THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Inventory resolution and the interpretive scope of life cycle assessment: environmental and resource profiles of passenger cars

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Gothenburg, Sweden 2026

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ISBN 978-91-8103-459-2

Acknowledgements, dedication, and similar personal statements in this thesis reflect the author's own views.

Doktorsavhandlingar vid Chalmers tekniska högskola.
Ny serie: 5916
ISSN 0346-718X
DOI: 10.63959/chalmers.dt/5916

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Gothenburg, Sweden 2025

Abstract

This thesis investigates how supplier-reported material data can be leveraged to improve the modelling and interpretation of life cycle assessments in the automotive industry. The empirical focus is on vehicle gliders, the vehicle excluding the powertrain, assessed using foreground inventories constructed from the International Material Data System (IMDS) at the level of individual basic substances.

Four appended papers build a progressive argument. Paper I establishes an IMDS-based inventory construction approach using a combustion engine as a test case and shows that inventory simplification affects impact categories differently, with resource-related categories being particularly sensitive to reduced material detail. Paper II extends the approach to vehicle gliders and reveals a portfolio of 55 metals and metalloids, many present in trace quantities yet dominant in the scarcity profile. Paper III tracks the production-phase environmental profiles of four gliders across a 12-year period under a static background model, showing that ozone depletion responds to targeted substitution, climate change scales with platform size and the carbon intensity of material choices, and resource scarcity remains near-stable at the vehicle level while redistributing across subsystems. Paper IV compares high-resolution inventories with a legacy proxy dataset, separates foreground and life-cycle scarcity perspectives, and maps the structural dispersion of scarcity-relevant elements within the product architecture.

The overarching conclusion is that foreground inventory resolution defines the interpretive scope of environmental and resource-scarcity assessment for automotive gliders, not merely its numerical precision. What an assessment can credibly address depends on what the inventory can resolve, and access to detailed, regularly updated, supplier-reported material data is what makes such resolution attainable in practice.

List of appended papers

Paper I

Bitencourt de Oliveira, F., Nordelöf, A., Sandén, B. A., Widerberg, A., Tillman, A-M. (2022). Exploring automotive supplier data in life cycle assessment – Precision versus workload. *Transport. Res. D.*,**105**, 103247. https://doi.org/10.1016/j.trd.2022.103247

Paper II

Bitencourt de Oliveira, F., Nordelöf, A., Bernander, M., Sandén, B. A. (2024). Assessing metal use and scarcity impacts of vehicle gliders. *Circ.Econ.Sust.*, **4**, 1851–1875. https://doi.org/10.1007/s43615-024-00353-x

Paper III

Bitencourt de Oliveira, F., Nordelöf, A., Sandén, B. A. (2026). Divergent environmental trends in passenger cars over a 12-year period. *Submitted manuscript*.

Paper IV

Bitencourt de Oliveira, F., Nordelöf, A., Sandén, B. A. (2026). How inventory resolution defines the interpretive scope of resource-scarcity assessment for vehicles. *Manuscript in preparation*.

To Lucas and Theodor:
Papai loves you. A better world starts from within.

Acknowledgements

“Nobody educates anybody, nobody educates themselves, we educate each other, mediated by the world.”
— Paulo Freire, Pedagogy of the Oppressed (1968)

To get here, I needed the help of so many people. This work is also theirs.

First, this work would not have been possible without the trust placed in me by Volvo Cars and the support of several individuals there. Even though our interactions were less frequent than I would have liked, whenever we did meet, I always felt welcomed and part of the group. I’m very thankful to my colleagues for all the help they provided me along the way. Special thanks to Karl-Henrik and Rei. Without them, my models would have been half-baked at best.

To my fine colleagues at Chalmers: thank you for being so welcoming, with a special mention to Eric, Henrik, Mudit, and Pedro for so many good laughs together.

Before starting this PhD, I had heard several horror stories involving PhD students and their supervisors. Thankfully, my experience couldn’t have been further from that.

Björn, what a steadfast supervisor you are. Always ready with a wise word and genuinely interested in my development. Your way of teaching makes complex ideas incredibly intuitive. Thank you for accepting this mission and for guiding me along the way.

Anders, I couldn’t have asked for a better supervisor. Your passion for our research topic is inspiring, and I think we can all agree that your sense of humour kept us sane during these years. Our trip to Skövde, our laughs on Teams, our vivid discussions about geopolitics… I’ll take them with me. Thank you.

Maria, you know very well that I would not have come this far without your help. Your confidence in me was oftentimes greater than my own confidence in myself. I do not take for granted your dedication or your genuine care for my personal well-being and professional growth. Thank you for being who you are.

Björn, Anders, and Maria: to me, you are more than just supervisors. You are friends. Thank you for being a constant part of my life during these years.

Finally, my deepest acknowledgement goes to those who usually bear the brunt of late nights spent working and the occasional words spoken under stress: my family. Emmie, Lucas, and Theo, you are an integral part of who I am. You are the reason I move forward, and I know exactly how lucky I am to have you by my side. Thank you for your unconditional love. I love you with all my heart.

I also love my parents deeply and am immensely grateful for their presence in our lives and for all the support they continue to give us.

Allan, wherever you are, this is also for you.

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List of key abbreviations

ADP – Abiotic depletion potential

ADPe – Abiotic depletion potential for elements

BEV – Battery electric vehicle

CIDD – Combined inverter–DC/DC converter

CMDL – Component material data list

CSI – Crustal scarcity indicator

CSP – Crustal scarcity potential

DFP – Demand fraction of primary production

EEG – Extra-equipped glider

GWP – Global warming potential

HVAC – Heating, ventilation, and air conditioning

ICE – Internal combustion engine

IMDS – International Material Data System

LCA – Life cycle assessment

LCI – Life cycle inventory

LCIA – Life cycle impact assessment

MY – Model year

ODP – Ozone depletion potential

SEG – Standard-equipped glider

SOP – Surplus ore potential

1 Introduction

1.1 Automotive sustainability and shifting life-cycle burdens

Environmental assessment in the automotive industry has long been shaped by the dominance of use-phase impacts. For conventional passenger cars powered by internal combustion engines, fuel consumption and tailpipe emissions have historically outweighed most burdens associated with vehicle production, making drivetrain efficiency and operational emissions a central focus of both industrial environmental work and regulatory development (Hawkins *et al.*, 2013; Nordelöf *et al.*, 2014). This balance is now shifting. As powertrains are electrified and electricity systems are progressively decarbonised, direct use-phase emissions lose relative importance, while production-phase processes and material-related burdens account for a growing share of the overall life-cycle profile (Nordelöf *et al.*, 2014; Dolganova *et al.*, 2020; Zhang *et al.*, 2023). Although this shift is increasingly acknowledged in automotive sustainability research, its implications remain only partially understood, particularly for the non-powertrain parts of the vehicle.

This development is not driven by electrification alone. Battery-electric vehicles make the shift especially visible, since the elimination of tailpipe emissions is partially offset by higher upstream burdens from battery production, thermal management, power electronics, and structurally more material-demanding vehicle architectures (Nordelöf *et al.*, 2014; Chordia, 2025). At the same time, several other design trends continue to reshape vehicles regardless of propulsion technology. Stricter safety requirements, increasing levels of connectivity, expanding infotainment and comfort content, and the integration of advanced driver-assistance systems all add functional complexity, mass, and material diversity to the vehicle (Gawron *et al.*, 2018; European Commission, 2019; McKinsey & Company, 2024). In parallel, lightweighting strategies introduce advanced high-strength steels, aluminium alloys, and other specialised materials to offset mass growth, often at the cost of higher embodied environmental impacts per kilogram of material (Modaresi *et al.*, 2014; Czerwinski, 2021; Saufnay & Demonceau, 2023). Together, these developments indicate that understanding automotive sustainability increasingly requires attention to how the material composition of the vehicle as a whole evolves, not only to what happens in the powertrain.

1.2 Life cycle assessment in automotive practice

Life cycle assessment (LCA) has been applied in the automotive sector for decades (Kaniut *et al.*, 1997; Sullivan *et al.*, 1998; Schweimer & Levin, 2000). Considerable focus has historically been placed on comparing propulsion technologies and quantifying fuel-cycle emissions, reflecting the then-dominant role of the use phase in overall environmental performance (Koffler & Rohde-Brandenburger, 2010; Hawkins *et al.*, 2013; Nordelöf *et al.*, 2014). Over time, its scope has broadened to include production-phase impacts, material selection, manufacturing processes, and end-of-life management (Warsen & Krinke, 2013; Broch *et al.*, 2015). Today, LCA underpins regulatory reporting, product-level carbon footprinting, strategic sustainability work, and is also used as an engineering tool that informs decisions on materials, components, and product development (Delogu *et al.*, 2018; Palm *et al.*, 2024).

For complex products such as vehicles, the inventory side of the assessment is often the most demanding step. Vehicles consist of thousands of components organised into multiple nested assemblies, and constructing a life cycle inventory that represents this product structure requires combining information from several sources (Fleischer *et al.*, 1998; Koffler *et al.*, 2008). Industrial practice has typically relied on internal material databases, engineering drawings, bills of materials, supplier communication, and, in some cases, teardown-based reconstructions (Keoleian *et al.*, 1998; Danilecki *et al.*, 2017). These approaches are labour-intensive and difficult to repeat systematically across multiple vehicle models, which has encouraged the use of more streamlined inventory representations, where vehicles or vehicle subsystems are modelled through broad material categories, generic component assumptions, or proxy datasets available in life cycle inventory databases (Del Duce *et al.*, 2016; Koroma *et al.*, 2022; Sacchi *et al.*, 2022; Cappelli *et al.*, 2025).

1.3 Supplier material data as enabling infrastructure

The emergence of supplier-reported material data systems within the automotive industry has gradually changed the conditions under which inventory data can be obtained. The International Material Data System (IMDS) provides material declarations for automotive components, resolved down to individual substances within each material (DXC Technology, 2025a). This makes IMDS a potentially important data source for automotive LCA, because it gives access to product-specific material composition at a level of detail that would be difficult to obtain through disassembly or material lists alone. In principle, it opens the possibility of constructing inventories that follow the actual material architecture of the vehicle more closely than aggregated or proxy representations allow.

In practice, however, this possibility is not straightforward to realise. IMDS was not originally designed as a tool for environmental assessment. The information it contains must first be extracted, structured, interpreted, and linked to suitable background datasets before it can support LCA modelling (Koffler *et al.*, 2008). Several elements typically required for a complete life cycle inventory, such as manufacturing processes, assembly operations, material losses, and production-route assumptions, are only partly available or not explicitly reported in the system (Koffler *et al.*, 2008). Supplier-reported material data therefore reduces one major barrier to high-resolution inventory construction, but it does not remove the need for methodological choices in data structuring, interpretation, and background dataset matching.

Earlier studies have recognised the potential of IMDS to support automotive LCA and have proposed procedures for streamlining inventory construction through automated or semi-automated extraction and matching routines (Koffler *et al.*, 2008; Yu & Kim, 2013). These efforts demonstrate that IMDS can reduce part of the workload associated with inventory compilation and support broader adoption of LCA in the industry. At the same time, the existing literature has largely treated IMDS-based inventory construction as a workload problem – how to extract and process supplier data efficiently – and less directly as a question of how the resulting inventory shapes the assessment it supports. IMDS allows access to detailed compositional information down to the individual substance, but whether that detail is preserved in the inventory or reduced through simplification strategies is itself a methodological choice that lies with the practitioner.

1.4 Inventory resolution as a methodological problem

The resolution at which an inventory represents a product is not only a parameter of modelling precision. At the compositional level, it determines whether specific alloying constituents, fillers, and low-mass but functionally specific elements are retained or aggregated into broader material categories. Many such elements are present only in small quantities, yet they may be significant because of their geological scarcity, supply constraints, or functional importance in specific components (André & Ljunggren, 2022). At the structural level, resolution determines whether the link between elemental composition and the position of materials within the product hierarchy is preserved. If the inventory model does not distinguish between specific material grades, elemental constituents, or subsystem-level embedding, it becomes difficult to identify which design choices drive the result and which material changes are meaningful. The concern therefore extends beyond numerical precision to interpretive scope. A model may yield plausible totals yet lack the resolution to identify which elements, materials, or subsystems drive them.

These methodological considerations are most informative when examined in a concrete empirical context. The vehicle glider, here defined as the vehicle excluding the powertrain and its directly associated components, offers such a context. It accounts for a substantial share of vehicle mass and integrates subsystems with markedly different material profiles, from steel-intensive body structures to electronics-rich communication, safety, and comfort modules. It also provides a useful system boundary for examining how changes in vehicle size, material strategies, and functional content affect production-phase burdens as vehicle architectures evolve (Gawron *et al.*, 2018; Czerwinski, 2021; Cheshmehzangi *et al.*, 2025). Despite this, vehicle gliders have received comparatively limited analytical attention in automotive LCA. Research has typically addressed the complete vehicle at an aggregated level (Koroma *et al.*, 2022; Oda *et al.*, 2022) or focused on high-profile powertrain subsystems such as traction batteries, electric motors, and power electronics (Nordelöf *et al.*, 2019; Arshad *et al.*, 2022). Longitudinal analyses of glider environmental profiles grounded in industrial product data remain particularly scarce (Oda *et al.*, 2022).

Whether and how inventory resolution affects what an LCA of a complex automotive product such as the glider can credibly address – not only the numerical precision of the impact scores it generates, but the analytical questions it is equipped to support – remains insufficiently examined.

2 Research aims and thesis structure

This chapter formulates the research aim and the four questions that guide this work and describes how the appended papers contribute to answering them.

2.1 Overall aim

The overall aim of this thesis is to investigate how supplier-reported material data can be leveraged to improve the modelling and interpretation of life cycle assessments in the automotive industry. Particular emphasis is placed on what different levels of inventory detail enable when assessing production-phase environmental burdens and resource use in vehicle gliders.

2.2 Research questions

The thesis is guided by four research questions (RQs), organised in two groups. The first group concerns methodological aspects of inventory construction and the relationship between data resolution and assessment outcomes. The second group concerns empirical findings about vehicle gliders as environmental and resource-relevant systems.

Methodological research questions

RQ-M1: How can supplier-reported material data be transformed into usable life cycle inventories for complex automotive systems?

This question addresses the extraction, structuring, and modelling of material composition data from IMDS, including the matching of supplier-declared information to background inventory datasets and complementary process data. It addresses both the development of the inventory construction approach and the relationship between modelling effort and inventory completeness.

RQ-M2: How does the technical and temporal resolution of foreground inventories affect the precision and interpretive scope of environmental and resource-scarcity assessment?

This question examines how inventory resolution affects assessment precision and the interpretations that can be supported. Resolution is understood here in two complementary dimensions. Technical resolution refers to the level of material, elemental, and structural detail preserved in the foreground inventory. Temporal resolution refers here to the extent to which inventories are specific to successive product generations and can be updated consistently as products evolve. The question therefore covers both the sensitivity of impact categories to technical simplification and the analytical value of repeatedly updated foreground inventories.

Empirical research questions

RQ-E1: What do high-resolution inventories reveal about the metal composition and resource-scarcity profiles of vehicle gliders?

This question examines what detailed foreground inventories reveal about vehicle gliders. It considers the breadth of the metal portfolio, the scarcity relevance of individual elements, the influence of equipment level, and the distribution of metals and metalloids across subsystems and components.

RQ-E2: How do the production-phase environmental and resource profiles of vehicle gliders evolve over time as vehicle architectures change?

This question introduces a longitudinal perspective. It examines how different impact categories respond to platform evolution, material substitution, and changing functional content across successive vehicle configurations. It also asks whether aggregate vehicle-level results conceal divergent subsystem-level trajectories.

The methodological and empirical questions are interrelated. The inventory construction approach and resolution insights developed through RQ-M1 and RQ-M2 provide the basis for the empirical analyses in RQ-E1 and RQ-E2, while the empirical findings illustrate why the methodological contributions matter. Together, the questions connect the construction and resolution of foreground inventories with the forms of environmental and resource-related interpretation those inventories support.

