CHALMERS
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A Methodology for Early-Phase Environmental Target Setting in Heavy-Duty Vehicle Development

Combining Baseline Life Cycle Assessment and Delta-Based Analysis for Reference LCA Construction

ALICIA SJÖBLOM Master’s thesis in Industrial Ecology
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Cover: Visualisation of a heavy-duty vehicle driving through nature. Provided by Volvo Group.

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Abstract

Environmental target setting in early-phase product development is challenged by limited data availability and reliability, as well as the difficulty of combining retrospective and prospective information. In industrial contexts such as heavy-duty vehicle development, full life cycle assessments (LCAs) are often not feasible at early stages, despite the significant influence of early design decisions on environmental performance.

This thesis develops a transparent and repeatable methodology for constructing reference LCAs by combining baseline Life-Cycle Impact Assessment (LCIA) data with structured delta values representing project-specific changes through a case study. The approach enables the estimation of environmental performance for early-phase projects without requiring complete product definitions.

The case-specific results demonstrate that climate impacts are highly concentrated within a limited number of systems, particularly the energy storage system (ESS) in battery electric vehicles (BEV). At the same time, the analysis reveals a weak alignment between identified hotspots and the locations of implemented changes. This indicates that development efforts are primarily driven by other factors than environment, with effects on sustainability often occurring as secondary outcomes.

From a methodological perspective, the proposed approach provides a pragmatic alternative to full LCAs, enabling structured and decision-relevant assessments under conditions of uncertainty. While subject to limitations related to data quality and standardisation, the methodology supports early-phase environmental target setting by combining hotspot identification with change analysis.

Overall, the study contributes a flexible and scalable framework that bridges the gap between environmental assessment and practical decision-making, supporting the integration of sustainability into industrial product development processes.

Keywords: BEV, Deltas, Early-Phase, ESS, Heavy-duty, LCA, LCIA, Methodology, Product Development, Sustainability

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Alicia Sjöblom & Vinod Chaudhari, Gothenburg, May 2026

Acronyms

Following is the list of acronyms used throughout this thesis, presented in alphabetical order:

ALCA	Attributional Life Cycle Assessment
BEV	Battery Electric Vehicle
BoM	Bill of Materials
CLCA	Consequential Life Cycle Assessment
CO_2-eq	Carbon dioxide equivalents
ESS	Energy Storage System
GHG	Green House Gas/-es
GWP	Global Warming Potential
ICE	Internal Combustion Engine
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
RC	Recycled Content
SOC	Substances of Concern
SoP	Start of Production
TRL	Technology Readiness Level

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1

Introduction

In this section, the background to the thesis is presented, outlining its relevance and contribution. Moreover, the aim and research questions are presented further, depicting the thesis.

1.1 Background

Climate change poses increasing ecological, social, and economic risks worldwide, affecting societies on a global scale [21]. Addressing these challenges requires collective efforts to reduce greenhouse gas (GHG) emissions while continuing to support societal and economic development. In 2015, governments committed to limiting global temperature increase to well below 2 °C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5 °C, through the Paris Agreement [20]. According to the Intergovernmental Panel on Climate Change [14], achieving the 1.5 °C target requires rapid and deep reductions in global CO_2 emissions and the attainment of net-zero emissions around mid-century.

The transport sector plays a significant role in global GHG emissions, with heavy-duty vehicles accounting for a substantial share due to their energy-intensive operation and material use [11]. In this context, industrial actors have an important responsibility in contributing to emission reductions, beginning already in early product development and extending throughout the supply chain. Initiatives such as the Science Based Targets initiative (SBTi) support companies by providing frameworks, guidance, and tools for setting emission reduction targets aligned with climate science and the 1.5 °C goal [17]. Achieving such targets requires addressing not only direct emissions from manufacturing processes, but also indirect upstream emissions associated with materials, components, and supplier activities [10].

Within industrial product development projects, environmental performance targets are often defined early in the project lifecycle and evaluated relative to a reference product or system. Such references commonly represent a combination of products currently in production and anticipated future technologies, as multiple development projects may run in parallel with long lead times. Particularly within the transition towards heavy-duty BEVs, early-phase environmental assessments have become increasingly important due to the substantial climate impacts associated with battery systems, material production, and evolving supply chains.

Therefore, a robust and transparent definition of the environmental baseline is essential to support meaningful target setting and internal comparison. LCA is widely used by industrial organisations as a method to quantify the environmental impacts of products and systems. In early project phases, reference and baseline LCAs are often limited to a cradle-to-gate perspective and focus primarily on climate impact, reflecting both data availability and decision-making needs [4], [5], [2].

This practice creates a methodological challenge: how to construct a reference LCA that is sufficiently grounded in current production data while remaining suitable for evaluating future product development projects. Addressing this challenge is particularly important for projects with long development timelines and evolving technologies. The present thesis is motivated by this need and focuses on developing a structured and transparent methodology for producing reference LCAs that can support early-phase target setting and decision-making in industrial product development contexts.

To further ground this challenge in an industrial context, the following subsection presents the specific case of Volvo Group with which this thesis has been conducted.

1.1.1 Volvo Group Context

Within Volvo Group, LCA is used as a practical tool to understand and manage the climate impact of truck products. In early development phases, baseline LCAs are created to support environmental target setting and internal decision-making. These baseline assessments are typically based on existing production trucks and available data, and they follow a cradle-to-gate approach with a primary focus on climate impact.

Volvo Group has committed to reaching net-zero greenhouse gas emissions across its value chain by 2040. To support this ambition, there is a strong focus on reducing emissions from materials, components, and supplier activities, as these represent a significant share of the total impact. This makes early-phase decisions especially important, as many of the environmental impacts are already defined during product design.

In practice, truck development projects within Volvo group often have long lead time, and several projects run in parallel. As a result, it is not always possible to rely only on fully defined product data when performing environmental assessments. Instead, engineers need to combine existing baseline data with assumptions and projections for future technologies, materials, and design changes.

This creates a practical challenge for the company: how to construct a reference LCA that is both grounded in current production data and still relevant for future truck projects. Today, this process is not always carried out in a fully structured or consistent manner, if at all, especially when combining retrospective and prospective information.

This thesis addresses this challenge by developing a structured and transparent method for creating reference LCAs via a battery electric heavy-duty vehicle case study within the Volvo Group. Beyond the specific case implementation, the thesis contributes to the broader challenge of integrating environmental assessment into industrial decision-making under conditions of incomplete and evolving product information. Rather than aiming to establish highly precise environmental performance values in early development phases, the work focuses on developing a scalable and decision-relevant methodology capable of supporting environmental target setting despite significant uncertainty and limited data maturity.

1.2 Aim

This master's thesis aims to develop a transparent and repeatable method for handling a combination of retrospective and prospective data when producing reference LCAs for ongoing heavy-duty truck projects. The method will be developed by creating a reference LCA for a current ongoing heavy-duty truck project, which will create a base for extracting the methodology workflow and generalising it to be widely applicable.

The objectives of this thesis are to:

- Develop a reference LCA for an ongoing early-phase battery electric heavy-duty truck project by updating the existing LCIA baseline data with prospective data.

- Extract a structured methodology for constructing a reference LCA for all types of heavy-duty truck projects from the case.

- Identify major climate impact hotspots and key sources of uncertainty that are relevant for early-phase target setting.

1.3 Research Questions

Specifications of the aim above are clarified in the following research questions:

1. How can retrospective data from an existing baseline LCIA be combined with prospective project sustainability data to construct a valid reference LCA for future truck developments?

2. What methodological choices, assumptions, and limitations arise when merging a baseline LCIA with prospective data in an industrial project context?

3. How can the resulting reference LCA method support early-phase environmental target setting and hotspot identification in future truck projects?

1.4 Limitations

This thesis is subject to several limitations related to the early-phase, reference-oriented, and industrial nature of the study.

System boundary limitations:

The assessment is limited to a cradle-to-gate perspective, with maintenance activities considered separately in accordance with Volvo Group's internal framework. Environmental impacts related to vehicle use, charging behaviour, and end-of-life treatment are excluded. Consequently, the results do not represent the complete life cycle environmental performance of the vehicle.

Impact category limitation:

The analysis focuses primarily on the climate impact known as global warming potential (GWP), measured in kilograms of carbon dioxide equivalents (CO_2-eq) over 100 years, also denoted GWP100. Other environmental impact categories are not assessed in detail. This limitation reduces the environmental breadth of the study but supports methodological clarity and comparability across projects.

Data availability and representativeness:

The study relies on a combination of internal company data and secondary LCA database data. Due to confidentiality constraints and limited Material Data Sheet (MDS) coverage in early project phases, generic datasets and proxy data were used for certain components and materials. In some cases, highly uncertain prospective data were excluded to reduce the influence of unstable assumptions on the results. These limitations may affect the precision and geographical representativeness of the results, particularly at lower levels of aggregation.

Uncertainty in prospective modelling:

The prospective considerations are based on assumptions related to material production, recycling input rates, and future development conditions. Although these assumptions represent plausible future developments, they remain uncertain, and actual future conditions may differ depending on technological development and implementation timing.

Industrial workflow maturity:

The study was conducted within an evolving industrial sustainability environment where sustainability tools, data structures, and reporting workflows are not yet fully standardised. This affects interoperability between datasets and limits the degree of automation achievable within the current workflow.

