Lunch Break	
13:00	13:45	Keynote IV Speaker: Beatriz Ildefonso, European Commission, DG Research & Innovation	
13:45	14:00	Break	
14:00	15:30	A1.1: Bridging Sustainability and Design I	A1.2: Societal perspective in decarbonized transport solutions
15:30	16:00	Afternoon Coffee Break	
16:00	17:30	A2.1: Bridging Sustainability and Design II	

17:30	17:45	Closing of second day	
from 18:30 onwards		Conference Dinner @Kunsthauscafé	
Programme day 3 (September 25th, 2025)			
From	To	Location	
09:00	12:00	Excursion @AVL List GmbH.	
13:30	15:00	Guided tour – City of Graz	

The 2nd Resource Efficient Vehicles Conference (rev2025), held from September 23–25, 2025, in Graz, Austria, brought together experts from academia, industry, and public agencies. It served as a platform for discussing innovative research centered on the conference theme *Enabling Circular and Decarbonized Vehicle and Transport Solutions*. The conference was structured around five key topics, ranging from sustainable design in the early stages of vehicle development, transforming the transportation system, and digitalization for sustainable transport solutions, to the role of societal perspectives in sustainable transport systems. The electronic proceedings of rev2025 serve as a repository of the presented contributions. The structure of the proceedings is based on the conference program.