2.3 Structure of the thesis and role of the appended papers

The thesis comprises four appended papers and an integrative essay (this document) that synthesises their contributions within a unified analytical framework. A licentiate thesis, comprising Papers I and II, serves as a conceptual midpoint in the research programme by formulating an initial set of thesis-level research questions and connecting the methodological and empirical strands of the early work (Bitencourt de Oliveira, 2023). The present thesis extends that foundation with two additional papers and a revised, more comprehensive framing.

The four papers contribute to the research questions as follows (see also Table 1):

RQ-M1 – the development of the inventory construction approach – is addressed primarily through **Paper I** (*Exploring automotive supplier data in life cycle assessment*), which establishes the IMDS-based extraction and modelling approach using a vehicle combustion engine as a test case. **Paper II** (*Assessing metal use and scarcity impacts of vehicle gliders*) extends this approach to full vehicle gliders and introduces elemental-level assessment, demonstrating its applicability to a more complex product system.

RQ-M2 – the relationship between inventory resolution and assessment outcomes – is addressed across all four papers, from different angles. **Paper I** provides initial methodological evidence by showing that simplification strategies affect impact categories differently, with resource-related categories being particularly sensitive to reduced material detail. **Paper IV** (*How inventory resolution defines the interpretive scope of resource-scarcity assessment for vehicles*) provides the most direct methodological examination by comparing high-resolution glider inventories with a legacy proxy dataset, separating foreground and life-cycle scarcity perspectives, and assessing the structural dispersion of scarcity-relevant elements. Papers II and III contribute empirical evidence. **Paper II** reveals metal composition and scarcity patterns in vehicle gliders that would not be identifiable without high-resolution foreground data. **Paper III** demonstrates that aggregate vehicle-level results can conceal divergent subsystem-level trajectories, reinforcing the case for subsystem-resolved inventory data. Together, these contributions show that inventory resolution affects not only the precision of impact scores but also which analytical questions the assessment can address.

RQ-E1 – the characterisation of glider resource profiles – is addressed primarily in **Paper II**, which reveals the breadth and scarcity relevance of the metal portfolio in vehicle gliders, examines how equipment level modulates the presence of specific metals, and uses entropy to describe how metals are distributed across components and subsystems.

RQ-E2 – the longitudinal evolution of glider environmental profiles – is addressed through **Paper III** (*Divergent environmental trends in passenger cars over a 12-year period*). Using high-resolution inventories for four glider configurations across a 12-year period, spanning a platform shift and a drivetrain transition, it illustrates distinct patterns in the environmental profile evolution of the gliders: impact scores mitigated by targeted substitution, impact scores that have scaled with platform size and structural requirements, and impact scores that have remained near-stable at vehicle level while redistributing across subsystems and material groups.

Table 1. Contributions of the appended papers to the research questions. Each paper addresses one or more questions. RQ-M = methodological research question; RQ-E = empirical research question.

	RQ-M1	RQ-M2	RQ-E1	RQ-E2
Paper I	●●	●●		
Paper II	●	●	●●	
Paper III		●	●	●●
Paper IV		●●		

(●● = primary, ● = contributing)

The remainder of the thesis is organised as follows. **Chapter 3** presents the methodology and analytical framework, including the common inventory construction approach, impact assessment methods, and the methodological choices that distinguish each appended study. **Chapter 4** synthesises the main results of the appended papers, organised thematically rather than paper by paper. **Chapter 5** discusses the findings in relation to the research questions, addresses limitations, and reflects on the generalisability and broader relevance of the work. **Chapter 6** concludes the thesis.

3 Analytical framework and methodology

The four appended papers share a common methodological foundation but differ in their analytical focus and in the specific choices that each study requires. This chapter first describes the shared framework (3.1–3.6) and then presents the methodological choices that distinguish each appended study (3.7–3.10).

3.1 Systems perspective and scientific positioning

This thesis is situated within the field of environmental systems analysis, a research tradition concerned with quantifying the environmental consequences of defined technical activities – a product, a process chain, or a sector – by tracing the material and energy flows that connect those activities to upstream resource extraction and downstream environmental cause-effect chains (Baumann & Tillman, 2004; Finnveden & Moberg, 2005). In this tradition, environmental problems are examined not in isolation but in relation to the material flows, energy transformations, and resource dependencies that connect products, processes, and supply chains.

Life cycle assessment is one of the principal methods in environmental systems analysis. It provides a structured framework for quantifying the potential environmental impacts associated with a product or service throughout its life cycle, from raw material extraction through production, use, and end-of-life treatment (Baumann & Tillman, 2004; Hauschild & Huijbregts, 2015). In industrial applications, LCA translates complex product systems into quantifiable environmental profiles that can inform material selection, design decisions, and strategic priorities (Baumann & Tillman, 2004; Schmidt, 2024). Its strength lies in the systematic tracing of environmental flows across system boundaries. Its limitation, particularly for complex products, lies in the dependence of the results on how the product system is represented in the inventory model.

How inventory representation shapes assessment results is the central methodological concern of the thesis. A vehicle glider is a complex product whose foreground inventory follows the product hierarchy of the vehicle – subsystems composed of components, components composed of materials, and materials composed of basic substances – with distinct material profiles and supply-chain dependencies at each level (Fleischer *et al.*, 1998; Koffler *et al.*, 2008). In LCA terms, the *foreground* processes are those close to the studied product, for which specific data are collected, while *background* processes lie further upstream (or downstream) and are usually represented by generic data from inventory databases (Schmidt, 2024). In this thesis, the phrase "life-cycle perspective" is used throughout to refer to the joint modelling of foreground and background processes, and not for the coverage of the complete *cradle-to-grave* life cycle; the system boundary applied across the appended studies is *cradle-to-gate* (see 3.2). The level at which the product hierarchy is resolved in the foreground inventory, i.e., material, elemental, and structural, determines not only the precision of the resulting impact scores, but also which environmental and resource-related questions the assessment can address.

This framing also explains the progressive structure of the appended papers. The thesis does not treat inventory resolution as a single parameter to be optimized. Instead, it examines how different levels of resolution interact with different types of environmental questions, from broad climate-oriented screening to element-specific scarcity assessment and structural dispersion mapping, and how these interactions become visible through the systematic application of high-resolution, supplier-derived material data to increasingly complex analytical tasks.

3.2 Research design and cross-paper logic

The thesis employs life cycle assessment as its primary analytical framework. Papers I, III, and IV apply attributional, cradle-to-gate modelling covering raw material extraction and processing, production of semi-finished materials, component manufacturing, and final assembly. Paper II uses the same supplier-reported foreground data structure but assesses the elemental composition of the gliders directly rather than constructing a full cradle-to-gate life cycle inventory. Across the studies, the use phase, maintenance, and end-of-life treatment are outside the analytical scope, as the thesis focuses on the production-phase implications of material composition and inventory resolution.

Within this context, the research design connects methodological development with empirical application. The methodological strand develops and applies an IMDS-based approach to inventory construction, examines how inventory simplification affects different indicator domains, and evaluates how inventory resolution shapes the interpretations an assessment can support. The empirical strand applies this approach to examine the composition, production-phase environmental burdens, and resource-scarcity profiles of vehicle gliders across configurations and model years. Together, the two strands examine the proposition that inventory resolution is not merely a technical modelling parameter but shapes the interpretive capacity of the assessment.

The foreground data source throughout the thesis is the International Material Data System (IMDS), linked to the manufacturer's internal product-structure data. This combination provides the material composition of the assessed product at the level of individual basic substances – the finest resolution available in IMDS. These basic substances are then matched to background inventory datasets representing their cradle-to-gate production, drawn primarily from Ecoinvent (Wernet *et al.*, 2016), with selected adaptations for specific materials and production routes. This shared inventory construction approach, from product-structure extraction through IMDS-based material declaration to basic-substance-level inventory modelling, provides the methodological backbone of the thesis and is described in section 3.4.

Within this common framework, the studies differ in their analytical scope and in the level at which the inventory construction is applied. Paper I uses a vehicle combustion engine as object of study for assessing how simplification strategies affect LCA results across a broad set of impact categories. Papers II–IV shift the focus to vehicle gliders. Among these, Paper II extends this approach to characterise the foreground metal portfolio of gliders and assesses scarcity relevance using indicators applied directly to the elemental composition, without full background modelling for the scarcity indicators. Paper III develops a full cradle-to-gate LCA framework for gliders, including background modelling, complementary manufacturing data, and assembly. Paper IV applies this framework to a different analytical question, comparing the resulting high-resolution inventories with a legacy proxy dataset and extending the assessment to foreground and life-cycle scarcity perspectives.

The remainder of this chapter is organised in two parts. Sections 3.3 through 3.6 present the elements that are shared or comparable across the appended papers: the vehicle glider as an analytical unit (3.3), the IMDS-based inventory construction procedure (3.4), the impact assessment methods (3.5), and the approach to confidentiality and normalisation (3.6). Sections 3.7 through 3.10 present the methodological choices that distinguish each appended study from the common framework, organised by research question.

3.3 The vehicle glider: definition, subsystem structure, and scope

In this thesis, the term glider refers to the vehicle excluding the powertrain and its directly associated components. The glider comprises the load-carrying body structure, closures and exterior trim, chassis, steering and suspension, wheels and brakes, interior systems, the low-voltage electrical system including the 12 V auxiliary battery, and all comfort, safety, infotainment, and communication equipment. Excluded from the glider are the internal combustion engine or electric traction motor, the transmission, the exhaust after-treatment system, the fuel storage and delivery system, the high-voltage traction battery and its battery management system, power electronics dedicated to traction or charging, and high-voltage cabling. This definition is applied consistently across Papers II–IV, which use vehicle gliders as their study object.

The glider integrates subsystems with fundamentally different material profiles. Body structures and chassis-related parts are dominated by ferrous metals and aluminium alloys, whereas electrical infrastructure relies on copper-based conductors, and multimedia, communication, and safety electronics incorporate a range of precious metals, rare-earth elements, and other low-mass but functionally important constituents. This material heterogeneity is one reason why the glider is a relevant unit for studying how inventory resolution affects LCA interpretation. Consequently, meaningful contribution analysis requires the ability to attribute materials, elements, and impact scores to defined parts of the product architecture.

To support this attribution, all glider components in the thesis are assigned to subsystem groups. The grouping follows the primary technical function of each component and is organised hierarchically. Two levels of aggregation are used across the appended papers. A disaggregated scheme comprising 21 subsystems is used in Papers II and IV, where the analysis requires finer structural resolution to support metal dispersion assessment and subsystem-level scarcity interpretation. A more aggregated scheme comprising 10 subsystems is used in Paper III, where the analytical focus is on longitudinal trends in production-phase impacts across a broader set of functionally distinct vehicle areas. The 10-subsystem scheme is a direct aggregation of the 21-subsystem scheme. For example, the disaggregated groups “Body structures”, “Doors and trunk”, “Exterior glass”, and “Exterior trim” are combined into a single group, “Body, closures and exterior trim”, in the aggregated scheme. Similarly, “Steering” and “Suspension, frames and mountings” are combined into “Steering and suspension”. Both schemes are based on the same underlying product-structure logic and differ only in the level at which components are grouped. The complete list of subsystems at both levels of aggregation, together with examples of representative components, is provided in the Supplementary Information of Paper III and Paper IV.

The subsystem assignment is held constant across model years within each study, so that observed differences in mass and impact scores reflect changes in vehicle design, material selection, and functional content, rather than reclassification of components. It is worth noting that the subsystems are adapted from, rather than identical to, the manufacturer's proprietary product-structure conventions, and they are intended to serve as functionally meaningful analytical categories rather than to reproduce an exact internal vehicle taxonomy.

3.4 IMDS-based inventory construction

The International Material Data System (IMDS) is a web-based, industry-wide database jointly developed by automotive manufacturers for collecting and communicating information about the material content of vehicle components (DXC Technology, 2025a). Its primary purpose is to support regulatory compliance with substance restrictions, including those specified in the EU End-of-Life Vehicles Directive (European Commission, 2000) and the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation (European Commission, 2006). Over 120,000 registered suppliers report material declarations for the components they deliver, making IMDS the most comprehensive source of component-level material data available across the automotive supply chain (DXC Technology, 2025b). Although IMDS was not developed for environmental assessment, the granularity of its material declarations, resolved down to individual basic substances within each material, makes it a potentially valuable data source for life cycle inventory modelling.

IMDS organises material information in a hierarchical structure. A component consists of one or more materials, and each material is described by its constituent basic substances. A material, in the IMDS definition, is a physically homogeneous entity, such as a specific steel grade, a thermoplastic compound, or a surface coating (DXC Technology, 2025a). Basic substances are standardised entries maintained by the IMDS Chemical Service and may represent chemical elements (e.g., iron, copper), standard compounds (e.g., acrylic resin, glass fibre), or, where proprietary formulations require confidentiality, wildcards (e.g., “miscellaneous, not to be declared”) (DXC Technology, 2025a). All material entries are additionally classified according to the VDA material classification system developed by the German Association of the Automotive Industry, which assigns each entry to a broad material category (e.g., steel, thermoplastic, ceramic) based on its composition, properties, and intended application (Verband der Automobilindustrie, 1997).

However, several types of information relevant to life cycle inventory modelling are not explicitly reported in IMDS material datasheets. These include material production routes (e.g., blast-furnace versus electric-arc-furnace steelmaking), recycled content shares, upstream manufacturing processes (e.g., casting, forming, machining performed within the supply chain), and final assembly operations. In addition, suppliers may report basic-substance concentrations as ranges rather than exact values (e.g., “Iron 90–99 wt.-%”) (DXC Technology, 2025a), introducing a degree of uncertainty in the foreground inventory. These gaps and uncertainties are addressed through complementary data sources and modelling assumptions described later in this section and, where relevant, through sensitivity analyses in the corresponding methods sections (3.7–3.10). In Paper III, the influence of concentration-range reporting is assessed through a bounding analysis using the lower and upper limits of the reported ranges.

The extraction of foreground inventory data follows a sequence of steps developed and progressively refined across the appended papers. Figure 1 provides an overview of the life-cycle inventory modelling workflow used in this thesis. For each assessed product, whether an engine (Paper I) or a vehicle glider (Papers II–IV), a complete list of components is first extracted from the manufacturer's internal product-structure database. This database organises all components present in a given vehicle or subsystem hierarchically and records each component's identity, quantity, mass, and position within the product structure. The component list does not contain information on material composition. To obtain this, each component identification number is matched to its corresponding material declaration stored in IMDS through an automated linking procedure. The result is the component material data list (CMDL): a structured dataset in which every component entry is associated with its materials, the basic substances constituting those materials, and the component's position within the product hierarchy. Across the set of vehicle gliders assessed in this thesis, the resulting

CMDLs collectively comprise several hundred thousand data entries, spanning thousands of unique components and thousands of distinct basic substances.