Pilot project generalisability:

The methodology was developed using a single industrial case study. While the methodological framework is intended to be reusable, the numerical results and specific conclusions remain case-dependent and cannot be directly generalised to all truck platforms without adaptation.

Despite these limitations, the thesis provides a transparent and methodologically consistent framework for constructing reference LCAs and supporting early-phase environmental target setting.

2

Theory

This chapter presents the theoretical foundation underlying the thesis. It begins with an introduction to LCA, including the International Organization for Standardization (ISO) framework, common modelling approaches, and temporal perspectives relevant to environmental assessment. The chapter also introduces GWP as the primary environmental impact category applied in this thesis.

The discussion then situates LCA within the context of industrial product development, with particular emphasis on early-phase development conditions characterised by uncertainty, limited data maturity, and evolving product definitions. In addition, the relationship between technology maturity and market maturity is discussed due to its relevance for methodological applicability and transferability.

Finally, the chapter addresses the theoretical basis for methodological generalisation from a case study. Together, these perspectives establish the analytical foundation for the methodology developed and evaluated in this thesis.

2.1 Life Cycle Assessment

This section presents the LCA framework defined by the ISO standards ISO 14040 and ISO 14044 while also introducing relevant modelling choices and temporal perspectives within LCA methodology. Finally, the section addresses sensitivity and uncertainty analysis as described in ISO 14044.

2.1.1 The LCA Framework

The ISO provides the general framework for LCA in ISO 14040:2006, while the detailed requirements and guidelines are specified in ISO 14044:2006 [4], [5]. These standards describe LCA as a methodology used to assess environmental impacts throughout the life cycle of a product, service, or system. This life cycle includes all stages from raw material extraction and production to use, recycling, end-of-life treatment, and final disposal, commonly referred to as a cradle-to-grave perspective.

According to ISO 14040, an LCA consists of four interrelated phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [4]. Their interconnected and iterative nature is illustrated in Figure 2.1. Since each phase informs the others, insights obtained during later stages may require revisions to earlier assumptions or methodological choices.

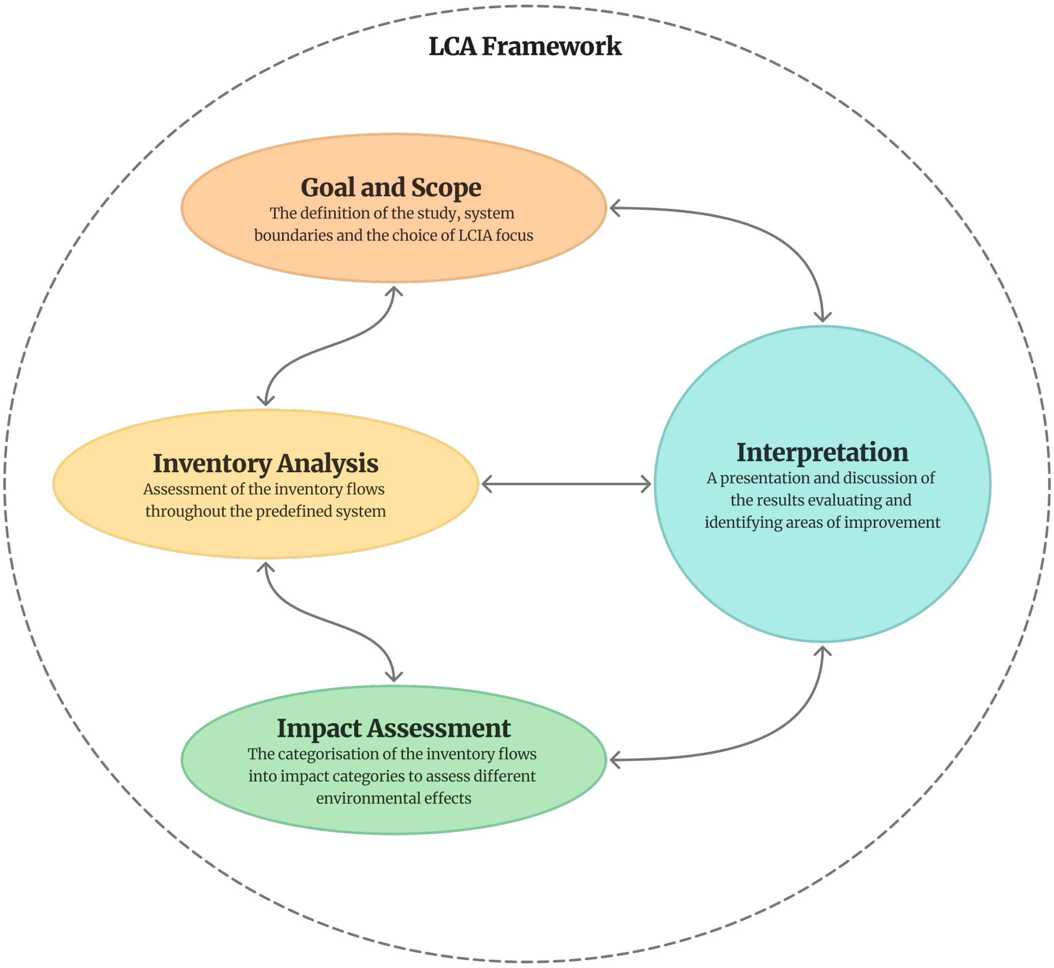

Figure 2.1: An illustration of the LCA framework in accordance with the methodology as described by ISO 14040/14044 with iterative depiction of the process.

Goal and scope definition

The goal and scope definition specifies the intended application of the study, the target audience, and the reasons for conducting the assessment. During this phase, the system boundaries are defined and a functional unit is established, to which all input and output flows are normalised. Since LCA is an iterative methodology, the goal and scope definition may be refined throughout the study as new insights emerge [4].

Within the goal and scope definition, system boundaries are commonly described using terms such as cradle-to-grave and cradle-to-gate. A cradle-to-grave perspective includes all life cycle stages from raw material extraction through production and use to end-of-life treatment, such as recycling or disposal. In contrast, a cradle-to-gate perspective includes processes from raw material extraction up to the point where the product leaves the production system, excluding the use phase and end-of-life stages [4]. The selection of system boundaries depends on the intended application of the study, data availability, and the decision context defined in the goal of the LCA.

Inventory analysis

The Life Cycle Inventory (LCI) analysis involves the collection, calculation, and allocation of data related to inputs such as materials, energy, and water, as well as outputs including emissions and waste. The purpose of the LCI is to quantify the material and energy flows associated with the defined system throughout its life cycle [4].

Impact assessment

The LCIA phase translates the quantified inventory flows into indicators of potential environmental impacts by assigning them to predefined impact categories. These indicators can be calculated at either midpoint level, representing specific environmental mechanisms such as GWP, or endpoint level, representing damage to broader areas of protection such as human health, ecosystems, or resource availability [4].

Interpretation

In the interpretation phase, the results from the inventory analysis and impact assessment are analysed in relation to the defined goal and scope of the study. This phase includes evaluation of the results, identification of significant findings, and formulation of conclusions and recommendations intended to support environmental improvement of the assessed system [4].

Sensitivity and uncertainty analyses are commonly included as part of the interpretation phase. A sensitivity analysis investigates how changes in assumptions, methodological choices, or input parameters influence the results. By systematically varying selected parameters within plausible ranges, the analysis identifies which assumptions have the greatest influence on the outcomes. This supports interpretation by highlighting parameters requiring careful evaluation regarding robustness and consistency [5].

An uncertainty analysis evaluates the reliability of the results by identifying uncertainties related to data quality, methodological choices, and model structure. Such uncertainties may arise from incomplete data, measurement errors, process variability, or underlying assumptions. Including uncertainty analysis improves transparency and clarifies the level of confidence associated with the results [5].

2.1.2 Temporal Perspectives of LCA

The temporal perspective is an important aspect of LCA because it influences the studied system, data quality, and associated uncertainties. Historically, LCAs have mainly focused on existing or recent systems, commonly referred to as retrospective or ex-post LCAs. In some cases, LCAs may also analyse historical systems and are then referred to as historical LCAs. More recently, the use of LCAs for modelling future scenarios has increased, commonly referred to as prospective or ex-ante LCAs [1].

In practice, some LCAs combine retrospective and prospective perspectives within the same assessment. For example, certain life cycle stages may represent existing production systems, while other stages reflect future assumptions related to recycling, end-of-life treatment, or future technologies [1].

To further distinguish between retrospective and prospective LCAs, technology maturity may be introduced as an additional dimension. By incorporating Technology Readiness Levels (TRLs), LCAs can be differentiated based on whether the assessed technology is mature at the time of analysis or still under development. A mature technology analysed using existing data reflects an ex-post perspective, whereas technologies expected to mature in the future represent an ex-ante perspective [1].

This thesis combines retrospective and prospective data, although in a different manner than described above. Rather than separating life cycle stages temporally, the methodology combines a retrospective baseline with prospective project-specific updates representing future developments. In this way, the temporal distinction relates primarily to the quality and maturity of the underlying data rather than to separate life cycle stages. Consequently, the methodology combines both ex-post and ex-ante perspectives.