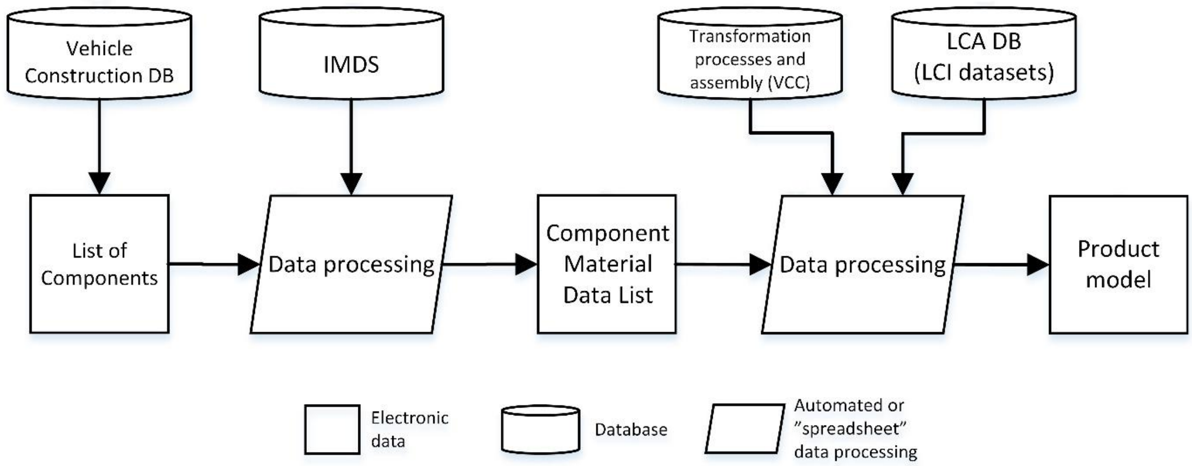

Figure 1. Overview of the IMDS-based inventory construction procedure used in this thesis. The figure illustrates the sequence from the manufacturer's product-structure database through IMDS material declaration matching to the generation of the component material data list (CMDL), material grouping, basic-substance-level modelling, and linking to background inventory datasets (adapted from Paper I).

Once the CMDL is generated, the material entries it contains are assigned to predefined material groups to support interpretation and life-cycle modelling. Material groups (e.g., low-alloyed steel, wrought aluminium, polyamide) are defined based on material composition, VDA classification, and intended application, following a grouping logic developed in Paper I and applied with minor adaptations in subsequent studies (Papers II–IV). For each material group present in a given subsystem, all individual material grades are combined into a single representative composition by calculating the mass-weighted average basic-substance profile across the grades in that group. This aggregation step reduces the number of distinct compositions requiring explicit background modelling while preserving the subsystem-level basic-substance flow structure. Each aggregated composition is then expressed at the basic-substance level, meaning that the inventory model represents materials through their constituent basic substances rather than through broad material-level designations. For example, a material reported in IMDS as a thermoplastic compound containing polypropylene as the polymer matrix, and glass fibre and talc as fillers, is represented by linking each of its constituent basic substances to corresponding cradle-to-gate background datasets. In this way, both material matrix and additive constituents are explicitly accounted for in the inventory model. This approach preserves the elemental resolution of the IMDS data and allows the model to capture the environmental implications of specific alloying constituents, filler compounds, and low-concentration elements that could otherwise be lost in a material-level representation.

The number of basic substances in a full vehicle glider inventory is large, with some material groups containing hundreds of distinct entries, many of them present at trace concentrations. Managing this complexity requires a coverage rule that balances modelling simplicity with the retention of environmentally relevant substances. The approach to this trade-off evolved across the thesis. In Paper I, the most detailed modelling option (the reference case) retains all basic substances reported in the CMDL, with no concentration threshold or coverage limit applied. This comprehensive approach is feasible for a single engine but becomes impractical for full vehicle gliders. The simplified options in Paper I then systematically reduce the number of substances – through mass-based material cut-offs and single-substance-per-material representations – to quantify how these reductions affect impact assessment results. The findings of Paper I inform the coverage strategy adopted in subsequent studies. In Paper III, where the foreground datasets together comprise over 400,000 data entries, a dual-threshold coverage rule is applied to each material group within each subsystem. First, all basic substances with a mass fraction at or above 0.005 wt.-% within each aggregated material composition are retained. This threshold is set low enough to capture trace metals with high scarcity characterisation factors (e.g., precious metals) that can dominate CSI results despite very low concentrations. Second, the retained set is required to cover at least 99.5 wt.-% of the material mass. If the concentration threshold alone does not reach this level, additional substances are included in descending order of mass fraction until the coverage target is met. The small remaining mass difference between the covered fraction and 100 wt.-% is redistributed proportionally among the retained substances so that their mass fractions sum to exactly 100 wt.-%. This procedure results in full mass coverage of the glider with at most 0.5 wt.-% of each material grade being redistributed, which is more conservative than the 1 wt.-% cut-off commonly applied in LCA practice and stricter than the cut-offs explored in Paper I.

In IMDS, suppliers may protect proprietary formulations by reporting certain basic substances as wildcards – entries with generic or undisclosed identities (e.g., “impact modifier”, “inorganic filler”) (DXC Technology, 2025a). These entries are retained where they meet the coverage thresholds described above and are modelled using proxy background datasets selected based on their chemical family or functional description (e.g., a generic organic chemical dataset for an “impact modifier”, a representative mineral dataset for an “inorganic filler”). This approach avoids the assumption that confidential additives share the environmental profile of the bulk matrix, while acknowledging the inherent uncertainty in their representation. Across the assessed gliders, wildcard entries account for less than 1.0 wt.-% of the total glider mass. Because scarcity-relevant elements may be present at very low concentrations, this mass share does not by itself bound the potential influence of undisclosed formulations on the results. Paper III assesses this uncertainty by examining the mass shares and basic-substance profiles of the wildcard entries and redistributed fractions.

The foreground inventory is complemented with data representing processes not reported in IMDS. Three categories of complementary data are included. First, upstream manufacturing processes, such as casting, forming, machining, and surface treatment performed within the supply chain are represented by background datasets that account for the energy, auxiliary materials, and emissions involved in converting intermediate products (e.g., metal billets, plastic pellets) into finished components. These processes are identified based on component names, material entries, VDA classifications, and expert judgement. Second, electronics manufacturing is modelled separately, recognising that the transformation processes for electronic hardware are generally more energy- and resource-intensive than those for bulk mechanical components (Nordelöf, 2019). Identifying electronic components in the CMDL is not straightforward, as IMDS does not consistently classify material entries as electronics. To address this, a recursive search traverses the hierarchical structure of IMDS data entries down to the deepest available reporting level, often six to seven tiers below the main assembly. A rule-based screening procedure then uses the nomenclature of these subcomponents, such as printed circuit boards, integrated circuits, and capacitors, to assign them to distinct electronic component classes. These assignments are reviewed manually and linked to suitable cradle-to-gate background datasets representing the manufacture of electronic components, including associated energy use, auxiliary materials, waste, and emissions. This modelling is applied in addition to the basic-substance-level representation of raw materials (e.g., copper, gold, silver) reported in IMDS, which are linked separately to corresponding production datasets. Third, final assembly at the manufacturer's production facilities is included using site-specific data on energy consumption, auxiliary materials, waste generation, and material losses, linked to background datasets representing the corresponding production conditions.

Background data are drawn primarily from Ecoinvent (Wernet *et al.*, 2016), with selected adaptations to reflect the compositions and production routes relevant to specific materials in the assessed products. For most material groups, basic substances are matched individually to their corresponding production datasets, as described for the polymer example earlier. Ferrous materials classified as steel and cast iron require a different treatment, because their constituent elements are not produced independently but enter joint metallurgical production routes. In such cases, iron and carbon are matched together to a single production-route dataset rather than to separate elemental datasets, since producing iron and carbon independently would not be representative of actual steelmaking or iron-casting processes. Unalloyed and low-alloyed steel grades are represented using blast-furnace/basic-oxygen-furnace routes, while high-alloyed steels are represented via electric-arc-furnace routes. In both cases, the remaining alloying elements reported in IMDS (e.g., chromium, nickel, manganese, molybdenum) are introduced via corresponding ferroalloy inputs (e.g., ferrochromium, ferronickel, ferromanganese), adjusted to match the IMDS-reported compositions. This distinction matters because IMDS reports alloying elements in their refined form, whereas in practice they enter metallurgical processing as ferroalloys. Matching them directly to refined-element production datasets would overestimate the environmental burden of the alloying step. Cast iron is represented using a cupola-furnace production route based on literature data, with the iron and carbon content matched jointly to this route and direct process CO_2 emissions included. In addition, aluminium alloys are represented by an adapted primary-aluminium dataset in which the alloying composition is adjusted based on IMDS elemental data. Other basic substances, including polymers, ceramics, and glass, are linked to global-market inventory datasets from Ecoinvent (Ecoinvent, 2023). An important exception in the glider assessments is the refrigerant R-134a, for which a hybrid inventory was constructed based on mass-balance data and recent atmospheric evidence of fugitive CFC-113a emissions, replacing the legacy Ecoinvent dataset to reflect modern production pathways (Ecoinvent, 2024a). The corresponding background datasets are documented in the Supplementary Information of Paper III.

In Papers III and IV, all model years are evaluated using the same versions of background databases and electricity mixes, resulting in a static background inventory model. This design isolates the effects of foreground design evolution – changes in mass, material composition, and functional content – from the simultaneous decarbonisation of energy systems and efficiency gains in material supply chains.

3.5 Impact assessment methods

The environmental and resource-related impacts assessed in this thesis are quantified using midpoint characterisation methods. The primary framework is the Environmental Footprint (EF) 3.1 (Andreasi Bassi *et al.*, 2023), which provides a recommended set of sixteen midpoint impact categories. In addition to these, the crustal scarcity indicator (CSI) (Arvidsson *et al.*, 2020) is used as a complementary measure of long-term mineral resource scarcity. CSI is not part of the EF 3.1 framework but is introduced here because of its central role in the thesis. The specific indicator selections are described in the corresponding methods sections (3.7–3.10). Three indicators recur across the thesis and are introduced below.

Climate change is characterised over a 100-year time horizon using global warming potentials (GWP) from the IPCC Sixth Assessment Report, as implemented in the EF 3.1 climate change category (Andreasi Bassi *et al.*, 2023). Climate change captures the contribution of greenhouse gas emissions to radiative forcing and is used in this thesis as the primary climate-related indicator. In the context of vehicle production, GWP results are typically driven by energy-intensive material production processes (e.g., primary aluminium smelting, steelmaking) and by manufacturing energy use. Because these contributions are usually associated with bulk material flows, GWP results tend to remain identifiable even in relatively aggregated inventory representations, a property that is relevant to the thesis's analysis of how inventory resolution affects different impact categories.

Ozone depletion is characterised using ozone depletion potentials (ODP) from the World Meteorological Organization (WMO, 2014), as implemented in the EF 3.1 ozone depletion category. Ozone depletion quantifies the potential contribution of emitted substances to stratospheric ozone destruction. In the context of this thesis, ozone depletion is used in Paper III to examine how a targeted substitution in the glider HVAC system affects upstream-production contributions and longitudinal trends in glider-level impact scores.

The crustal scarcity indicator (CSI) is used to assess long-term mineral resource scarcity. CSI expresses the potential scarcity pressure associated with extracting metals of different crustal abundances. Each element i is assigned a crustal scarcity potential (CSP), derived from estimates of its average concentration in the Earth's upper continental crust. The CSI score for a given product is then calculated as:

$$CSI = \sum_{i} m_i \times CSP_i$$

where m_i is the mass of element i in the assessed product (in kg) and CSP_i is the crustal scarcity potential for that element (in kg silicon equivalents per kg). Due to its reliance on elemental composition, CSI is sensitive to the presence of low-mass but geologically scarce constituents, such as precious metals and specific alloying elements. This sensitivity makes CSI a useful complement to indicators dominated by high-mass material flows, such as climate change, when examining how inventory resolution affects impact assessment results.

CSI is limited to elements found in the Earth's crust and does not account for other environmental compartments (e.g., oceans) that may contain extractable quantities of some elements. It also does not capture short-term supply dynamics, geopolitical factors, or market-driven scarcity. These dimensions are addressed by other indicator families developed to characterise mineral and metal resource use (Sonderegger *et al.*, 2020; Berger *et al.*, 2020; Jabara *et al.*, 2025). To situate CSI relative to established LCIA practice, this thesis also reports results for two complementary mineral-resource indicators: the abiotic depletion potential for elements (ADPe) (van Oers *et al.*, 2020) and surplus ore potential (SOP) (Vieira *et al.*, 2017). ADPe relates annual production to ultimately extractable reserves, while SOP represents the additional ore expected to be mined in the future as ore grades decline. Together with CSI, they provide conceptually distinct perspectives on long-term mineral resource scarcity. ADPe and SOP results are reported in the Supplementary Information of Paper III.

In this thesis, CSI is adopted as the principal resource-scarcity indicator because its characterisation factors (CSP) depend only on natural-system data (crustal abundance) and carry no technosphere parameter. Because the CSP does not itself encode production, market, or supply-chain variables, differences in CSI scores between assessments can be attributed to differences in the inventory itself – a property that supports the foreground/life-cycle separation developed in section 3.10. The positioning of CSI relative to alternative resource indicators, including its strengths and limitations, is discussed in section 5.3.

3.6 Confidentiality and normalisation

The foreground inventories used in this thesis are based on proprietary industrial data, including component-level bills of materials, supplier-reported material declarations, and manufacturer-specific product-structure information. Confidentiality requirements restrict the direct reporting of absolute masses, material formulations, and impact scores. Across the appended papers, results are therefore presented using formats that preserve analytical content while protecting commercially sensitive information. These formats include normalisation to a reference case, contribution shares, and ratios.

In Paper III, all absolute impact scores are normalised to the model year 2012 (MY12) glider, which serves as the reference case (MY12 = 1.0). Mass values are normalised in the same way. This linear scaling preserves the relative magnitude of all subsystem and material contributions. Percentage differences between model years and contribution shares reported in the study are mathematically identical to those derived from the underlying confidential data. In Paper IV, results are presented as ratios relative to the proxy dataset and contribution shares depending on the analytical context. Paper II reports some metal masses directly where permitted, while scarcity results are presented in formats that do not disclose confidential product information. Paper I, which assesses a combustion engine, reports impact scores normalised to the most detailed modelling option (A100), which serves as the reference case.

These reporting conventions affect the presentation of results but not the relative differences or contribution patterns on which the analysis is based. The methodological procedures, system boundaries, and analytical logic are described in the appended papers and their supplementary information, allowing the approach and interpretation to be evaluated independently of the confidential absolute values.

The preceding sections describe the methodological elements common to the appended papers. The following sections present the methodological choices that distinguish each appended study, organised by research question. Each section identifies the study object, the analytical scope, and the key design decisions that distinguish the study from the common framework described above.

3.7 Inventory construction, simplification strategies, and precision assessment (RQ-M1–RQ-M2)

To establish the IMDS-based inventory construction approach and assess how simplification strategies affect LCA precision, Paper I uses an internal combustion engine as its study object. An engine is selected because it captures much of the material variability present in a complete vehicle while remaining suitable for systematic comparison of multiple modelling options. The inventory is constructed following the procedure described in section 3.4.

The study defines eight modelling options by varying the level of data aggregation and data completeness of the inventory (Table 2). The reference option (#0) retains all reported basic substances without mass-based cut-offs or substance-level simplifications. The remaining options simplify the inventory along three dimensions: i) the structural level at which the engine is modelled (sub-parts or complete engine), ii) whether a 1 wt.-% mass cut-off is applied at the material level, and iii) whether all reported basic substances are retained or only the single dominant basic substance per material. Each option is evaluated both with and without the complementary manufacturing, assembly, and material-loss data described in section 3.4. Impact scores are calculated across the full EF 3.0 midpoint indicator set (Fazio, 2018) and are normalised to the reference option.

Table 2. Summary of the modelling options assessed in Paper I. The reference option (#0) retains the highest level of detail. Options #1–#7 simplify the inventory along one or more dimensions. Each option is additionally evaluated with and without complementary data (not shown).

Modelling option		Modelling choices		
		Function group level	Mass cut-off	Basic substances retained per material
#0	(most detailed)	Sub-parts	None	many
#1	⇕	Complete engine	None	many
#2		Sub-parts	1 wt.-%	many
#3		Complete engine	1 wt.-%	many
#4		Sub-parts	None	one
#5		Complete engine	None	one
#6		Sub-parts	1 wt.-%	one
#7	(least detailed)	Complete engine	1 wt.-%	one

The modelling effort associated with each option is also investigated. In IMDS-based inventory construction, the primary sources of workload are the identification and classification of individual materials, and the matching of their constituent basic substances to suitable background inventory datasets. These tasks scale with the number of distinct materials and basic substances retained in the inventory model. Paper I therefore evaluates how each simplification strategy affects the volume of entries requiring manual processing, providing a basis for assessing the trade-off between modelling effort and impact-score precision. This trade-off is directly relevant to RQ-M1, which addresses the practical conditions under which supplier-reported data can be transformed into usable life cycle inventories.