2.1.3 LCI Modelling Choices

When conducting an LCA, two main modelling approaches are commonly used: attributional LCA (ALCA) and consequential LCA (CLCA). Neither approach is explicitly standardised, and there is limited consensus regarding their practical implementation [16]. Even the International Reference Life Cycle Data System (ILCD) handbook contains internally inconsistent recommendations regarding the choice between ALCA and CLCA [7]. Despite this, a general consistency exists regarding how the two approaches are conceptually defined, largely based on conclusions from an international workshop held in 2001.

These definitions are commonly summarised as follows:

- *"Attributional LCI considers the flows in the environment within a chosen temporal window."* [7]
- *"Consequential LCI considers how the flows may change in response to deci-*

sions." [7]

The key difference is that CLCA focuses on environmental changes caused by decisions, while ALCA focuses on describing the environmental flows associated with an existing system. Both approaches may theoretically be applied across different temporal perspectives, although practical implementation may become more complex in certain combinations [16].

According to the ILCD handbook, three main application contexts for LCA can be identified: micro-level applications such as product development, macro-level applications related to policy and stakeholder decision-making, and accounting applications spanning multiple levels. For both micro- and macro-level applications, the handbook often recommends CLCA because the effects of decisions are central in these contexts. However, the handbook simultaneously recommends ALCA for certain micro-level applications, including product development and product updates, leading to an internal inconsistency [7].

For this thesis, the explicit recommendation related to product development is followed, and an ALCA approach is applied. This choice is motivated by the micro-level nature of the case study, together with the focus on methodological development rather than modelling broader decision-induced system changes.

2.1.4 Global Warming Potential

GWP is one of the most commonly used impact categories in LCA and is generally expressed in CO_2-eq. GWP quantifies the contribution of greenhouse gases to radiative forcing and expresses these contributions relative to CO_2, enabling emissions such as CO_2, CH_4, and N_2O to be aggregated into a single indicator. The calculation is performed for a specified time horizon, most commonly 100 years, in accordance with ISO 14044 [12], [5]. The indicator is then referred to as GWP100.

In this thesis, GWP100 is selected as the primary environmental impact indicator. Additional indicators may be reviewed where relevant to identify potential environmental trade-offs and reduce the risk of overlooking important environmental effects. However, these additional indicators are not central to the results or the main methodological focus of the thesis.

2.2 Life Cycle Assessment in Product Development

As described in Section 2.1, LCA is a comprehensive methodology for evaluating the environmental impacts of products, services, and systems throughout their life cycle, from raw material extraction and production to use and end-of-life treatment [3], [9]. Traditionally, LCAs have often been conducted late in the product development process, when opportunities for significant design changes are limited [6]. However, approximately 80% of a product's environmental impact is determined during the early design phases [9], [13]. This creates a challenge because the stages with the greatest influence on environmental performance are also those characterised by the highest uncertainty and the lowest data availability.

Historically, the limited use of LCA in early product development has largely been associated with insufficient data quality and low data maturity during early project phases [6]. Despite these challenges, the relevance of LCA as a support tool for environmental decision-making in product development is increasingly recognised. Early-phase LCAs can support technology development, influence design choices, and stimulate innovation aimed at achieving environmental targets [2].

At the same time, implementing LCA in early-stage product development introduces additional methodological challenges related to technology and market maturity. Technology maturity refers to the extent to which a technology has been developed, tested, and stabilised, while market maturity concerns the degree to which infrastructure, regulations, and user acceptance support its implementation. Bergerson et al. [2] emphasise that these dimensions do not necessarily develop simultaneously and should therefore be evaluated separately. Furthermore, products may consist of components with different maturity levels, meaning that an otherwise established product may still contain emerging technologies due to new components, novel applications, or evolving system integrations. [2]

In the context of this thesis, the studied case represents a situation in which market conditions are comparatively mature, while parts of the underlying technology are still evolving. This creates a misalignment between technology maturity and market maturity, introducing uncertainty and affecting the transferability of the results. Understanding this relationship is therefore important when developing methodologies intended for application in early-phase industrial product development under varying maturity conditions.

Overall, this highlights a central challenge addressed in this thesis: how environmental assessments can support decision-making under conditions characterised by incomplete product definitions, evolving technologies, and limited data availability. The ability to provide structured environmental guidance despite such uncertainty is therefore an important requirement for methodologies intended for early-phase industrial applications.

2.3 Methodological Generalisation from a Case Study

When considering a case study as the basis for developing a generalised methodology, the approach may initially appear counterintuitive, since a case study represents a specific situation characterised by context-dependent conditions. Nevertheless, methodological generalisation from case studies is common in research, particularly when the objective is to identify underlying principles, structures, or decision processes rather than to generalise numerical results directly.

According to Evers and Wu [8], methodological generalisation from case studies is possible because observations and interpretations are always connected to existing theoretical knowledge rather than being entirely situation-specific. They describe several forms of generalisation, including empirical, regulative, and constitutive generalisation. In the context of this thesis, the primary focus is on regulative and constitutive generalisation, since the objective is to identify methodological principles and decision structures relevant for conducting similar studies in comparable industrial settings.

Regulative generalisation concerns the existence of underlying rules and structures that enable coordinated and consistent practices, while constitutive generalisation concerns practices that are themselves shaped by such rules. Together, these perspectives support the idea that methodological insights can be extracted from a single case study when the objective is to understand how a method functions rather than to generalise specific numerical outcomes [8].

Evers and Wu further describe abductive inference, or inference to the best explanation, as an additional basis for methodological generalisation. In this context, a proposed methodology is considered justifiable when it represents the most plausible explanation for a successful application within the studied case [8]. Although such conclusions remain context-dependent, they may still provide a valid analytical basis for methodological development when grounded in theory and iterative evaluation.

In this thesis, the purpose of the case study is therefore not to generalise empirical results directly, but rather to extract methodological principles relevant for constructing reference LCAs in early-phase industrial product development. Consequently, the resulting methodology should be interpreted as an analytically grounded and industrially contextualised framework developed within clearly defined boundaries and conditions.

Overall, the theoretical framework presented in this chapter highlights three central challenges relevant to this thesis: the difficulty of applying LCA in early-phase product development under uncertain conditions, the methodological implications of combining retrospective and prospective perspectives, and the need to balance methodological robustness with industrial applicability. Together, these perspectives form the analytical foundation for the methodology developed in this thesis.

3

Methods

This chapter describes the methodological approach applied in the thesis. First, a conceptual overview is presented subsequent by the goal and scope definitions of the reference LCA. This is followed by a description of the internal mapping process and method selection, the developed methodology for combining LCIA outputs and sustainability data, the extracted and generalised methodology, and finally the use of AI tools throughout the thesis.

3.1 Conceptual Overview of Reference LCA Approach

This section presents the conceptual logic underlying the reference LCA approach developed in this thesis. The approach was designed to support consistent environmental assessment across multiple truck development projects characterised by long development lead times and evolving product definitions.

In Figure 3.1, the conceptual illustration of the reference LCA approach is depicted.

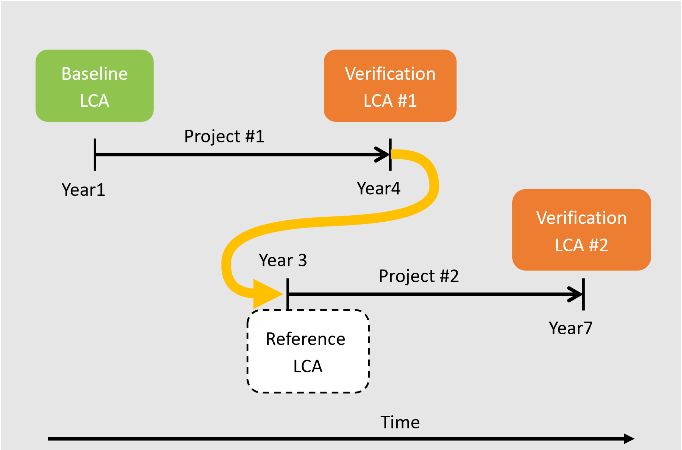

Figure 3.1: Conceptual illustration of the reference LCA approach across multiple truck development projects.

As illustrated in Figure 3.1, the process begins with a baseline LCA representing a comparatively mature truck configuration already close to, or currently in, production. Due to its relatively high data maturity and coverage, this baseline serves as the primary environmental reference point. However, since future development projects are not fully defined during their early phases, the baseline alone is insufficient for environmental target setting.

To address this limitation, the baseline LCA is updated using prospective information available at the start of a new project. This includes anticipated changes related to technologies, materials, and design configurations. The result is a reference LCA (#1 in Figure 3.1) that provides a forward-looking yet grounded estimate of environmental performance.

In practice, this approach means that a new development project does not begin with a completely new environmental assessment. Instead, an existing baseline is incrementally updated using the best available information regarding expected future changes in technologies, materials, and component configurations. As additional information becomes available throughout the project lifecycle, the reference can be refined further and eventually serve as the baseline for subsequent projects.

Figure 3.1 should therefore not be interpreted as a sequence of isolated LCAs, but rather as a continuously evolving assessment process in which each project builds upon previously established environmental knowledge together with updated project-specific information. The arrows between projects illustrate how baseline information and project-specific updates are transferred and refined over time.