3.8 Metal composition and scarcity assessment (RQ-E1)

To characterise the metal portfolio and scarcity relevance of vehicle gliders, Paper II assesses two gliders based on the same vehicle model but configured with different equipment levels: an extra-equipped glider (EEG) and a standard-equipped glider (SEG). All components are assigned to the 21 subsystem groups described in 3.3. The study does not develop a full cradle-to-gate LCA model. Instead, it assesses the elemental composition of the foreground inventory directly. Where a metal is reported in IMDS as part of a compound, its elemental content is calculated primarily from the molecular formula identified through the CAS registry number assigned to the basic substance.

The assessment is limited to metals and metalloids. Two scarcity indicators are used: CSI (section 3.5) as a long-term scarcity indicator and the demand fraction of primary production (DFP), formulated in Paper II as an indicator of short-term potential primary metal scarcity. DFP expresses the ratio between the metal demand of a hypothetical global fleet of 80 million gliders and the annual global primary production of that metal:

$$DFP_i = \frac{m_i \times F}{P_i}$$

where m_i is the mass of metal i per glider (kg), F is the hypothetical annual fleet size (80 million units), and P_i is the annual global primary production of metal i (kg per year). A high DFP value indicates that the hypothetical automotive sector's demand for a given metal would represent a large share of current global primary production and may therefore signal potential pressure on near-term primary supply.

Paper II also assesses the distribution of metals and metalloids across the glider structure using Shannon entropy. It is calculated from the mass shares of each metal across all components in which it occurs:

$$S_i = -\sum_{j=1}^{N_i} p_{i,j} \ln(p_{i,j})$$

where N_i is the number of components containing the metal i, and $p_{i,j}$ is the mass of metal i in component j divided by the total mass of metal i in the glider. A higher entropy indicates a more even distribution of the metal across components, while a lower entropy indicates that a larger share is concentrated in a smaller number of components.

Component-level entropy values depend on the granularity at which the product structure is decomposed in the supplier-reported data. This dependence is discussed as a limitation in section 5.6.

3.9 Longitudinal environmental assessment (RQ-E2)

To examine how production-phase environmental profiles evolve as vehicle architectures change, Paper III assesses four vehicle gliders spanning a 12-year period: model years 2012, 2016, 2020, and 2024. The earlier pair (MY12, MY16) corresponds to a hatchback architecture, while the later pair (MY20, MY24) corresponds to a compact SUV architecture. MY24 additionally represents a battery-electric vehicle configuration. The selection thus captures a platform shift, a drivetrain transition, and the cumulative effects of evolving safety, connectivity, and comfort content on glider composition. All glider components are assigned to the 10 subsystem groups described in 3.3.

The foreground inventories are constructed following the approach described in 3.4, including the dual-threshold coverage rule and complementary data for manufacturing and assembly. In this study, the background inventory model is held static across all four model years, isolating the effects of foreground design evolution from simultaneous changes in energy systems and supply-chain efficiency. This design answers the question of how the production-phase burden would change if all four glider generations were manufactured under identical background conditions. It does not represent the actual historical emissions of gliders produced in their respective years, and background modelling choices should not be interpreted as reflecting manufacturer-specific procurement or production practices.

The functional unit is one complete glider, capturing the production burden per vehicle and the scale effects associated with platform upsizing and increased material content. Results are also reported per kilogram of glider as a complementary mass-normalised basis, allowing changes in impact intensity to be distinguished from changes in total glider mass. Three impact indicators are assessed: climate change, ozone depletion, and crustal scarcity (3.5). In this study, climate change primarily reflects bulk material flows and energy-intensive processes. Ozone depletion is linked to specific substances in the supply chain. Crustal scarcity reflects both the elemental composition of the glider and upstream processes represented in its supply chain. This selection enables the study to examine whether different types of impact categories respond differently to the same underlying design evolution.

In this study, CSI is applied across all characterised elements, unlike Paper II. An important boundary choice concerns the battery-electric glider (MY24), where a combined inverter–DC/DC converter (CIDD) is included in the main case to represent the low-voltage power-supply function consistently across model years, although this introduces a partial overlap with the powertrain boundary. A sensitivity analysis excluding the CIDD shows that this boundary choice affects the MY24 scores but does not alter the overarching longitudinal patterns. Additional sensitivity analyses address IMDS concentration-range reporting and background dataset selection, while a targeted validity audit and proxy reconstruction address anomalous supplier-reported values in the “Exterior visibility” subsystem.

3.10 Inventory resolution and interpretive scope (RQ-M2)

To clarify how foreground inventory resolution shapes the interpretation of LCA results, Paper IV uses the MY12 and MY24 high-resolution glider inventories developed in Paper III as reference cases, evaluated under the same static background model and modelling assumptions (3.4, 3.9).

The analysis is organised around three complementary assessments. First, climate change and CSI results from the high-resolution inventories are compared with those from a legacy proxy dataset. The legacy proxy is represented by a scope-aligned inventory based on the Ecoinvent dataset “glider production, passenger car” (Ecoinvent, 2024b). Although the dataset functions as a generic glider module in the Ecoinvent database, its composition traces back substantially to the Volkswagen Golf A4 inventory reported by Schweimer & Levin (2000), subsequently split into glider and drivetrain modules and scaled for compact-class modelling (Althaus & Gauch, 2010). It is therefore better understood as a legacy, model-specific representation than as a sampled fleet average. Because the proxy's system boundary includes end-of-life treatment and production infrastructure exchanges that fall outside the scope of the high-resolution inventories, a scope-aligned proxy case is constructed by removing these processes.

Second, foreground and life-cycle scarcity perspectives are separated. Foreground CSI is calculated by applying crustal scarcity potentials (section 3.5) directly to the masses of metals and metalloids reported in the foreground inventory, describing which scarce elements are physically present in the glider. Life-cycle CSI is obtained from the full cradle-to-gate model and additionally reflects upstream scarcity burdens attributed through supply-chain modelling, co-production, and allocation procedures. Treating the two perspectives interchangeably risks misattributing upstream burdens as product-level material requirements.

Third, a structural dispersion analysis describes how scarcity-relevant metals and metalloids are distributed across the component and subsystem hierarchy. This analysis uses occurrence count and normalised Shannon entropy. Occurrence count records the number of components or subsystems in which a given element is present. Normalised entropy extends the non-normalised measure used in Paper II (section 3.8) by dividing by $\ln(N)$, where N is the total number of reported units in the analysed hierarchy level. This bounds the metric between 0 and 1 and places the MY12 and MY24 distributions on a common scale relative to the maximum entropy permitted by their respective reported product structures. Values closer to 1 indicate that the element mass is distributed more evenly across the full set of reported units, whereas values closer to 0 indicate stronger concentration within a limited part of the reported structure. Because the attainable value also depends on how many units contain the element, normalised entropy is interpreted jointly with occurrence count.

CSI scope differs across the three assessments. In the proxy comparison, CSI is applied across all characterised elements, consistent with Paper III. In the foreground and life-cycle separation and in the dispersion analysis, CSI is limited to metals and metalloids, consistent with Paper II.

4 Results

The results follow the progressive logic of the thesis, from the characteristics of the constructed foreground inventories and the effects of inventory simplification to the metal composition and scarcity profiles revealed by high-resolution data, the longitudinal evolution of glider environmental profiles, and the interpretive consequences of inventory resolution.

4.1 Building high-resolution inventories from supplier data

A foundational result of this thesis is the development and demonstrated scalability of the IMDS-based inventory construction approach. The procedure described in section 3.4 transforms supplier-reported material declarations into foreground inventories resolved at the basic-substance level, preserving the link between elemental composition and the subsystem-level position of each material within the product structure. By systematising what has traditionally relied on manual data extraction from dispersed sources, the approach enables repeated inventory construction across different products and model years. This section presents what this approach enables when applied across the studies appended to this thesis.

For the combustion engine assessed in Paper I, the component material data list comprises approximately 30,000 data entries, containing over 2,000 unique material entries, and about 650 unique basic substances. For the vehicle gliders assessed in Papers II–IV, the scale increases substantially. Individual glider inventories range from approximately 80,000 to 130,000 data entries, encompassing 1,000 to 1,500 unique components, 8,000 to 14,000 unique material entries, and over 1,500 unique basic substances. Across the four gliders assessed in Paper III, the combined dataset exceeds 400,000 data entries, approximately 3,500 unique components, and 2,500 unique basic substances.

The progression from a single engine to four complete vehicle gliders indicates that the approach scales to complex automotive products, not only to contained subsystem test cases. More importantly, the resulting inventories retain a level of elemental and structural resolution that is generally not available in aggregated or proxy representations. It is this resolution that supports the analyses presented in the remainder of this chapter: the sensitivity of impact categories to inventory simplification (4.2), the characterisation of metal portfolios and scarcity profiles (4.3), the longitudinal tracking of production-phase environmental profiles (4.4), and the assessment of interpretive limits in lower-resolution inventories (4.5).

4.2 Inventory detail, aggregation, and impact-category sensitivity

A central finding of Paper I is that inventory simplification affects results differently depending on the impact category considered. When the reference option (#0), i.e., the inventory accounting for all materials, all basic substances, and complementary manufacturing, assembly, and material-loss data, is compared with the simplified options described in section 3.7, the deviations in impact scores range from small to substantial depending on the category and the type of simplification applied (Table 3).

Table 3. Impact scores normalised to the reference option (#0 = 100%), with impact categories ordered by descending deviation between the reference (#0) and the most simplified option (#7). Each column represents one of the modelling options described in section 3.7. The colours in the cells vary from "green" (100%) to "yellow" (75%) to "red" (50% and lower). All categories are calculated with midpoint characterisation methods as recommended in the European framework of the Environmental Footprint 3.0 (Fazio et al., 2018).

	Modelling options					
Impact categories	**#0 & #1**	**#2**	**#3**	**#4 & #5**	**#6**	**#7**
Resource use, minerals and metals	100%	91%	88%	41%	34%	32%
Ozone depletion	100%	96%	93%	50%	48%	44%
Ecotoxicity, freshwater	100%	81%	79%	75%	57%	55%
Land use	100%	94%	93%	73%	68%	66%
Human toxicity, cancer	100%	97%	97%	73%	71%	71%
Human toxicity, non-cancer	100%	91%	90%	82%	74%	72%
Eutrophication, terrestrial	100%	91%	89%	84%	75%	73%
Particulate matter	100%	96%	95%	79%	75%	74%
Acidification	100%	89%	87%	88%	77%	75%
Eutrophication, freshwater	100%	83%	81%	94%	78%	76%
Eutrophication, marine	100%	92%	89%	90%	82%	79%
Photochemical ozone formation	100%	93%	90%	91%	83%	81%
Climate change	100%	95%	92%	93%	88%	86%
Resource use, energy carriers	100%	94%	93%	95%	90%	88%
Ionising radiation	100%	97%	96%	98%	96%	95%
Water scarcity	100%	98%	97%	100%	98%	97%

Applying a 1 wt.-% mass cut-off at the material level while retaining all basic substances for the remaining materials (#2) produces comparatively small deviations for most impact categories. For climate change and resource use (minerals and metals), this is consistent with the fact that the material flows contributing most to these categories – steel and aluminium alloys for climate change, and steel, aluminium alloys, and copper alloys for resource use – are individually heavy enough to remain in the model at this threshold. Materials more likely to fall below the cut-off include those with low total mass, such as entries containing precious metals, ceramics, and glass, whose removal reduces their contribution to the corresponding impact scores. Applying the same cut-off to the complete engine rather than separately to its sub-parts (#3) retains fewer low-mass material entries and therefore produces slightly lower scores than #2, although the difference between the two options remains small across impact categories.

Reducing the number of basic substances to one per material (#4, #5) introduces larger deviations across a broader set of categories, because alloying elements, fillers, and low-concentration constituents are no longer represented in the model. For resource use (minerals and metals), this effect is pronounced. The contribution analysis (Figure 2) shows that the contributions attributed to steel and aluminium decrease in these options, consistent with the removal of alloying elements (e.g., chromium, nickel, molybdenum in steel; minor constituents in aluminium alloys) that contribute to resource-use scores but are not the mass-dominant basic substance in their respective material entries. When both simplifications are applied simultaneously (#6, #7), the deviations are largest. Impact scores for resource use (minerals and metals) decrease by nearly 70% relative to the reference, while climate change scores remain within 14% of the reference across all options.

Figure 2 also illustrates the role of complementary data. For climate change, manufacturing and assembly processes account for a substantial share of the reference score (approximately 24–28% across options), indicating that excluding these data could reduce the climate change result noticeably even when the material inventory itself is complete. For resource use (minerals and metals), complementary data contributes a smaller share, and the dominant source of deviation is instead the progressive loss of low-concentration material constituents through the simplification strategies described above.

At the substance level, the pattern is consistent with these category-level observations. Metals such as gold, platinum, and palladium are largely excluded from the model when a mass cut-off is applied, because the material entries containing them fall below the threshold. Other metals, including cadmium and titanium, are usually “lost” when only the dominant basic substance is retained per material. Copper and zinc are partially affected by both strategies. These are among the substances that contribute most to resource-use scores, which illustrates why this impact category is disproportionately sensitive to inventory simplification.

The workload implications of each option are assessed qualitatively in Paper I and suggest that the largest reductions in effort stem from decreasing the number of materials and basic substances requiring identification and matching.

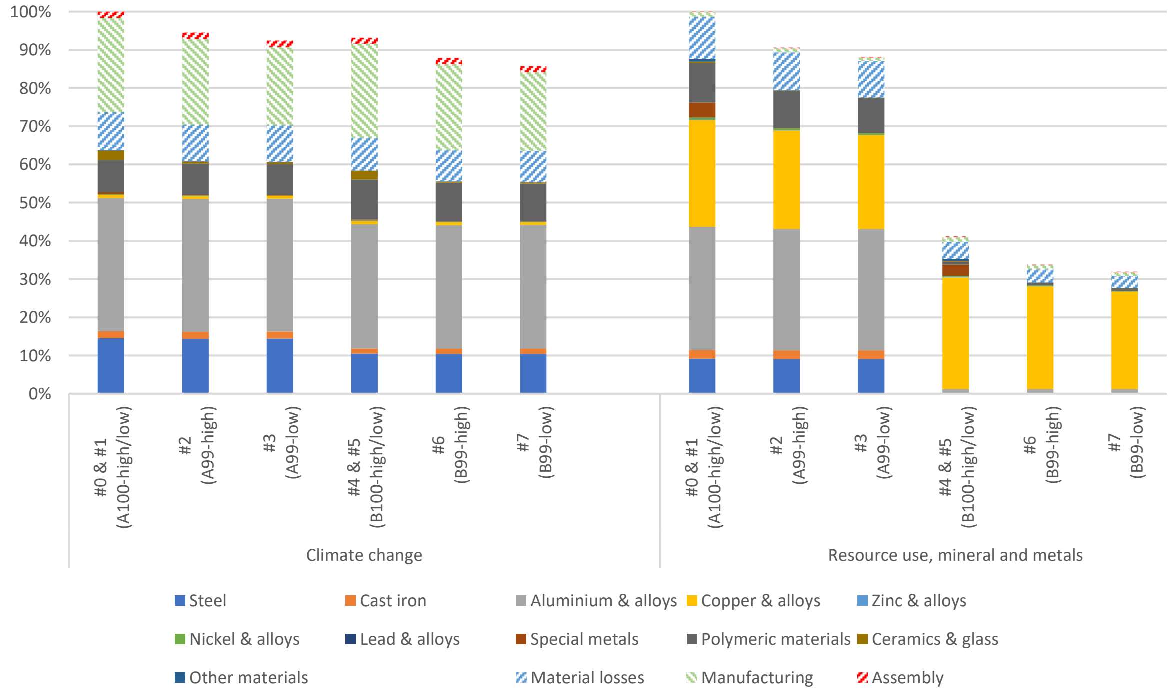

Figure 2. Contribution analysis for climate change and resource use (minerals and metals) across the modelling options. Material categories include steel, cast iron, aluminium and alloys, copper and alloys, polymeric materials, special metals (precious and scarce metals), and complementary data (manufacturing, assembly, material losses). All values are normalised to the reference option. The names in parentheses refer to the abbreviated option names used in Paper I.

Together, these results establish a principle that recurs throughout the thesis: the adequacy of an inventory model depends on the environmental question being asked. Simplifications that retain sufficient precision for climate-oriented screening and reporting may substantially alter results for impact categories that depend on low-concentration material constituents.

4.3 Metal composition and scarcity in vehicle gliders

Paper II reveals a broad portfolio of metals in the assessed vehicle gliders. The analysis identifies 55 distinct metals and metalloids in the extra-equipped glider (EEG) and 54 in the standard-equipped glider (SEG), with gadolinium being the only metal present in the EEG but absent from the SEG. Iron and aluminium together account for approximately 90% of the total metal mass. The remaining share is distributed among over 50 metals, most of which are present in small quantities. In the EEG, 35 of the 55 metals weigh less than 100 grams and 19 weigh less than 1 gram. This compositional breadth indicates that vehicle gliders are not adequately characterised by their dominant bulk metals alone. A substantial number of low-mass metals are embedded across the product structure, many of which serve specific functions in alloying, coatings, and electronics.

The scarcity assessment groups the identified metals according to their short-term supply risk (DFP) and long-term geological scarcity (CSI), as described in 3.8. Figure 3 presents this dual assessment for the EEG. Gold, copper, lead, bismuth, and molybdenum fall in the group with comparatively high values for both DFP and CSI, indicating relevance from both near-term primary-production and long-term geological-scarcity perspectives. Gold, despite being present in only a few grams, accounts for approximately 45% of the glider's total CSI score, reflecting its rarity in the upper crust and its use in electronic contacts and coatings. A hypothetical fleet of 80 million extra-equipped gliders would demand approximately 15% of global primary gold production, about 30% of primary lead, and around 10% of primary copper production. Among rare-earth metals, most fall in the lowest risk group. However, terbium, neodymium, dysprosium, and praseodymium show elevated short-term supply risks. A fleet of extra-equipped gliders would require the equivalent of the total annual global production of terbium.

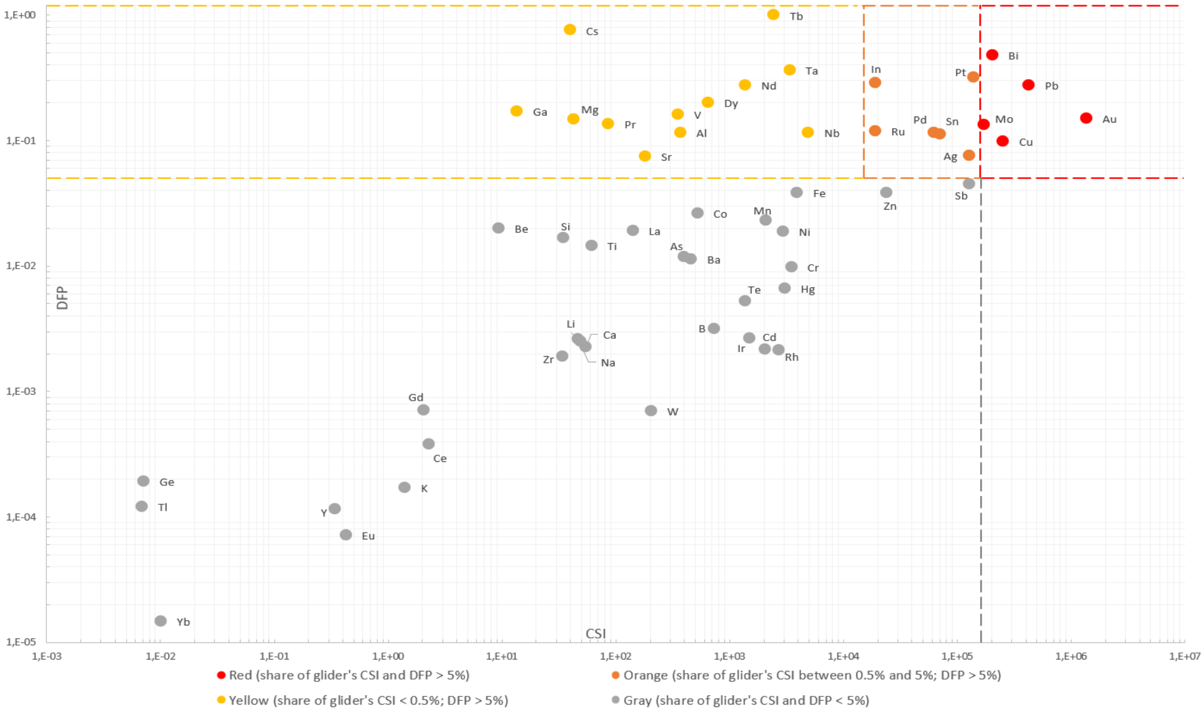

Figure 3. Short-term (DFP) and long-term (CSI) potential primary metal scarcity for metals identified in the extra-equipped glider. Each point represents one metal. The colour-coded groups distinguish metals with comparatively low or high values along the DFP and CSI dimensions, according to the threshold-based classification used in Paper II.

Equipment level modulates the scarcity profile for specific metals. For approximately half of the metals found in both gliders, the mass variation between the EEG and SEG is less than 10%, and their scarcity groupings remain unchanged. However, three metals – dysprosium, terbium, and gallium – are present in substantially larger quantities in the EEG, with mass variations exceeding 1,000%. The short-term supply risk for these metals decreases correspondingly in the SEG. For example, while an EEG fleet would demand the full annual global terbium production, a fleet of standard-equipped gliders would require less than 1%. These metals are predominantly associated with permanent magnets in the multimedia and communication subsystem, which contains more such components in the higher-equipped configuration.

The mass distribution of metals across the glider's 21 subsystems (section 3.3) shows that scarcity-relevant metals tend to concentrate in subsystems where they are introduced to provide a specific function. Over half of the metals in the highest-risk groups have more than 10% of their total glider mass located in the multimedia and communication subsystem, which also contains the largest mass shares of rare-earth metals. The electrical infrastructure subsystem concentrates the largest shares of copper and tin, consistent with the role of conductive materials in this subsystem. The exterior visibility subsystem accounts for a significant share of the gold, silver, and indium, used as reflective coatings in exterior mirrors. Molybdenum, niobium, and vanadium are concentrated in the body structures and suspension subsystems, where they serve as alloying elements in high-strength steels.

While the subsystem-level analysis identifies where metals are functionally concentrated, the component-level entropy analysis described in section 3.8 provides a complementary view of how evenly each metal's mass is spread across individual parts (Figure 4). Copper exhibits one of the highest entropies, present in over 700 components, predominantly wire harnesses. Lead, despite being reported in a comparable number of components, shows a much lower entropy because most of its mass is concentrated in the 12 V lead-acid battery. Certain rare-earth metals, such as terbium, are concentrated in only a few components, identifying potential targets for component-level recovery. Conversely, the dispersion and low total mass of gold and silver, together with their use in dissipative applications, may complicate effective recovery.

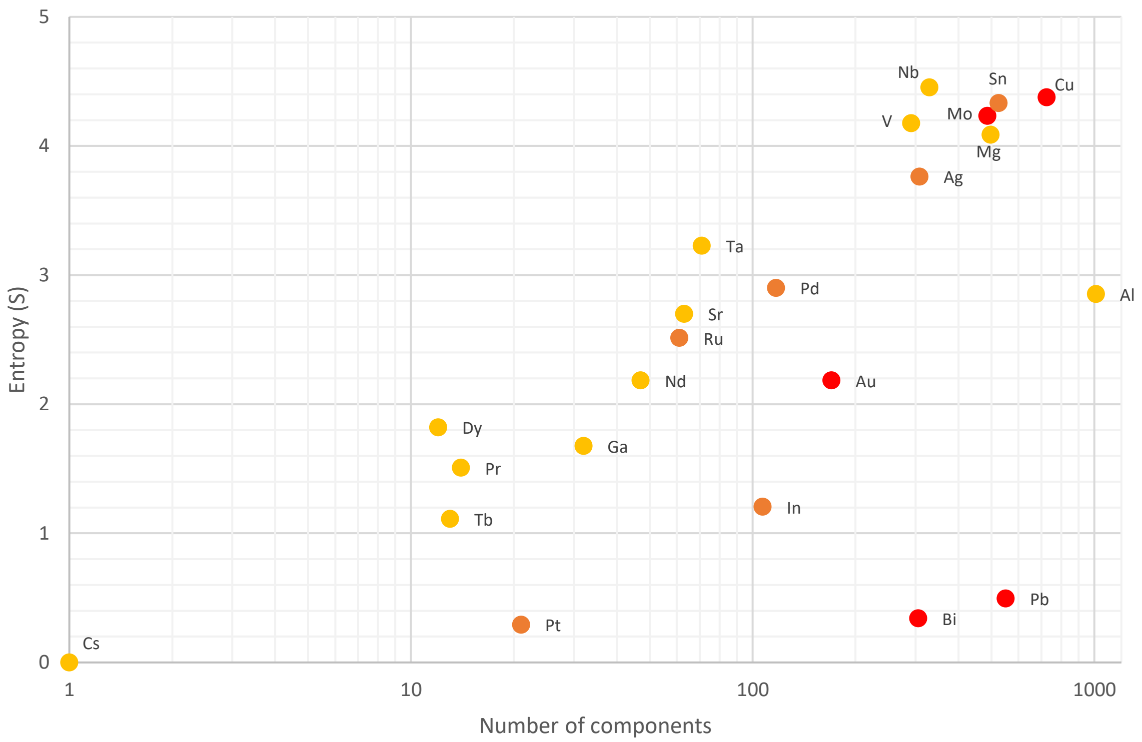

Figure 4. Component-level entropy and occurrence count for selected metals in the extra-equipped glider. Higher entropy indicates a more even mass distribution across components. Colours refer to different metal grouping in Paper II.

These findings show that high-resolution inventories make visible a layer of material complexity in vehicle gliders that is not accessible through aggregated material representations. The breadth of the metal portfolio, the sensitivity of specific metals to equipment level, the subsystem-level concentration patterns, and the component-level dispersion profiles all depend on the ability to resolve individual elements and trace their position within the product architecture.

4.4 Longitudinal evolution of glider environmental profiles

Paper III tracks the production-phase environmental profiles of four vehicle gliders across a 12-year period (MY12–MY24) under a static background model (section 3.9). All impact scores are normalised to the MY12 glider (MY12 = 1.0). Results for the three assessed indicators – ozone depletion, climate change, and crustal scarcity – show distinct responses to glider design evolution (Figure 5).

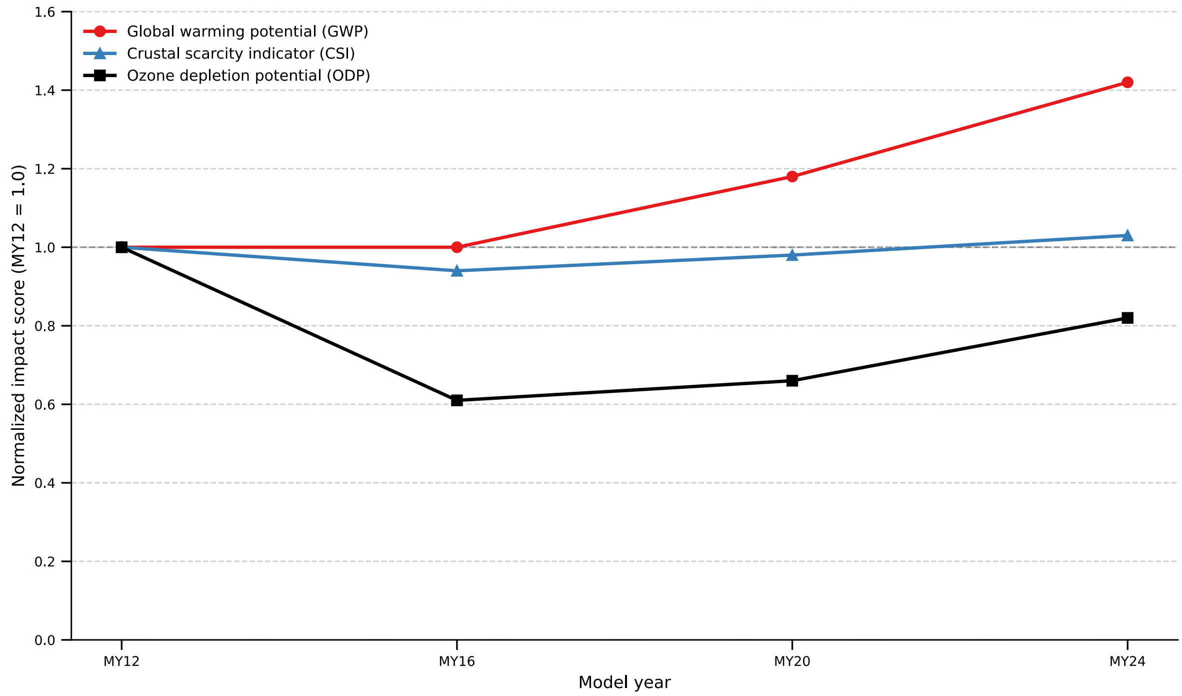

Figure 5. Normalised glider-level impact scores for ODP, GWP, and CSI across four model years (MY12–MY24). All values normalised to MY12 (= 1.0) and calculated under a static background inventory.

ODP scores decrease by approximately 40% between MY12 and MY16 and remain below the MY12 baseline in subsequent model years. A contribution analysis traces this decrease to the HVAC subsystem, where the transition from R-134a to R-1234yf removed the modelled upstream ODP contributions associated with CFC-113a and HCFC-124 emissions in the R-134a production inventory. A slight rebound in ozone depletion results is observed in MY20 and MY24, but this does not reflect a reversal in the HVAC subsystem. It is instead associated with dispersed, small contributions from increased polymer use and a greater number of electronic components in later model years.

The pattern for climate change contrasts the targeted nature of the ozone depletion reduction. Over the study period, glider mass increases by 20%, while the cradle-to-gate GWP score rises by 42%, indicating that the glider's climate impact grows faster than its mass. The primary driver is an increase in aluminium content. The normalised contribution of aluminium to the glider's GWP score more than doubles (0.30 in MY12 to 0.62 in MY24), accounting for approximately 76% of the total increase. This is consistent with the broader adoption of aluminium in body panels, hoods, and suspension components as part of lightweighting strategies and the transition to the SUV platform. Steel contributions show a more nuanced pattern. The combined GWP score from all steel grades rises slightly (0.37 to 0.40), but this reflects two opposing trends: declining contributions from conventional unalloyed and high-alloyed steels (0.13 to 0.10) and increasing contributions from low-alloyed steels (0.24 to 0.30). At the subsystem level, the body, closures and exterior trim subsystem remains the largest contributor throughout the period (0.39 to 0.54), while the steering and suspension subsystem more than doubles its contribution to the GWP score (0.12 to 0.27).

CSI results present a third, distinct pattern. While glider mass increases by 20%, the total CSI score remains near-stable, rising by only 3% (1.00 to 1.03). Consequently, scarcity intensity per kilogram of glider declines by approximately 14%. The near-stable total at the glider level, however, masks substantial redistribution across material groups and subsystems (Figure 6). The contribution of precious metals to the glider's CSI score decreases from 0.28 in MY12 to 0.10 in MY24, a reduction of approximately 65%. This decline is concentrated in the multimedia and communication subsystem, where gold remains the dominant CSI driver but its content decreases by nearly a factor of four over the period. In the opposite direction, contributions from low-alloyed steel (0.13 to 0.22) and aluminium (0.09 to 0.16) increase, reflecting the growing use of high-strength steel grades and aluminium alloys in structural subsystems. Within the low-alloyed steel group, molybdenum is the dominant elemental contributor, with its share of the group's CSI score increasing from approximately 60% in the earlier model years to approximately 70% in MY24.