The methodology is therefore iterative across projects, where each completed or updated project contributes new knowledge and data that can support future reference LCAs. In this way, the approach enables a cumulative and learning-based process that can improve both consistency and environmental understanding over time.

Overall, the conceptual approach combines mature baseline LCIA data with prospective project-specific changes to create a continuously updated environmental reference. This supports environmental target setting and hotspot identification already during early project phases, despite incomplete product definitions and evolving development conditions.

3.2 Goal and Scope Definitions

In accordance with ISO 14040 and ISO 14044, this section presents the goal and scope definition of the study. The purpose of the goal and scope definition is to specify the intended application of the study, the investigated system, and the methodological boundaries within which the assessment was conducted.

3.2.1 Goal Definition

The goal of this study was to develop a structured and transparent methodology for constructing reference LCAs for truck projects in early development phases through a case study. The methodology is intended to support early-stage environmental target setting and hotspot identification within industrial product development. The results were developed primarily for internal decision support rather than external communication, with emphasis placed on methodological transparency, consistency, and repeatability rather than highly precise environmental impact values.

The assessment was conducted as a non-comparative and case-specific study. Consequently, the results should be interpreted as indicative and subject to revision as project maturity and data quality improve over time. The case-specific implementation therefore, serves primarily as the empirical basis for extracting and evaluating a generalisable methodological workflow.

3.2.2 Scope Definition

The functional unit of the study was defined as one complete truck manufactured and assembled according to the configuration specified for the case project. The functional unit includes all materials and processes required to produce the vehicle up to the factory gate. Maintenance-related activities were quantified relative to this functional unit to ensure consistency throughout the assessment. This approach is aligned with Volvo Group's standard practice for baseline LCAs.

The environmental assessment focused exclusively on climate change impacts, expressed as GWP100 in CO_2-eq. Other environmental impact categories were not included, as the primary objective of the study was to establish a climate-focused reference baseline for environmental target setting and decision support.

The geographical scope corresponds to the locations represented in the underlying production and supply chain data used in the baseline LCA, primarily reflecting Volvo Group's existing manufacturing and supplier network. The temporal scope combines retrospective data representing current production systems with prospective information for future-relevant components, reflecting the long development lead times characteristic of the studied truck projects. All assumptions, data sources, and exclusions within the scope were documented to support transparency and repeatability.

3.2.3 System Boundaries

The main system boundary of the study was defined as cradle-to-gate. An overview of the applied system boundaries is illustrated in Figure 3.2. The figure visualises the included and excluded processes together with the flows of materials, energy, and emissions within the studied system.

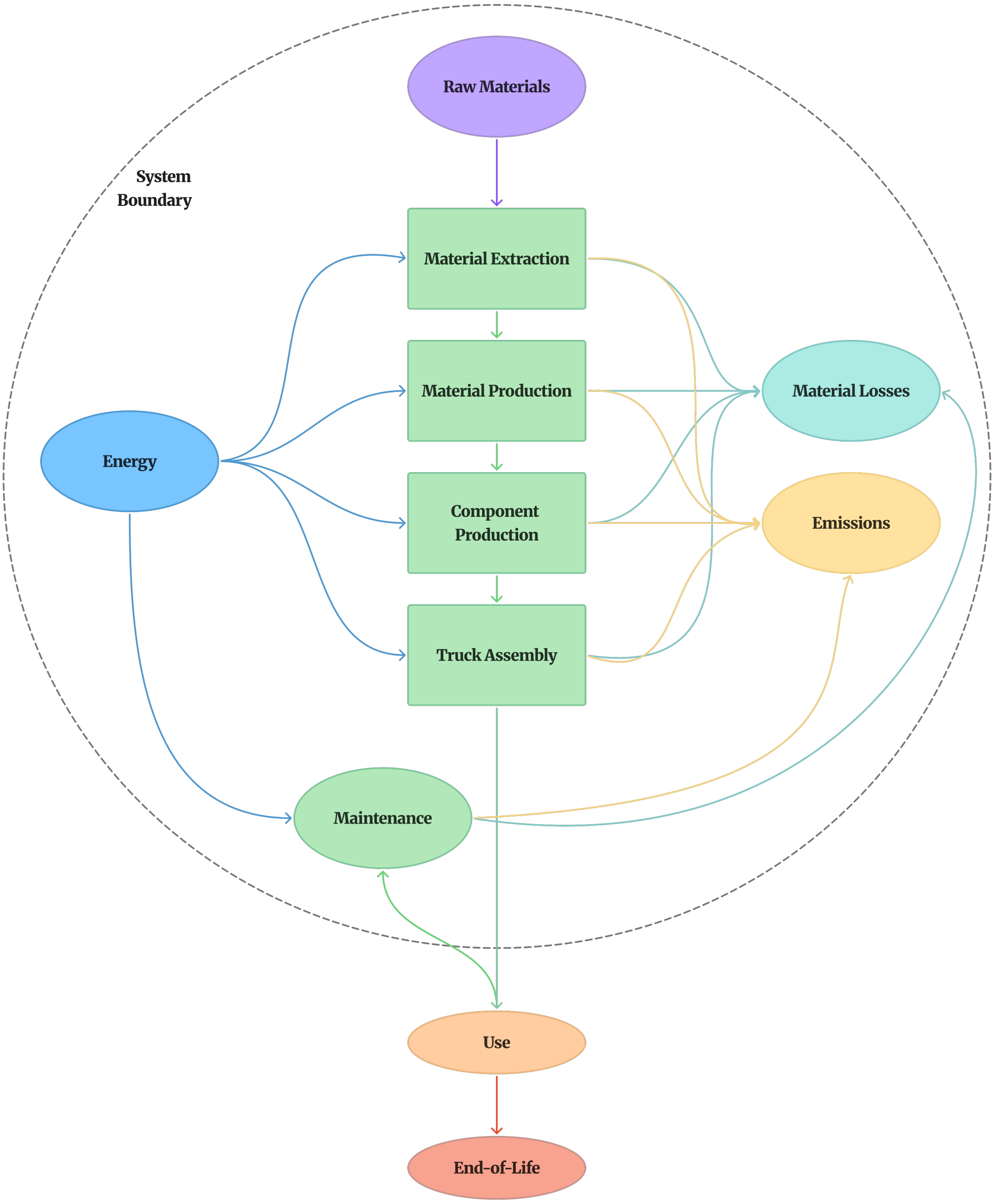

Figure 3.2: Illustration of the system boundaries applied in the study, showing the cradle-to-gate perspective and the separate consideration of maintenance activities.

As illustrated in Figure 3.2, the system boundary includes processes from raw material extraction to final truck assembly. These processes encompass raw material extraction, material production, component manufacturing, and vehicle assembly, including associated energy use, material losses, and emissions.

The use phase is excluded from the primary system boundary. However, maintenance activities related to vehicle operation are considered separately. Processes outside the defined system boundary include vehicle operation, fuel or electricity production and consumption during driving, and end-of-life treatment such as recycling or disposal.

3.2.4 Delimitations

The delimitations presented in this section specify how the broader limitations discussed in Section 1.4 are implemented within the methodological framework of the study. While the limitations describe overarching constraints, the delimitations define the practical boundaries applied during the methodological implementation.

The assessment is limited to a cradle-to-gate system boundary, including maintenance activities, in accordance with internal organisational practice. Consequently, use-phase and end-of-life processes are excluded. Furthermore, the methodological implementation focuses exclusively on climate change impacts expressed as GWP100. This delimitation supports consistency in data processing and aggregation when combining LCIA outputs with sustainability tool data, but limits the broader environmental scope of the analysis.

From a data perspective, the methodology is constrained to available baseline LCIA datasets and sustainability tool outputs. Consequently, the structure, resolution, and quality of the final results remain dependent on these input sources. Where data gaps occur, no additional modelling or extrapolation was introduced beyond the available datasets.

Finally, the study does not introduce new allocation procedures or modify the underlying LCA modelling assumptions. Instead, it relies on pre-defined attributional datasets to maintain consistency with existing organisational practices and baseline LCIA data. While this supports methodological consistency, it also limits methodological flexibility.

Together, these delimitations ensure that the developed methodology remains aligned with the practical constraints of early-phase industrial applications, where limitations related to time, data availability, and standardisation are unavoidable.

3.3 Internal Process Mapping and Method Selection

To understand how environmental target setting could be integrated into ongoing truck development processes, an initial mapping phase was conducted focusing on existing organisational workflows and available product data structures. During this process, as well as the subsequent method selection phase, AI tools were used as supportive instruments for brainstorming and structuring potential methodological approaches. The tools were primarily applied to explore alternative process alignments, identify possible analytical pathways, and support the interpretation of insights obtained through stakeholder discussions. All suggestions were critically evaluated and served only as input to the authors' own methodological reasoning.

An initial step in the project was to investigate how other organisational functions address comparable needs during early project phases. Since the sustainability function is comparatively small and still developing its long-term working routines, understanding established practices in more mature functions was considered important both to avoid duplication of effort and to support the development of a scalable methodology for environmental target setting.

The initial working hypothesis was that sustainability activities could align with the cadence and governance structures already used within functions such as product costing and load capacity. In practice, this would potentially allow sustainability assessments to utilise existing project follow-ups, early-phase gates, and decision forums to establish environmental baselines, reference configurations, and associated targets.

To investigate this hypothesis, an exploratory mapping phase was conducted during the first month and a half of the project, as illustrated in Figure 3.3. The purpose was to clarify which data were used, how they were processed, who owned them, and how they contributed to organisational decision-making processes. The mapping relied primarily on structured discussions with stakeholders connected to functions such as product costing and load capacity. These discussions focused on understanding both process logic, including sequencing, timing, and handovers, and the level of system support in terms of tools, templates, and data availability.

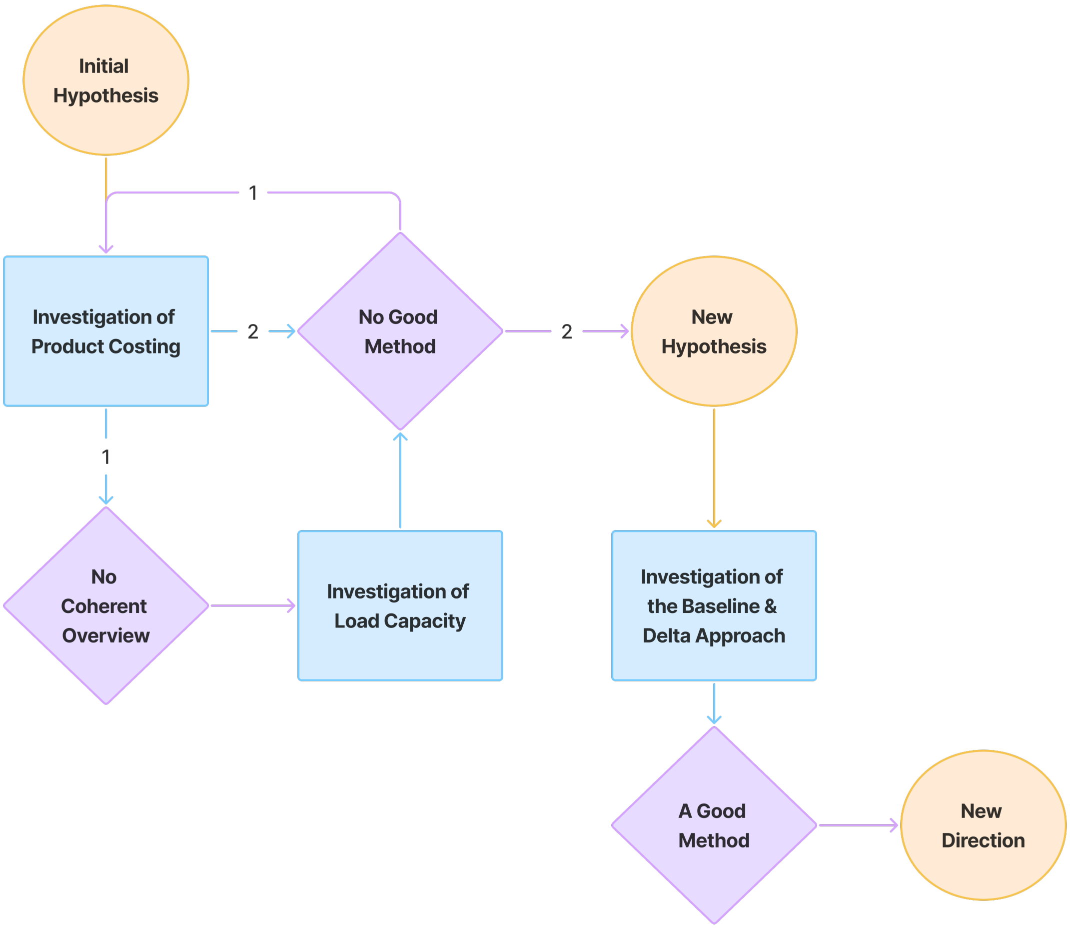

Figure 3.3: Illustration of the exploratory process mapping and methodological investigation leading to the selected approach used in this thesis.

The investigation initially focused on the product costing function, as illustrated in Figure 3.3. These discussions provided valuable insight into detailed operational activities and local uses of product data. However, the information was often described at a highly granular level and varied depending on the interviewee's role and responsibilities. As a result, it proved difficult to establish a coherent system-level understanding solely from these detailed descriptions.

To complement this perspective, attention was temporarily redirected towards the load capacity function, as illustrated in Figure 3.3. The discussions within this function provided a clearer overview of process structure, information flow, and decision logic. This offered a useful reference point for understanding how baselines are established and how results are communicated throughout project development.

Nevertheless, the mapping also indicated that the maturity and planning horizon of the load capacity workflow were not substantially more advanced than the potential sustainability-specific approaches under consideration. While the process itself was structured, it did not provide a sufficiently distinct framework that sustainability could adopt directly without major adaptation. This challenged the original assumption that long-established organisational functions would necessarily provide a substantially more mature model for early-phase environmental target setting.

Based on these findings, the mapping returned to the product costing function with a refined focus on identifying stakeholders with broader process ownership and cross-functional visibility. These follow-up discussions enabled the development of a more comprehensive understanding of how costing activities were intended to function across project phases, including key inputs, outputs, and governance structures. When comparing these perspectives, it became apparent that product costing and load capacity followed broadly similar approaches regarding timing, information flow, and dependence on available project data. Importantly, neither function consistently provided a ready-made framework that sustainability could adopt without significant modification.

This resulted in a revised methodological direction, as illustrated in Figure 3.3. Rather than attempting to integrate sustainability target setting directly into existing costing or load capacity workflows, the project shifted towards using existing sustainability programs and sustainability tool datasets as the primary basis for establishing references and defining environmental targets.

The rationale behind this shift was twofold. First, sustainability-specific tools already contained relevant environmental information maintained for other organisational purposes, thereby improving both data availability and consistency. Second, building upon existing sustainability systems was assessed to be less resource-intensive than adapting workflows from functions that would still require substantial translation and modification to support sustainability applications. Consequently, the project evolved from an initial “piggyback” strategy towards a sustainability-led approach that leveraged existing sustainability infrastructure while remaining compatible with broader project governance where appropriate.

In parallel with these organisational investigations, an exploratory technical workflow was also developed to examine how product configuration data could be structured and utilised within a potential environmental target-setting process.

The primary objective was to investigate how an adjusted reference Bill of Materials (BoM) could be constructed from the baseline BoM by incorporating known project changes while maintaining traceability and maximising the use of available data. The workflow focused on identifying unchanged parts that could be reused directly, modified parts requiring updates, and added or removed parts requiring further environmental assessment.

To reduce manual handling and improve repeatability, parts of the workflow were automated using Python scripting. This enabled structured screening of large datasets and supported the identification of changes likely to be environmentally relevant.

However, following the process mapping, the methodological direction shifted towards leveraging existing sustainability tools and datasets as the primary basis for baseline establishment and environmental target setting. Consequently, the workflow described above was not retained as the primary methodological backbone of the thesis.

Overall, the exploratory mapping phase and the associated technical investigations were important for testing assumptions, understanding organisational dependencies, and selecting a methodology proportionate to the available resources and practical constraints of a comparatively small organisational function.

The exploratory work also highlighted important practical and methodological challenges related to data maturity, system compatibility, and the need for automation when handling large and evolving product datasets. More importantly, the investigations clarified that the primary methodological challenge was not the absence of sustainability data itself, but rather how existing sustainability information could be integrated into a structured and repeatable workflow suitable for early-phase environmental target setting.

3.4 Combining LCIA Outputs and Sustainability Data

The shift in project direction following the initial process mapping resulted in a sustainability-led approach based on existing sustainability tools and datasets for constructing a reference LCA to support environmental target setting. Conducting full LCAs for early-phase project developments would be both time-consuming and associated with considerable uncertainty. Consequently, existing LCIA baseline results were used as the primary environmental reference.

The LCIA results were based on a BoM for a truck with a Start of Production (SoP) approximately six months in the future. As a result, the dataset had relatively high coverage, with only limited uncertainties related to the prospective nature of a small number of components. These LCIA results, therefore, served as the baseline configuration.

To estimate the environmental performance of future truck projects, delta values representing changes relative to the baseline configuration were incorporated, as illustrated in Figure 3.4.

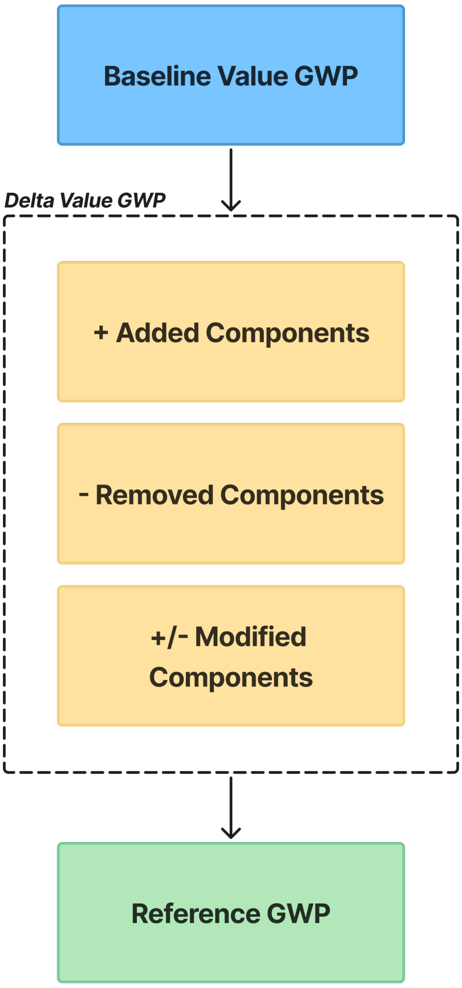

Figure 3.4: A chart depicting how the baseline LCIA GWP values were used as a basis with the sustainability tools adding, removing and modifying their GWP via delta values to attain a reference GWP.