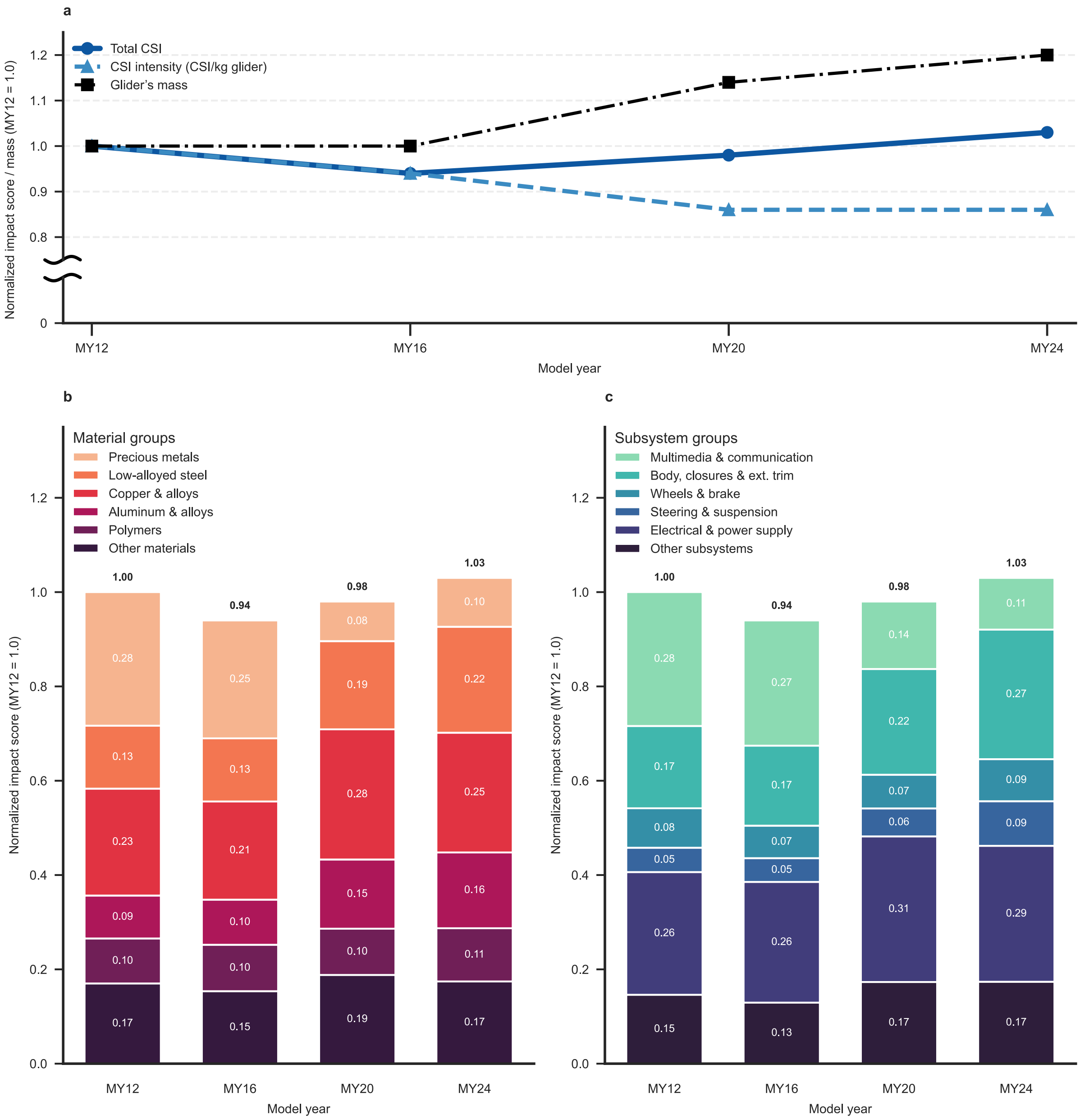

Figure 6. Evolution of glider CSI scores and their main material-group and subsystem-level drivers. The stacked bars show normalised contributions summing to the total CSI score. All values normalised to MY12 (= 1.0).

These three patterns illustrate that different impact categories respond to the same underlying design evolution through fundamentally different mechanisms. An impact driven by a specific substance (ozone depletion) may be mitigated through a targeted substitution. An impact driven by bulk materials and energy-intensive processes (climate change) may scale with platform size and the carbon intensity of the material mix. An impact driven by low-mass, functionally specific elements (resource scarcity) may remain near-stable at the vehicle level while redistributing across subsystems and material groups in ways that lower-resolution inventory representations do not surface.

4.5 Interpretive scope of high-resolution inventories

Paper IV examines the types of analysis supported by high-resolution glider inventories and the interpretive limits of lower-resolution representations. The study is organised around three complementary assessments, each addressing a different aspect of the relationship between inventory resolution and interpretive scope (section 3.10).

Comparison with a legacy proxy dataset

When the MY12 and MY24 high-resolution inventories are compared with the scope-aligned proxy case based on the Ecoinvent "glider production, passenger car" dataset (section 3.10), the proxy yields lower GWP and CSI scores per kilogram of glider than both high-resolution cases. Expressed relative to the proxy, MY12 gives a GWP score approximately 1.3 times higher and a CSI score approximately 1.6 times higher. For MY24, the corresponding ratios are approximately 1.5 and 1.4. A first-order breakdown by input group indicates that the high-resolution inventories contain substantially more aluminium (approximately 17 and 30 times the proxy value for MY12 and MY24, respectively) and approximately three times more copper. Direct energy inputs, by contrast, are approximately half of the proxy value. At the elemental level, the divergence in resource scarcity results extends beyond totals. More than half of the assessed metals and metalloids show proxy CSI scores below half of the corresponding MY12 values, and several elements are absent or nearly absent from the proxy. For instance, molybdenum-related CSI scores in the proxy correspond to approximately 15% of the MY12 value, and niobium to approximately 4%. Conversely, chromium and nickel yield higher scores in the proxy, at approximately 190% and 460% of the MY12 values, consistent with a larger share of high-alloyed steel in the proxy composition. The observed divergences are consistent with differences in the vehicle represented, temporal drift in composition, and loss of elemental detail through material-class aggregation, as discussed in section 5.

Foreground versus life-cycle scarcity

The separation of foreground and life-cycle CSI perspectives shows that the two identify partly different elemental drivers. Across both model years, gold, molybdenum, and copper remain prominent in both perspectives. However, lead accounts for approximately one quarter of the foreground CSI score but only a small share of the life-cycle score, reflecting how background modelling of lead supply, including assumptions about secondary production and cut-off allocation, redistributes the scarcity burden among upstream co-products. By contrast, tellurium, selenium, and rhenium are negligible in the foreground results but contribute several percent each to the life-cycle CSI scores, appearing through upstream copper mining and refining represented in the background system. These asymmetries indicate that foreground and life-cycle perspectives serve complementary but non-interchangeable roles. Foreground CSI identifies which scarce elements are physically present in the product. Life-cycle CSI captures upstream scarcity burdens, including elements that may not enter the final product. Treating the two interchangeably risks misattributing upstream burdens as product-level material requirements.

Structural dispersion

The dispersion analysis shows that elements with similar total scarcity contributions may differ substantially in how they are distributed across the product architecture. Lead remains close to the lower boundary of component-level entropy despite being reported in many components, consistent with its concentration in the 12 V battery. Molybdenum increases in both occurrence count and entropy between MY12 and MY24, indicating a broader distribution across structural components in the later model year. Gold is present in more components in MY24 yet its entropy decreases slightly, illustrating that broader occurrence does not necessarily imply a more even mass distribution. These structural differences affect where design, substitution, or recovery questions would need to be directed. An element concentrated in a few identifiable components presents different options than one dispersed across hundreds of small applications.

Together, the three assessments converge on the same methodological point. Inventory resolution affects not only the magnitude of impact scores but also the analytical questions the assessment is equipped to address, including element-specific scarcity attribution, foreground versus upstream separation, and structural mapping within the product architecture.

5 Discussion

The preceding chapter presents the main findings of the appended papers organised thematically. This chapter interprets those findings in relation to the research questions, discusses their broader methodological and practical implications, and addresses the limitations and future research directions of the work. The questions are discussed in an order that follows the progressive logic of the thesis rather than their numbering sequence.

5.1 Addressing the research questions

RQ-M1 – How can supplier-reported material data be transformed into usable life cycle inventories for complex automotive systems?

The papers appended to this thesis demonstrate that IMDS data can be systematically extracted, structured, and linked to background inventory datasets to produce foreground inventories resolved at the basic-substance level. Paper I establishes this capability using a vehicle combustion engine as a methodological test case, showing that the resulting inventory preserves the elemental composition of each material and supports contribution analysis across impact categories. The subsequent application of this approach to full vehicle gliders in Papers II–IV confirms that it can be scaled to substantially more complex automotive products without requiring a fundamentally different data architecture. However, realising this potential is not straightforward. The approach operates under several methodological boundary conditions that affect both the completeness and the interpretive capacity of the resulting inventory, and these conditions merit explicit discussion.

An important constraint in IMDS-based modelling is that IMDS was designed for regulatory compliance with substance restrictions, not for environmental assessment. Material production routes, recycled content shares, and manufacturing processes are not explicitly reported in the system. Paper I shows that complementary data representing manufacturing and assembly processes account for approximately one quarter of the climate change score of the assessed engine, indicating that omitting such data may introduce a non-trivial underestimation for energy-related impact categories. The practical difficulty of obtaining recycled content information, given the large number of suppliers involved, further limits the precision achievable from IMDS data alone.

A related limitation concerns the form in which basic substances are reported. IMDS records substances in their refined state, as they are present in finished components. For example, alloying elements in steels are reported as chromium, nickel, and manganese. In practice, these elements enter metallurgical processing as ferroalloys, such as ferrochromium and ferronickel, whose production routes carry different environmental profiles than the corresponding refined metals. Paper I identifies this mismatch and addresses it by linking alloying elements to ferroalloy-based background datasets adjusted to reflect the compositions reported in IMDS. The implication is that IMDS-based inventory construction is not a purely automated translation exercise. It requires domain knowledge about production processes and access to suitably resolved background datasets. Where such datasets are unavailable, the practitioner faces a choice between accepting a representation mismatch or investing additional effort to construct or adapt inventory data. This trade-off is not unique to IMDS but is made more visible by the elemental resolution the system provides. Together, these gaps indicate that IMDS provides the material architecture of the product but must be complemented with process-level data from other sources to support credible life cycle assessment. It is the combination of supplier-reported material data and practitioner-compiled process data that renders the inventory usable in practice, rather than IMDS data in isolation.

A further aspect of the methodological contribution concerns scalability and reusability. The progression from approximately 30,000 data entries for a single engine in Paper I to over 400,000 entries across four vehicle gliders in Paper III illustrates that the approach accommodates increasing product complexity. This progression is supported by the cumulative nature of the underlying structure. Once material groupings, background dataset libraries, and matching conventions are established for one product, they become reusable in subsequent studies. This scalability does not imply that the effort becomes trivial. New products and model years still introduce materials, suppliers, and compositions that require verification and, in some cases, new background dataset development. The contribution is therefore not a one-time procedure but a methodological framework that accumulates and improves with repeated application.

RQ-E1 – What do high-resolution inventories reveal about the metal composition and resource-scarcity profiles of vehicle gliders?

The detailed foreground inventories developed in this thesis reveal that vehicle gliders are materially diverse assemblies whose resource significance extends well beyond their dominant bulk metals. Paper II identifies more than 50 metals and metalloids in the assessed gliders, with iron and aluminium accounting for approximately 90% of the total metal mass. The remaining share is distributed among over 50 metals, most present in small quantities. Despite their low mass, several of these metals dominate the scarcity profile. Gold, present in only a few grams, accounts for approximately 45% of the glider's total CSI score. This inversion between mass dominance and scarcity relevance illustrates a broader point. Aggregated material representations may understate the resource significance of the glider when low-mass, scarcity-relevant elements are omitted. These elements are also among those most likely to “disappear” when inventories are simplified or aggregated.

The comparison between gliders configured with different equipment levels shows that for approximately half of the assessed metals, the mass variation between configurations is less than 10%. However, three metals – dysprosium, terbium, and gallium – are present in substantially larger quantities in the extra-equipped glider, with mass variations exceeding 1,000%. These metals are predominantly associated with permanent magnets in the multimedia and communication subsystem. For terbium, the DFP corresponds to approximately the entire annual global primary production for the hypothetical extra-equipped fleet, compared with less than 1% for the standard-equipped fleet. The comparison shows that equipment level can substantially influence the use of specific metals within the two configurations studied. Broader industry trends toward increased safety, connectivity, comfort, and automation may extend some of the metal-demand patterns observed in the extra-equipped glider to a wider range of vehicles (Trovão, 2022, 2024). As these trends continue, the gap in metal use between standard- and extra-equipped configurations may narrow, potentially making some of the scarcity patterns observed in the extra-equipped glider more characteristic of typical vehicles. This remains a hypothesis, however, as the thesis does not assess changes in equipment-related metal use across additional vehicle models or equipment levels.

The entropy analysis in Paper II adds a structural dimension to the scarcity assessment that is not accessible through mass totals or subsystem shares alone. Two metals with comparable scarcity contributions may present fundamentally different distribution profiles. Copper, present in over 700 components, exhibits one of the highest entropies, consistent with its widespread use in wire harnesses throughout the glider. Lead, despite appearing in a comparable number of components, shows a much lower entropy because nearly all of its mass is concentrated in the 12 V battery. These structural differences affect the practical interpretation of scarcity scores. An element concentrated in identifiable components presents different opportunities for targeted recovery or substitution than one dispersed across hundreds of small applications. Certain rare-earth metals are concentrated in only a few components, identifying potential targets for component-level recovery. Precious metals present a different challenge because of their low total mass, dispersion across applications, and frequent use in coatings or electronic components. This structural information is only accessible through inventories that preserve the link between elemental composition and the component hierarchy of the product, a point that is further developed in the discussion of RQ-M2 in this section.

The breadth of the glider's metal portfolio also carries implications beyond the product itself. The gliders assessed in Paper II contain approximately 80% of all naturally occurring metals and metalloids, a figure comparable to complete vehicles when the powertrain is included. This indicates that systems beyond the powertrain contribute substantially to the broad metal demands of automotive manufacturing, a finding that has received limited attention in a literature focused largely on traction batteries and electric motors (Nordelöf *et al.*, 2019; Arshad *et al.*, 2022). The automotive sector's demand for these metals may exacerbate supply risks to other industries that rely on the same resources, which points to the relevance of cross-sectoral interdependencies for the management of metal supply chains. At the same time, the assessment points to a potential intra-sectoral tension. The electrification of powertrains increases the demand for metals such as copper, rare-earth elements, and precious metals – several of which are already identified as scarcity-relevant in the glider. Multiple concurrent trends within the automotive industry, including electrification, lightweighting, and growing electronic content, may inadvertently escalate the demand for the same metals. Recognising and reconciling these competing pressures can support more informed resource management across the sector.

RQ-E2 – How do the production-phase environmental and resource profiles of vehicle gliders evolve over time as vehicle architectures change?

The longitudinal assessment in Paper III shows that different impact categories respond to the same underlying design evolution through fundamentally different mechanisms. An impact driven by a specific substance in the supply chain (ozone depletion) is largely mitigated through a targeted substitution. An impact driven by bulk materials and energy-intensive processes (climate change) scales with platform size and the carbon intensity of the material mix. An impact driven by low-mass, functionally specific elements (resource scarcity) remains near-stable at the vehicle level while redistributing substantially across subsystems and material groups. Together, these patterns indicate that no single strategy is likely to address all dimensions of the production-phase environmental profile of the assessed gliders, and the differential response of impact categories to design evolution is likely to hold in comparable vehicle contexts where a similar range of design changes takes place. Some problems respond to targeted intervention, while others require systemic responses involving vehicle designers, component manufacturers, and materials suppliers.