The prospective projects considered in this thesis had SoP dates extending up to two years beyond the baseline configuration. Relevant project changes were identified through project documentation, while the corresponding delta values were obtained from concept documents derived from sustainability tool data.

These delta values represented both components removed from the baseline configuration and components introduced in their place. Although the baseline representation within the sustainability tools differed slightly from the LCIA baseline, it was considered sufficiently representative for calculating the deltas and supporting environmental target setting.

The resulting output consisted of a total vehicle GWP, representing the combined contribution of the baseline LCIA and the delta values, as illustrated in Figure 3.4.

The results were generated both as a fully aggregated vehicle-level value and as disaggregated values corresponding to different parts of the vehicle structure. To support this spatial representation, the datasets included hierarchical classification codes describing the position of each component within the truck structure.

Figure 3.5 conceptually illustrates the hierarchical classification structure.

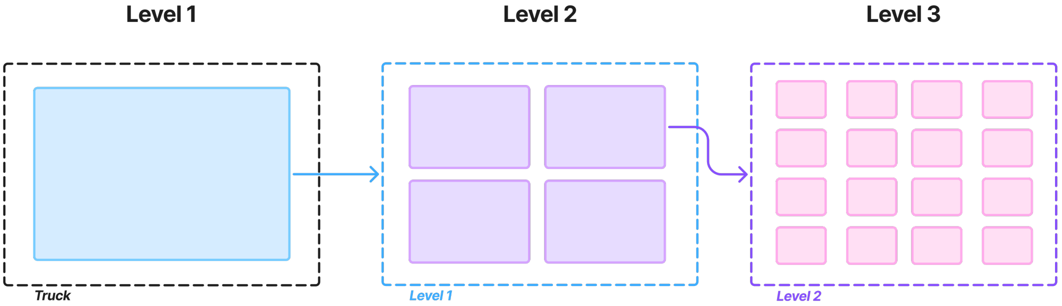

Figure 3.5: An illustration of the hierarchical levels used to classify the data. Level 1 corresponds to a system, Level 2 a subsystem and Level 3 depicts a component. A classification code on Level 3 inherently includes Level 1 and Level 2.

The classification system followed three hierarchical levels, illustrated in Figure 3.5, corresponding to the product structure of the vehicle: system, subsystem, and component. These levels are referred to as Level 1, Level 2, and Level 3, respectively. The classification codes consist of numerical identifiers representing the spatial placement of concepts, items, or components within the truck structure.

Aggregating and disaggregating results across these hierarchical levels enabled the localisation of environmental impact hotspots within the vehicle, thereby supporting more targeted environmental target setting and interpretation of project-specific changes.

While the resulting reference does not constitute a complete LCA due to limitations in time, data maturity, and resource availability, combining a baseline LCIA with structured delta updates provides an approximation considered sufficiently robust for early-phase environmental target setting under the given industrial constraints.

Similar to section 3.3, the methodology distinguished between two configurations: the baseline configuration and the reference configuration. The baseline represents the initial LCIA dataset, while the reference configuration represents the updated environmental performance after incorporating project-specific delta values.

The following subsections describe the methodological workflow used to combine the baseline LCIA data with sustainability tool deltas in order to construct the reference LCA for the case study. AI tools were occasionally used to explore alternative data-handling approaches during methodology development, but did not influence the final analytical procedures.

3.4.1 Adjustment and Handling of the Initial Data

The initial dataset consisted of one LCIA output representing the baseline configuration, together with four datasets representing individual development projects. In total, five spreadsheet-based input files were used. The original baseline dataset was used directly, while copies of the project datasets were created to allow manual preprocessing while preserving the integrity of the source data.

The baseline dataset did not require manual modification and was therefore retained in its original form. This also enabled the establishment of live-links to the source dataset, allowing updates in the source file to propagate automatically to the final output when refreshing the data connections.

Following the collection of the project datasets, an initial screening was conducted to determine whether all concepts and items were relevant to the specific vehicle configuration studied in this thesis, namely a BEV truck. During this screening, rows corresponding to Internal Combustion Engine (ICE)-specific components were removed from several datasets.

The screening process also included verification of whether hierarchical classification codes had been assigned to all concepts and items. Only one project dataset initially contained such codes, and only at Level 1.

Consequently, additional work was required to assign appropriate hierarchical classification codes at the lowest possible level of detail. Where part numbers were available, internal databases were used to identify the corresponding classification codes. In cases where part numbers were unavailable, a reference guide containing code descriptions was consulted. Remaining uncertainties were resolved through consultation with internal expertise.

As a result of this process, all concepts and items in the four project datasets were assigned Level 3 codes corresponding to the component level of the hierarchical structure. Since Level 3 inherently includes the higher levels of system and subsystem classification, the datasets achieved a high degree of spatial resolution. Consequently, all input datasets contained the required classification information for the subsequent data processing and merging workflow.

3.4.2 Processing and Merging of the Data

Since all input datasets were provided in spreadsheet format and the objective of the thesis was to develop a repeatable methodology, spreadsheet-based data handling was applied throughout the study. In particular, Excel Power Query was used to establish structured data connections between source datasets and output workbooks. This enabled live-linked workflows, where updates in the source files could be propagated through refreshable queries, thereby reducing the need for repeated manual processing.

An important consideration during this process was that the sustainability tool outputs used for deriving delta values were not fully standardised across projects. Variations in data structure, level of detail, and included parameters required a flexible and adaptable data-handling approach. Consequently, a fully automated and rigid scripting solution was not considered suitable within the scope of this thesis. Instead, a semi-structured workflow based on Power Query was adopted, combining repeatability with the flexibility to manage project-specific variations and iterative adjustments. This also highlighted the importance of future standardisation efforts for improving interoperability and automation within sustainability assessments.

Figure 3.6 depicts the merging processes for the methodology in Excel Power Query.

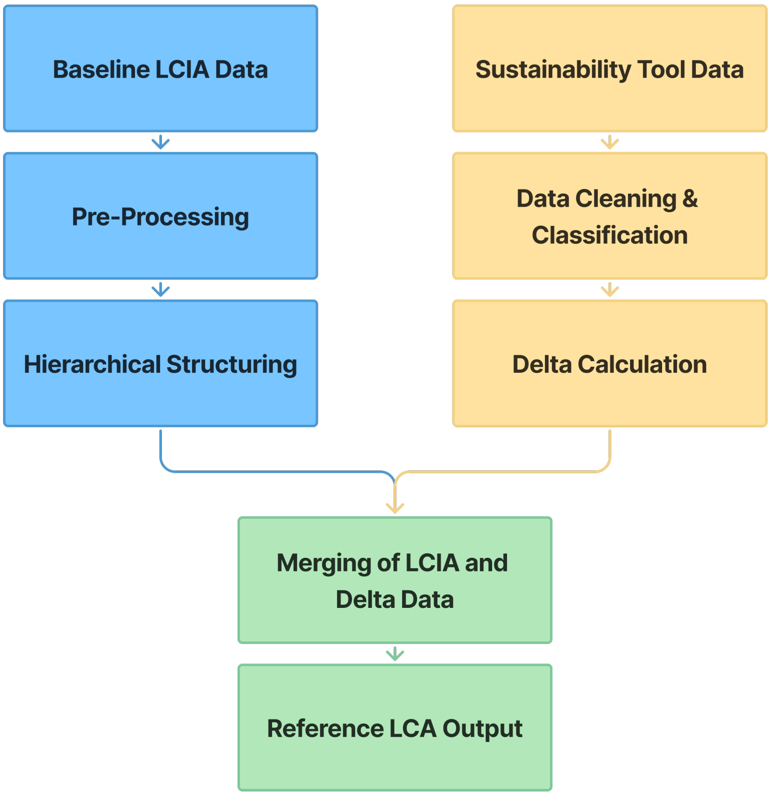

Figure 3.6: An illustration of the three main steps when merging the Baseline LCIA with sustainability tool data to attain a reference LCA for target setting.

The merging workflow consisted of three main stages, as illustrated in Figure 3.6. First, the baseline dataset was processed. Second, the delta datasets originating from the sustainability tools were processed. Finally, the datasets were merged to construct the reference LCA at each hierarchical level.

A dedicated workbook named *Reference* was created to manage the workflow. Power Query connections were established to both the baseline dataset and the project-specific sustainability datasets. From these datasets, relevant information such as hierarchical classification codes, GWP values, material information, and material weight was extracted.

To support hierarchical analysis, the classification codes were separated into three levels representing system, subsystem, and component structures. The datasets were subsequently grouped according to the relevant hierarchical level, enabling aggregation of environmental impacts and associated information at Level 1, Level 2, and Level 3.