The ozone depletion results illustrate one pattern that can arise from targeted mitigation in complex products. The transition from R-134a to R-1234yf removed the dominant modelled upstream source of ozone-depleting substances associated with the R-134a production inventory, reducing the glider's ODP score by approximately 40% between MY12 and MY16. However, once this dominant driver is addressed, the remaining ozone depletion profile becomes dispersed across many small contributions from increased polymer use and a growing number of electronic components in later model years. This structure suggests that further reductions would require managing a larger set of individually minor contributors rather than targeting a single substitution. The pattern is likely not unique to ozone depletion. It points to a broader dynamic in which early mitigation gains tend to be concentrated, while subsequent improvements become increasingly diffuse and difficult to achieve through isolated measures at the vehicle-design level. A qualification applies, however. Contributors that appear dispersed at the vehicle level may still be concentrated within a single type of component repeated throughout the vehicle, in which case targeted intervention through component design, rather than vehicle design, could remain feasible. This thesis does not analyse such opportunities in detail.

The climate change results reveal an intensity effect beyond simple mass growth. The glider's GWP score rises by 42% over the study period while mass increases by 20%, indicating that changes in material composition increase the production-phase GWP score faster than mass under the static background conditions applied. The increase is driven primarily by the greater contribution from aluminium, alongside a smaller increase in the contribution from low-alloyed steel. Structural requirements related to larger platforms, crash performance, and battery integration provide plausible context for these changes, but their individual influence cannot be isolated from the inventory data. An important interpretive consideration is that the static background model used in Paper III isolates the consequences of foreground design evolution from simultaneous changes in the wider industrial system. In practice, the carbon intensity of material supply chains has likely declined over the study period. Data from the Global Carbon Project indicate that the carbon intensity of the global economy has followed a near-linear downward trend since 1960, declining at a rate of approximately 5–6 g fossil-CO_2 per PPP-adjusted US$_{2017}$ per year[1] (Friedlingstein *et al.*, 2026; GCB, 2025). Over the 2012–2024 period covered by Paper III, this trend corresponds to a reduction of approximately 15–20%. While this figure does not map directly onto automotive supply chains, it provides a useful comparator. The foreground-design-driven increase of approximately 42% identified in this thesis would have required supply-side improvements substantially larger than the economy-wide trend to be fully offset over the same period. This separation is methodologically useful because it clarifies that manufacturers can influence production-phase climate impact through two complementary but distinct levers: foreground design choices that determine which materials and how much of them enter the product, and upstream procurement strategies that affect how carbon-intensively those materials are produced.

The resource scarcity results present the most structurally complex pattern. The glider's total CSI score increases by only 3% over the study period despite a 20% increase in mass. However, the near-stable result at the vehicle level masks substantial redistribution. The contribution of precious metals decreases by approximately 65%, driven by a nearly fourfold reduction in gold content within the multimedia and communication subsystem. In the opposite direction, contributions from low-alloyed steel and aluminium increase, reflecting the growing use of high-strength steel grades

[1] Carbon intensity is here expressed as fossil CO_2 emissions per unit of gross domestic product, adjusted for purchasing power parity (PPP) in constant 2017 US dollars.

and aluminium alloys in structural subsystems. A plausible interpretation of the declining precious-metal contribution is that successive generations of electronic hardware deliver comparable or greater functionality with lower precious-metal intensity, consistent with trends such as component integration and changes in interconnect and surface-finish practices (Ardebili *et al.*, 2019; Zhou *et al.*, 2023; Chavez, 2024). However, the data do not resolve electronics design choices at a level that can confirm specific mechanisms. The broader implication is that aggregate vehicle-level indicators can conceal opposing subsystem-level trajectories. A near-stable total may suggest that scarcity is well managed, when in fact the drivers of scarcity are migrating across the product architecture. Identifying where these shifts occur, and whether they represent deliberate design choices or unintended consequences of other trends, calls for subsystem-resolved, high-resolution inventory data of the kind developed in this thesis. This point connects directly to the discussion of RQ-M2 below.

RQ-M2 – How does the technical and temporal resolution of foreground inventories affect the precision and interpretive scope of environmental and resource-scarcity assessment?

Paper I establishes that inventory simplification affects impact categories differently. Climate change scores remain within 14% of the reference across all modelling options, whereas resource use scores decrease by nearly 70% under the most simplified option. This asymmetry is influenced by different mechanisms. Applying a mass cut-off excludes materials below the threshold from the model, and with them the low-concentration substances they contain. This effectively removes gold, platinum, and palladium from the inventory, while reducing the number of basic substances representing materials neglects cadmium, titanium, and most of the lead. Iron and aluminium, by contrast, are only marginally affected by either simplification and become overstated in the simplified options. The result is not a uniformly scaled-down version of the detailed model but a model in which the set of represented substances differs from the reference. Paper I concludes that the utility and risks of any simplification strategy depend on the type of assessment being conducted. This principle – that the adequacy of an inventory model is not a fixed property but depends on the environmental question being asked – became a guiding consideration across Papers II–IV.

The differential sensitivity of impact categories to foreground resolution can be understood through the distinction between first-order and second-order effects. First-order effects arise directly from the material composition of the product: the choice to use a specific alloy, the inclusion of a particular metal in an electronic component, or the selection of a coating material. These are foreground design decisions, and their environmental consequences are encoded in the foreground inventory. Second-order effects arise from the upstream processes required to produce those materials –

mining, refining, smelting, and the energy systems that power them. These are mediated through the background system and depend on assumptions about production routes, energy mixes, and allocation procedures that lie largely outside the direct control of the product designer. Foreground resource scarcity scores are first order in the sense used here: they respond directly to what is physically present in the product and are therefore highly sensitive to whether the foreground inventory preserves elemental detail. Life-cycle scarcity scores additionally incorporate upstream processes and modelling choices represented in the background system. Climate change scores, by contrast, are more strongly influenced by second-order effects, since the carbon intensity of material production depends on process routes and energy systems represented in the background model. This does not mean that climate change results are insensitive to foreground composition – the shift from steel to aluminium documented in Paper III demonstrates otherwise – but the mechanism operates through the energy-intensity of upstream production rather than through the identity of specific elements in the product. This distinction carries practical relevance. Vehicle designers can most directly influence first-order outcomes through material selection and component specification, while second-order outcomes additionally depend on procurement strategies and supply-chain conditions that evolve independently of vehicle design. Recognising which order of effect dominates a given impact category helps clarify both the analytical value of foreground resolution and the scope of action available to different actors.

Paper IV extends the question of inventory adequacy from precision to interpretive scope. Where Paper I asks how much the numbers change under simplification, Paper IV asks which forms of interpretation remain possible when the inventory lacks elemental, material, or structural resolution. The empirical findings discussed above for RQ-E1 and RQ-E2 reinforce this from a different angle. The metal portfolios, equipment-level sensitivities, subsystem-level redistributions, and longitudinal trajectories presented there are forms of interpretation that depend on the technical and temporal resolution of the underlying inventory. In this sense, RQ-M2 provides the methodological counterpart to what the empirical questions demonstrate. The remainder of this section discusses the three complementary assessments in Paper IV that make this relationship explicit.

The comparison with the legacy proxy dataset reported in section 4.5 shows that the proxy yields lower GWP and CSI scores per kilogram of glider than both high-resolution cases, and that more than half of the assessed metals and metalloids show proxy CSI scores below half of the corresponding high-resolution values. Paper IV interprets these divergences as being consistent with three conceptually distinct, but empirically overlapping, mechanisms. The first is a *representation* mechanism: the proxy traces back to a specific historical vehicle configuration but is commonly applied as a generic representation of contemporary passenger-car gliders. The second is a *temporal* mechanism: vehicle material composition has shifted since the proxy was compiled, most notably toward higher aluminium content and greater use of advanced high-strength steels. The third is a *resolution* mechanism: the proxy representation does not preserve the elemental information needed to identify many scarcity-relevant constituents, whether because these constituents were aggregated, omitted, or not reported in the underlying inventory. The comparison does not quantify the contribution of each mechanism independently, since differences in represented vehicle, inventory age, and reporting resolution are partly confounded. While the first two mechanisms affect both GWP and CSI scores, as they concern the material structure being represented, the third is particularly consequential for resource scarcity, where impact scores depend on the presence and quantity of specific elements that may be invisible in broad material classes. This suggests that proxy inventories may remain defensible for screening-level assessments where the glider is not the analytical focus. However, conclusions about material-specific scarcity drivers, substitution strategies, or the identification of impact-dominant low-mass elements depend on compositional resolution that proxy inventories of this type typically do not preserve.

The separation of foreground and life-cycle CSI perspectives shows that the two identify partly different elemental drivers. Gold, molybdenum, and copper remain prominent in both perspectives. Lead accounts for approximately one quarter of the foreground CSI score while contributing only a small share of the life-cycle score. Tellurium, selenium, and rhenium appear almost exclusively through upstream supply-chain modelling. These asymmetries reflect how background modelling, including assumptions about co-production, allocation, and secondary production routes, redistributes scarcity burdens among upstream flows. The methodological implication is that foreground and life-cycle perspectives serve complementary but non-interchangeable roles. Foreground CSI identifies which scarce elements are physically present in the product and supports interpretation related to design change, material substitution, and recovery-relevant considerations. Life-cycle CSI also captures upstream scarcity burdens, including elements that may never enter the product. Treating the two interchangeably risks misattributing upstream supply-chain burdens as product-level material requirements. This distinction is operational only when the foreground inventory is resolved at elemental level; without such resolution, the product-side and the supply-chain-side scarcity contributions cannot be separated.

The structural dispersion analysis extends this argument to the internal architecture of the product. As discussed for RQ-E1, Paper II introduces entropy as a descriptor of how metals are distributed across components. Paper IV refines this by normalising entropy relative to the total number of reported units in each analytical scope, enabling comparison across two model years with different reported product structures. The results show that elements with similar total scarcity contributions may differ substantially in their structural profiles. Lead remains concentrated despite broad occurrence. Molybdenum becomes more widely distributed in later model years, consistent with the growing use of high-strength steels across structural subsystems. Gold appears in more components in MY24, yet its entropy decreases slightly, illustrating that broader occurrence does not necessarily imply a more even mass distribution. These structural differences affect where design, substitution, or recovery questions would need to be directed, and they are only accessible through inventories that preserve the link between elemental composition and the component hierarchy. Taken together, the three assessments in Paper IV converge on the central methodological observation of this thesis: inventory resolution does not only affect the magnitude of impact scores. It defines which analytical questions the assessment is equipped to address.

The longitudinal dimension of this thesis (Paper III) further demonstrates that the ability to systematically update foreground inventories as products evolve (the temporal dimension of resolution defined in section 2.2) enables the detection of compositional shifts and subsystem-level redistributions that static or infrequently updated datasets cannot capture. However, unlike the effect of technical resolution on impact-score precision, which is tested directly through inventory simplification, temporal resolution is not assessed through a controlled comparison of alternative update frequencies. Its contribution in this thesis is instead demonstrated through the analytical value of developing product-specific inventories for successive glider generations. These inventories enable compositional changes and subsystem-level redistributions to be detected without conflating successive vehicle configurations.

5.2 Broader methodological implications

A recurring finding across the appended papers is that the adequacy of a given level of inventory detail depends on the type of environmental question being asked. This relationship is not a new idea in LCA, but the thesis provides empirical content for a principle that is often stated abstractly. The progression from Paper I to Paper IV shows that a given level of foreground detail can be adequate for one question and inadequate for another, not because the data are wrong, but because different impact categories and different forms of interpretation draw on different features of the inventory. Climate-oriented screening draws primarily on bulk material flows and energy-intensive processes, which tend to be preserved even in simplified representations. Scarcity assessment, subsystem-level attribution, and structural dispersion mapping draw on elemental resolution, component-level traceability, and the distinction between foreground composition and upstream-attributed burdens, all of which require that the inventory retains information that aggregation removes. This suggests that inventory resolution is more usefully treated as a scope parameter than as a fixed quality criterion, and that alignment with the intended interpretation, together with explicit reporting, supports credible use of the results.

A second methodological implication concerns the design of longitudinal assessments. Paper III applies a static background model across all four model years, holding energy mixes, supply-chain efficiencies, and background datasets constant. This design isolates the effects of foreground design evolution from simultaneous changes in the wider industrial system. The approach does not represent actual historical emissions, and it does not capture the benefits of supply-chain decarbonisation that may have occurred over the study period. Its value lies in making foreground change visible as an independent variable. For automotive LCA, where vehicles evolve incrementally across model years, this separation supports the distinction between the environmental consequences of design decisions and those of broader system transitions.

A third implication concerns the relationship between foreground and background data in shaping what an assessment can conclude. The LCA literature has emphasised the improvement of background inventory quality as a route to more reliable impact scores (Kalverkamp *et al.*, 2020; Kim *et al.*, 2022; Albano *et al.*, 2024). The findings of Paper IV indicate that such improvements, while valuable, do not on their own resolve the interpretive limits identified in this thesis. When the foreground model does not distinguish individual elements, their subsystem-level embedding, or their association with specific material formulations, refinement of the background system is unlikely to restore the compositional and structural information that aggregation has removed. Background improvements are likely to deliver their full analytical value against foreground inventories that already carry sufficient elemental and structural detail.

5.3 Resource scarcity indicators and the positioning of CSI

Mineral and metal resource use is addressed in life cycle impact assessment through a range of indicator families that operationalise different concerns. Reviews coordinated within the UNEP Life Cycle Initiative organise these into four broad categories – depletion (e.g., ADP), future-efforts (e.g., SOP, ReCiPe), thermodynamic accounting (e.g., CExD), and supply-risk methods (e.g., ESSENZ, GeoPolRisk) (Sonderegger *et al.*, 2020; Berger *et al.*, 2020). More recent literature complements this taxonomy with additional families, including resource dissipation (e.g., EDP, ADR) and price-based indicators (e.g., VLP), and lists over twenty distinct resource use indicators developed since the 1990s (Jabara *et al.*, 2025). Across these reviews, no single method emerges as the preferred choice for all assessment contexts (Berger *et al.*, 2020), reflecting the diversity of legitimate concerns that resource use can refer to.

The methodological diversity tracks a deeper conceptual diversity. Depletion indicators ask how a product system contributes to reducing natural stocks of a given element. Future-effort indicators ask how current extraction shifts the conditions, e.g., ore grade, cost, energy requirement, under which the next unit of the same element will be produced. Thermodynamic indicators quantify the cumulative useful work removed from the natural environment. Supply-risk and geopolitical indicators assess the probability and consequences of short-term supply disruption for specific user contexts. Price-based and dissipation indicators capture the economic functionality of resources and their irreversible loss to inaccessible compartments, respectively. The choice of resource use indicator can therefore be interpreted as a question of alignment between the analytical concern and the impact mechanism embedded in the characterisation factor (Berger *et al.*, 2020).

Within this landscape, the crustal scarcity indicator occupies a particular position. Its characterisation factor depends on a single natural-system variable, namely the average crustal concentration of each element, and contains no technosphere parameter (Arvidsson *et al.*, 2020). Most alternative indicator families embed technosphere data directly in the characterisation factor. For instance, ADP uses annual production rates, ESSENZ aggregates several economic and governance indicators, GeoPolRisk weights political-instability indices by import shares, VLP rests on market prices, and dissipation indicators depend on sector-specific yields, lifetimes, and recycling rates (Sonderegger *et al.*, 2020; Jabara *et al.*, 2025). This “simplicity” is methodologically consequential for the analyses presented in this thesis. Applying CSI to a foreground-only inventory yields a descriptor of which geologically scarce elements are physically embedded in the product, while applying the same characterisation factor to a full life-cycle inventory captures, in addition, the scarcity burdens mobilised upstream. The contrast between the two scores reflects only the difference in inventory scope, because the characterisation factor carries no implicit weighting from production or market conditions. Indicators that embed such variables can also be applied across foreground and life-cycle inventories, but the resulting contrast may combine inventory effects with technosphere assumptions already embedded in the characterisation factor. The foreground versus life-cycle separation described in sections 4.5 and 5.1 (RQ-M2) thus relies on CSI’s characterisation factors being constructed in a way that preserves the boundary the thesis seeks to examine.

The same property that enables this “clean” separation also bounds what CSI can describe. Crustal abundance is a long-term geological reference and is not always a reliable proxy for geological availability or economic extractability, since most material in the crust may never enter accessible deposits (Drielsma *et al.*, 2016; Sonderegger *et al.*, 2020). CSI scores do not reflect short-term supply dynamics, co-production constraints, geopolitical exposure, recycling rates, or substitutability – dimensions that other indicator families are specifically designed to capture (Berger *et al.*, 2020; Jabara *et al.*, 2025). Conclusions drawn from CSI results in this thesis are best understood as statements about long-term geological scarcity under stable crustal reference values, not about market accessibility or supply security. For analyses concerned with these latter aspects, indicators such as ESSENZ or GeoPolRisk provide complementary perspectives that CSI cannot substitute for (Berger *et al.*, 2020).

Paper II complements the long-term CSI perspective with the demand fraction of primary production (DFP), formulated as an indicator of short-term potential primary metal scarcity. DFP relates the metal demand of a hypothetical annual glider fleet to current global primary production and therefore addresses a narrower question than broader supply-risk methods, i.e., whether the implied automotive demand would represent a substantial fraction of present primary supply. Keeping DFP and CSI separate preserves the distinction between near-term primary-production pressure and long-term geological scarcity, allowing metals to be compared across two conceptually distinct dimensions rather than combining them into a single score. This separation also differs from depletion-oriented methods such as ADP, whose characterisation factors incorporate both stock estimates and annual production data within one indicator rather than reporting the two perspectives independently.

The contribution of this thesis lies in inventory modelling rather than in life cycle impact assessment method development. CSI is selected because its natural-system anchoring aligns with two analytical needs central to the appended papers: the comparison of glider configurations and model years under a stable long-term reference, and the separation of foreground composition from upstream-attributed scarcity burdens. Other indicator families would inform different questions. The high-resolution, elementally resolved, subsystem-traceable inventories developed here provide a foundation suitable for re-characterisation through complementary methods. Re-characterising the same inventory through such indicators is one possible extension of this thesis and is identified as a direction for further research in 5.6.

5.4 Implications for industrial LCA practice and data infrastructure

Earlier studies have recognised the potential of IMDS to support automotive LCA and have proposed procedures for streamlining inventory construction through automated extraction and matching routines (Koffler *et al.*, 2008; Yu & Kim, 2013). More recently, Haun *et al.* (2022) addressed a related challenge by developing standardised LCI model constructs for automated IMDS-based LCA of automotive aluminium components. These efforts demonstrate that IMDS can reduce part of the workload associated with inventory compilation. The present thesis builds on this foundation by providing quantitative findings of how different levels of IMDS data usage affect LCA results (Paper I) and by extending the approach from a contained subsystem to full vehicle gliders across multiple model years (Papers II–IV).

A complementary study by Accardo et al. (2023), published after Paper I, reinforces the conclusion that mass cut-offs and substance-reduction strategies affect resource-related categories more than climate change. For industrial practitioners who rely on IMDS as their primary foreground data source, these findings carry a practical consequence. The appropriate level of data resolution depends on the analytical purpose of the assessment. Simplified modelling options may suffice for climate-oriented screening, whereas scarcity assessment and material-specific attribution can benefit from the elemental resolution provided by IMDS. This resolution is often not fully retained when standard simplification strategies are applied.

Another practical implication of the thesis concerns the development of shared data infrastructure for automotive LCA. Paper I notes that the modelling effort associated with IMDS-based inventory construction decreases once material groupings, background dataset libraries, and matching conventions are established, since these libraries are reusable across subsequent studies. However, the current state of practice still requires individual practitioners to construct and maintain these libraries, often independently. The availability of industry-wide or publicly maintained material-level LCI datasets, e.g., for specific steel grades, aluminium alloys, or polymer compounds, matched to the substance representation used in IMDS, would likely reduce duplication of effort and improve consistency across studies. Recent work by Sturm et al. (2026) illustrates one direction of progress in this area, proposing a machine-learning framework for the automated classification of electronic and similar components whose environmental profile is module-driven, such as printed circuit boards, within IMDS-derived inventories.

The methodological relationship between inventory resolution and interpretive scope is unlikely to be restricted to automotive products. Paper III proposes that the approach could be applied to products of comparable material and structural complexity, provided that access to high-resolution, standardised, and repeatedly updated material declaration data is available. This transferability is a hypothesis rather than a demonstrated result of the thesis, as the empirical work is confined to vehicle gliders. Paper IV proposes the three mechanisms identified in the proxy comparison – representation mismatch, temporal drift, and resolution loss – as a potentially transferable diagnostic for evaluating proxy adequacy in LCA studies of products with comparable complexity to vehicles. The condition for transferability is not that other industries adopt IMDS specifically, but that comparable data systems exist or emerge for linking component-level product data to material and substance-level declarations. Recent developments in other sectors suggest that this condition is increasingly met or under development, including standardised material declaration practices in the aerospace and defence supply chain (IAEG, 2026), the cross-sector material declaration standard (IEC, 2026), and the digital battery passport mandated for industrial and electric-vehicle batteries under EU regulation 2023/1542 (European Commission, 2023). Where such systems are absent, the interpretive limitations demonstrated in this thesis for legacy automotive proxies are unlikely to be smaller.

5.5 Implications for resource management and stakeholders

The findings of this thesis indicate that impacts associated with vehicle production emerge from decisions distributed across multiple actors, including vehicle designers, component manufacturers, and materials suppliers. As shown in the RQ-E2 discussion, climate-related impacts are strongly influenced by supply chains of selected materials and structural design choices, while resource-scarcity impacts are often linked to specific elements embedded in components or material formulations. This distribution of drivers indicates that addressing these impacts is likely to require action by several actors. For LCA to support decision-making in this context, information that can be mapped onto these different levels of responsibility is likely to be more useful than aggregate product-level scores alone.

A direct implication for vehicle manufacturers concerns the distinction between design-driven and procurement-driven interventions. The results discussed for RQ-E2 show that design changes can increase or decrease impact scores by altering material composition, subsystem content, or embedded functionality. Simultaneously, the same impact categories can be influenced through supply-side measures, such as sourcing materials with lower embodied emissions or higher recycled content. These two levers act on the same indicators but operate through different mechanisms and timescales. Design changes may require platform-level redesign and long development cycles, whereas procurement strategies can be adjusted more incrementally, depending on supplier capabilities and market availability.

For resource-scarcity considerations, the cross-sectoral and intra-sectoral demand pressures identified for RQ-E1 imply that the automotive sector's metal demands cannot be assessed in isolation from other industries or from competing trends within the sector itself. A further challenge concerns the structural dispersion of scarcity-relevant metals across the product architecture. Elements concentrated in identifiable components may be addressed through targeted substitution or recovery efforts, while elements distributed across many components may require more systemic design changes or improved separation technologies. Resource strategies in the automotive sector are therefore likely to require a combination of material substitution, product design, and end-of-life considerations.

The dispersion patterns identified for RQ-E1 also have implications for recycling and circular-economy strategies. Traditional recycling metrics based on total mass recovery, such as those established under the EU End-of-Life Vehicles Directive (European Commission, 2000), are aligned with bulk materials, such as steel and aluminium, which dominate vehicle mass and are often recovered efficiently. However, the scarcity-relevant elements identified in this thesis are frequently present in small quantities, embedded in complex material formulations, or distributed across multiple subsystems. High-resolution inventories reveal that such elements may require targeted recovery approaches, including component-level dismantling, selective separation, or the development of new processing technologies. At the same time, dispersion patterns are not deterministic descriptors. High dispersion indicates increased complexity of recovery but does not by itself determine feasibility. Instead, it highlights where additional information, technological development, or design-for-disassembly considerations may be required. In this sense, the combination of elemental resolution and structural mapping provides a bridge between resource-scarcity assessment and circularity strategies, without relying on assumptions about specific recycling rates.

5.6 Limitations and future research

The empirical work in this thesis is based on vehicles from a single manufacturer and a limited set of well-equipped configurations sold on the European market. The results should therefore not be interpreted as statistically representative of the broader automotive industry. However, the observed trends – increasing aluminium content, growing electronic complexity, rising use of advanced high-strength steels – are consistent with reported industry developments (Czerwinski, 2021; Trovão, 2022), suggesting that the patterns identified here are unlikely to be unique to this manufacturer. A further constraint concerns the nature of IMDS data itself. Material declarations are supplier-reported, and the quantitative plausibility of every individual entry cannot be independently verified in an assessment of this scale. Paper III addresses this limitation through targeted validity checks on top-contributing subsystems and identifies one set of anomalous values with a measurable influence on CSI results. The absence of similar findings in the additional targeted audits does not prove the accuracy of every individual declaration. Paper I also identifies the absence of production-route and recycled-content information in IMDS as a limitation. Addressing this gap would require either expanding the scope of supplier reporting or developing complementary data channels within the automotive supply chain. Both directions imply a governance effort that extends beyond individual manufacturers.

In addition, suppliers may report substance concentrations as ranges rather than exact values, introducing uncertainty at the foreground level. Paper III assesses the influence of this uncertainty through a sensitivity analysis in which range-reported substances in the MY12 and MY24 inventories are assigned their lower or upper reported limits. The MY12-to-MY24 trends in GWP and ODP remain essentially unchanged across these scenarios. For CSI, the corresponding change ranges from approximately −8% to +10%, compared with +3% in the reference model. This sensitivity is consistent with the dependence of CSI scores on low-mass elemental flows in the foreground inventory (RQ-M2) and indicates that longitudinal changes in resource scarcity scores should be interpreted with attention to the underlying concentration uncertainty.

A related uncertainty arises from wildcard entries and from the redistribution applied under the dual-threshold coverage procedure. Wildcard entries account for less than 1.0 wt.-% of total glider mass, while the redistributed fraction represents at most 0.4 wt.-% within the subsystems examined for MY12 and MY24. The redistributed mass is not omitted but assigned proportionally to the retained basic substances, thereby preserving complete mass coverage while approximating the identity and environmental profile of the residual substances. These small mass shares likely limit their influence on mass-dominated results, but do not by themselves exclude an influence on element-sensitive indicators. Their mass shares and basic-substance profiles are therefore reported in the Supplementary Information of Paper III.

Confidentiality requirements further constrain the reporting of results. All absolute impact scores and masses are normalised, which preserves relative differences and contribution patterns but limits the ability of external researchers to reproduce or benchmark the results against other studies using absolute values. A related caveat applies to component-level dispersion metrics. The number and definition of "components" reflect the granularity of the IMDS-reported product structure rather than an absolute physical decomposition, so entropy and occurrence-count values are most informative when compared within a consistent product-structure convention.

Several deliberate modelling choices define the boundaries of what the thesis can conclude. The system boundary is cradle-to-gate across all studies, excluding the use phase and end-of-life treatment. This scope is aligned with the thesis's focus on production-phase implications of material composition and inventory resolution, but it means that the findings do not address the full life-cycle trade-offs associated with design changes. For instance, lightweighting strategies that increase production-phase climate change may reduce use-phase energy consumption, a trade-off that falls outside the present scope. A comparable trade-off applies to the growing electronic content documented in this thesis. Safety systems, driver-assistance features, and comfort and infotainment equipment all require materials whose production-phase scarcity burdens are captured by the assessment. However, these systems may also deliver use-phase benefits, such as improved occupant safety, reduced accident severity, and enhanced driving experience, that are not reflected in a cradle-to-gate scope. These aspects are part of a broader functional trade-off that this thesis does not attempt to quantify.

The static background model applied in Papers III and IV isolates foreground design evolution but does not capture the simultaneous decarbonisation of energy systems and efficiency gains in material supply chains. As discussed for RQ-E2, this design answers the question of how the production-phase burden would change if all vehicle generations were manufactured under identical background conditions, but it does not represent actual historical emissions. The set of impact categories assessed also narrows across the thesis. Paper I applies the full EF 3.0 midpoint set, while later papers focus on a limited set of indicators. Within the categories assessed, alternative LCIA methods and frameworks are available for the assessed categories, including ReCiPe (Huijbregts *et al.*, 2017) and IMPACT World+ (Bulle *et al.*, 2019) for climate change and ozone depletion, and ADP (van Oers *et al.*, 2020), SOP (Vieira *et al.*, 2017), and supply-risk indicators for mineral resource use (Bach *et al.*, 2016; Cimprich *et al.*, 2019). Categories related to toxicity, biodiversity, water use, and social dimensions are not systematically addressed, and the thesis does not claim that the conclusions drawn for scarcity and climate change extend to these other domains.

Several directions for future research emerge from the limitations identified above. Extending the longitudinal assessment to include dynamic background modelling would allow the separation of design-driven and supply-driven changes to be quantified explicitly, rather than inferred from the static-background results and external data on economy-wide trends. Broadening the scope to include end-of-life treatment would connect the dispersion patterns identified in Papers II and IV to quantitative assessments of material recovery potential, moving from structural descriptors toward actionable circularity metrics. Expanding the range of impact categories, particularly toward toxicity and biodiversity-related indicators, would test whether the resolution-dependence observed for scarcity categories extends to other environmentally relevant domains. Within the resource domain, CSI characterises long-term geological scarcity, while Paper II's DFP addresses one specific aspect of potential short-term scarcity by relating hypothetical automotive demand to current global primary production. DFP does not capture geopolitical exposure, production concentration, substitutability, or the broader vulnerability of metal supply chains. Future research could therefore apply complementary supply-risk and criticality indicators to the high-resolution inventories developed in this thesis, extending the assessment beyond the geological and primary-production perspectives examined here. On the data structure side, the persistent absence of information on production routes and recycled content in IMDS remains a limitation that future developments in supplier reporting or complementary data channels could address. Finally, applying the methodological framework developed in this thesis to other complex products, where comparable standardised material declaration systems exist or are emerging, would test the generalisability of the relationship between inventory resolution and interpretive scope beyond the automotive sector (see examples in section 5.4).

6 Conclusions

This thesis demonstrates that supplier-reported material data from the International Material Data System can be systematically transformed into life cycle inventories for complex automotive products, resolved at the level of individual substances and traceable to specific components within the product architecture. The approach scales to full vehicle gliders across multiple model years, and the underlying modelling structure accumulates with repeated application.

High-resolution inventories reveal that vehicle gliders are materially diverse assemblies whose resource significance extends well beyond their dominant bulk metals. Low-mass elements can dominate the scarcity profile. The scarcity relevance of specific metals varies with equipment level and evolves as vehicle architectures change, while scarcity contributions redistribute across subsystems in ways that aggregate indicators conceal. Climate change scores, by contrast, increase faster than glider mass, driven primarily by the greater contribution from aluminium under the static background conditions applied. Moreover, different impact categories may respond to the same design evolution through fundamentally different mechanisms, making the production-phase environmental profile of the assessed gliders irreducible to any single narrative.

The overarching conclusion is that foreground inventory resolution defines not merely the numerical precision but also the interpretive scope of environmental and resource-scarcity assessment for passenger cars, as demonstrated here for vehicle gliders. What an assessment can credibly address depends on what the inventory can resolve, including element-specific attribution, the separation of product composition from upstream-attributed burdens, structural mapping within the product architecture, and the tracking of changes across successive vehicle generations. Access to detailed, regularly updated, supplier-reported material data makes such resolution attainable in practice.

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