For the project datasets, delta values were calculated by comparing baseline and reference GWP values. Additional information related to Recycled Content (RC) and Substances of Concern (SOC) was also retained where available. Although these parameters were not directly included in the analysis, they were preserved to support future target-setting discussions and sustainability evaluations.

After preprocessing, the baseline and project datasets were merged using append operations within Power Query. The merged datasets were subsequently regrouped by hierarchical classification code to ensure consistent aggregation and unique entries for each level of analysis. This resulted in consolidated datasets representing the combined baseline and delta-adjusted reference LCA structures.

The workflow was repeated for all three hierarchical levels before the final datasets were loaded into the workbook for subsequent analysis. Although the process remained semi-structured and required limited manual adjustments, the workflow demonstrated how large and evolving sustainability datasets could be integrated into a transparent and repeatable methodology suitable for early-phase environmental target setting.

3.5 Extracted and Generalised Methodology

Based on the implementation described in the previous section, a generalised methodology for constructing reference LCAs for future truck projects was derived. The purpose of the methodology is to enable systematic aggregation and comparison of LCIA data from multiple truck projects in order to generate a representative reference LCA suitable for early-phase environmental target setting.

Although the methodology was developed through a single case study, it relies on structured LCIA datasets and hierarchical classification systems commonly used within product development environments at Volvo Group. The following section presents the extracted methodology as a sequence of generalised workflow steps applicable to future projects.

3.5.1 Workflow

The methodological workflow is illustrated in Figure 3.7, with detailed step descriptions provided below. The figure presents the workflow at a higher conceptual level, while the subsequent descriptions explain the corresponding methodological stages in greater detail.

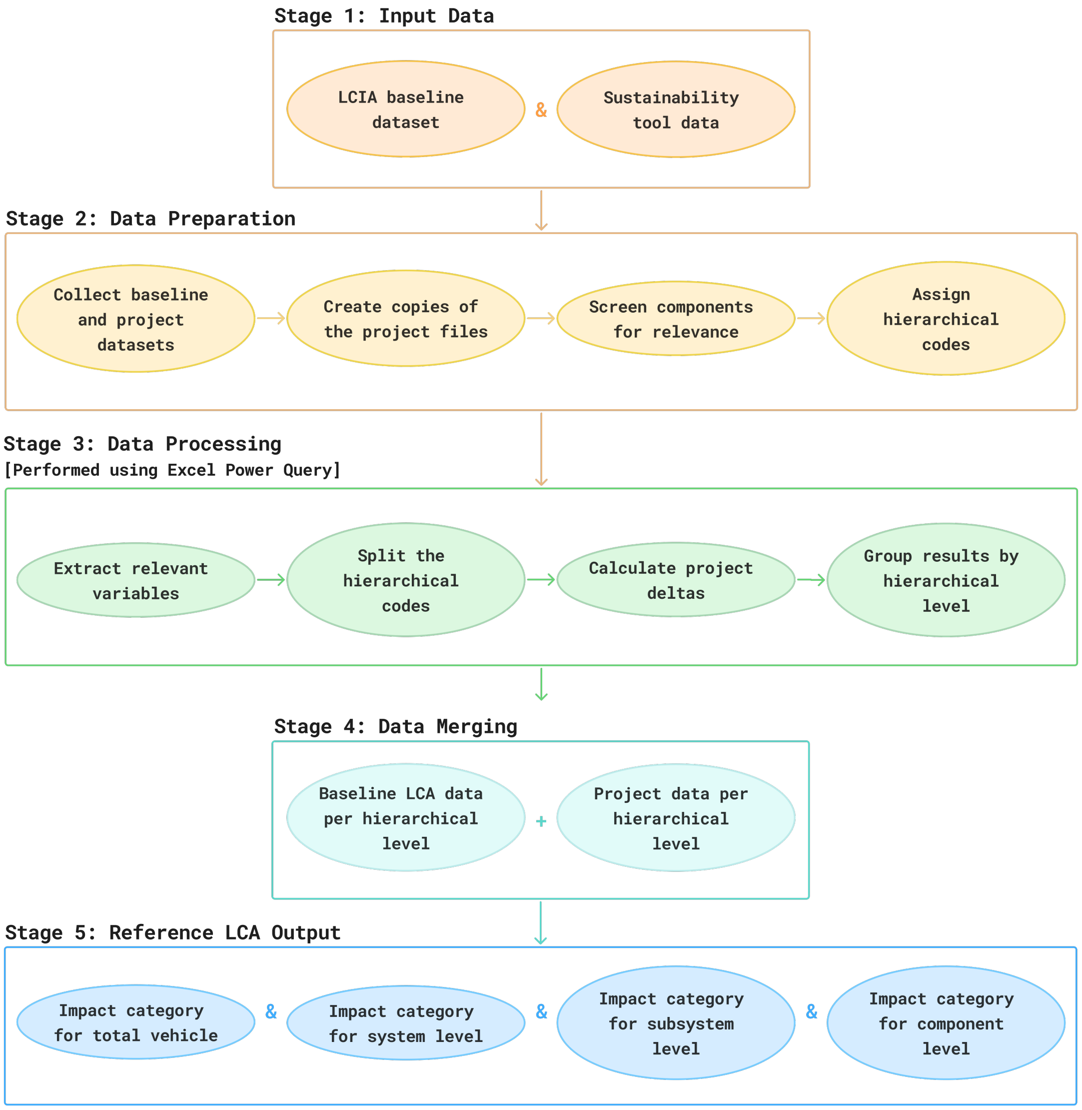

Figure 3.7: An illustration of the methodological flow of the extracted and generalised methodology.

Stage 1: Input Data

The methodology requires two primary types of input data: a baseline LCIA dataset representing the baseline vehicle configuration and project-specific datasets derived from sustainability tools. Each dataset should contain environmental impact indicators (e.g., GWP values) linked to individual components together with hierarchical classification codes describing their position within the vehicle structure.

To preserve data integrity and support repeatability, data connections to the source files should be established within the processing environment. For example, tools such as Excel Power Query may be used to create refreshable data connections without modifying the source datasets.

Stage 2: Data Preparation

The collected datasets should be screened to ensure relevance, completeness, and consistency. This includes verifying that all entries contain complete hierarchical classification codes and removing or correcting entries not relevant to the studied vehicle configuration, for example, BEV- or ICE-specific components.

Where classification codes are missing or incomplete, they should be reconstructed using available documentation, internal databases, or expert input. Ensuring complete and consistent classification information is necessary to support reliable aggregation across different hierarchical levels.

Stage 3: Data Processing

Following the preparations, the datasets should be structured and standardised within a suitable data-processing environment such as Excel Power Query. This includes separating the hierarchical classification codes into different levels representing the product structure, for example, system, subsystem, and component levels.

To support analysis at multiple levels of detail, separate datasets or queries should be established for each hierarchical level. Within each level, the data should be grouped according to the relevant classification code to ensure one unique entry per code. Numerical parameters, such as GWP values and material weight, should be aggregated through summation, while text-based information may be retained where relevant to preserve contextual information.

For each project dataset, environmental impact differences between the reference configuration and the baseline configuration should be calculated to derive delta values. These deltas represent the environmental changes introduced by the project-specific modifications.

To improve traceability, identifiers such as change flags may also be included to distinguish modified entries from unchanged content. The structured project datasets should subsequently be grouped according to the same hierarchical levels and procedures applied to the baseline dataset.

Stage 4: Data Merging

The processed baseline dataset and grouped project datasets should then be combined within the same processing environment. This may be achieved by appending datasets corresponding to each hierarchical level while maintaining consistent column structures and naming conventions.

Following the append operation, the combined dataset should be regrouped according to the hierarchical classification codes to ensure one unique entry per code. During this aggregation process, baseline values and project deltas are combined to generate updated environmental impact values representing the reference configuration.

Stage 5: Reference LCA Output

The final output consists of a reference LCA dataset with environmental impacts aggregated at multiple hierarchical levels, for example, system, subsystem, and component levels. Separate outputs may be generated for each level to support analysis at different resolutions.

The resulting dataset provides a structured representation of the environmental impact distribution across the vehicle while incorporating contributions from multiple development projects. By maintaining refreshable connections to the original datasets, the reference LCA can be updated efficiently as new information becomes available, thereby supporting continuous benchmarking and environmental target setting throughout future project development.

3.6 Use of AI Tools

Throughout this thesis, AI-based tools were used as supportive instruments during several stages of the research and writing process. The tools were primarily used to support brainstorming, report structuring, language refinement, and methodological reflection. All AI-generated suggestions were critically evaluated by the authors, modified where necessary, and incorporated only after manual review. Consequently, the authors retain full responsibility for all content presented in the thesis. The specific areas in which AI tools were used are described below to ensure transparency.

Brainstorming and ideation:

AI tools were used during early-stage brainstorming activities related to the research topic and the overall direction of the thesis. This included exploring potentially relevant theoretical perspectives, identifying possible research angles, and discussing alternative approaches to methodological and analytical challenges. AI tools were also used to support the identification of potentially relevant literature, which was subsequently reviewed and evaluated manually by the authors.

Report structuring:

AI tools were used to support the development of the report structure, including preliminary chapter outlines, subsection organisation, and suggestions related to the overall logical flow of the thesis. These suggestions were used only as supportive input during the structuring process.

Writing support:

During the writing process, AI tools were used for proofreading and language refinement. This included improving readability, clarity, grammar, and academic tone in text originally written by the authors. In some cases, alternative wording and phrasing suggestions were explored to improve linguistic precision and readability. All modifications were reviewed and approved manually before inclusion in the thesis.

Methodological reflection and data-handling support:

AI tools were occasionally used as reflective discussion partners when considering possible methodological approaches and data-handling strategies. These interactions supported exploration of alternative perspectives and potential workflow structures. However, all methodological decisions, analytical procedures, and data-processing activities were designed and conducted by the authors.

Confidentiality and anonymisation:

AI tools were also used to support the reformulation and generalisation of methodological descriptions to ensure that confidential information covered by non-disclosure agreements (NDAs) was not disclosed. This included assisting in anonymising operational details and generalising descriptions of internal organisational processes.

Explicit limitations of AI use:

AI tools were not used for:

- Generating empirical data used in the study
- Conducting the primary data analysis
- Performing data-processing steps included in the results
- Independently interpreting research findings or determining the implications

of the results

- Formulating the conclusions of the thesis
- Making independent methodological decisions regarding the research design

Overall, AI tools were used strictly as supportive instruments throughout the research and writing process. All research design decisions, data collection, data processing, analysis, interpretation of results, and conclusions presented in the thesis were carried out by the authors. Any AI-generated suggestions incorporated into the thesis were critically reviewed and assessed prior to inclusion.

4

Results and Analysis

This chapter presents the results of the case study from which the generalised methodology was developed. While the results are primarily case-specific and should be interpreted in the context of the studied system, several findings offer broader insights relevant beyond the case, particularly regarding the methodology's applicability and performance.

The results begin with a presentation of the hotspot and contribution analyses across all three hierarchical levels. This is followed by a change analysis based on the derived delta values, highlighting how modifications are distributed within the system. The hotspots and changes are then evaluated together. Subsequently, results related to structural insights from the hierarchical aggregation are presented. Finally, the chapter concludes with an assessment of sensitivity, uncertainty, and robustness, providing insight into the reliability and limitations of the results.

4.1 Hotspot and Contribution Analysis

This section presents the distribution of climate impact across the hierarchical levels in order to identify major contributors to the total vehicle GWP. These contributors are subsequently referred to as hotspots, as they represent areas with the highest potential for impactful emission reductions.

Figure 4.1 illustrates all the contributors to GWP at the highest hierarchical level (Level 1), corresponding to the system level of the vehicle.

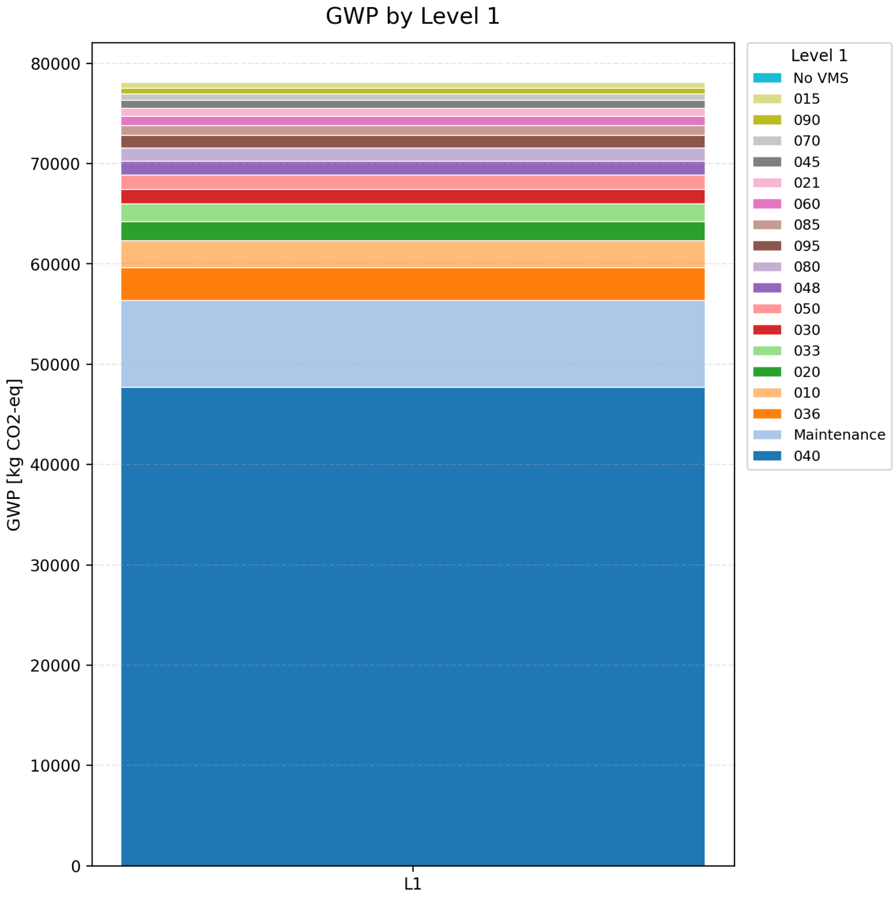

Figure 4.1: The chart shows all contributors to GWP at Level 1 (system level) in size order, highlighting how emissions are distributed across major vehicle systems.

The results in Figure 4.1 show a highly uneven distribution of emissions, where a limited number of systems account for a substantial share of the total impact. For instance, system 040 alone contributes almost 48 tonnes of CO2-eq out of a total of circa 78 tonnes. This indicates a strong concentration of emissions within a few dominant systems.

This pattern is characteristic of hotspot-driven systems, where the majority of the environmental impact is governed by a small subset of systems. From a methodological perspective, this validates the relevance of hotspot analysis for early-phase target setting, as focusing on a limited number of systems can yield large reductions in overall impact.

While the Level 1 analysis provides an overall system perspective, it does not reveal which specific subsystems drive the observed impacts. Increasing the level of detail, therefore, allows for a more refined identification of emission sources.

At a more detailed level, Figure 4.2 presents the corresponding results for Level 2 (subsystem level).

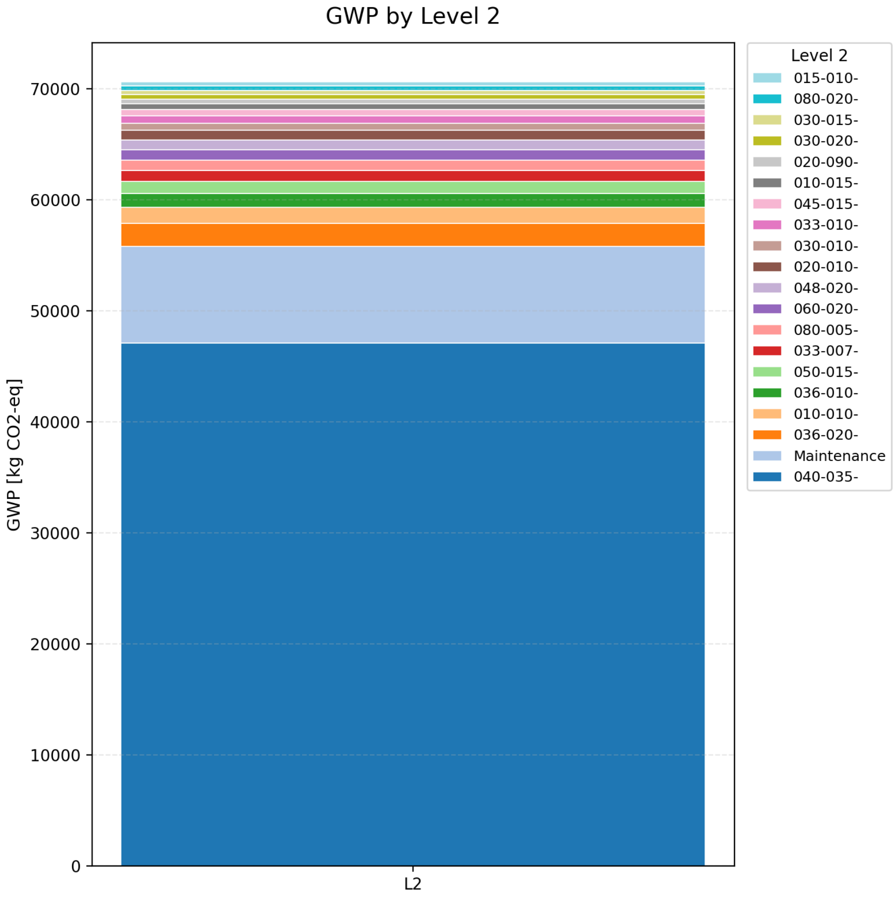

Figure 4.2: A chart illustrating the 20 largest contributors to GWP at Level 2 (subsystem level), providing a more detailed breakdown of the main systems.

The disaggregation reveals a more granular distribution of emissions, where contributions are divided across a larger number of subsystems. While the general concentration pattern remains, the results show that some systems identified as hotspots at Level 1 consist of multiple subsystems with varying contributions.

Further disaggregation at Level 3, as shown in Figure 4.3, enables a detailed examination of subsystems identified at Level 2.

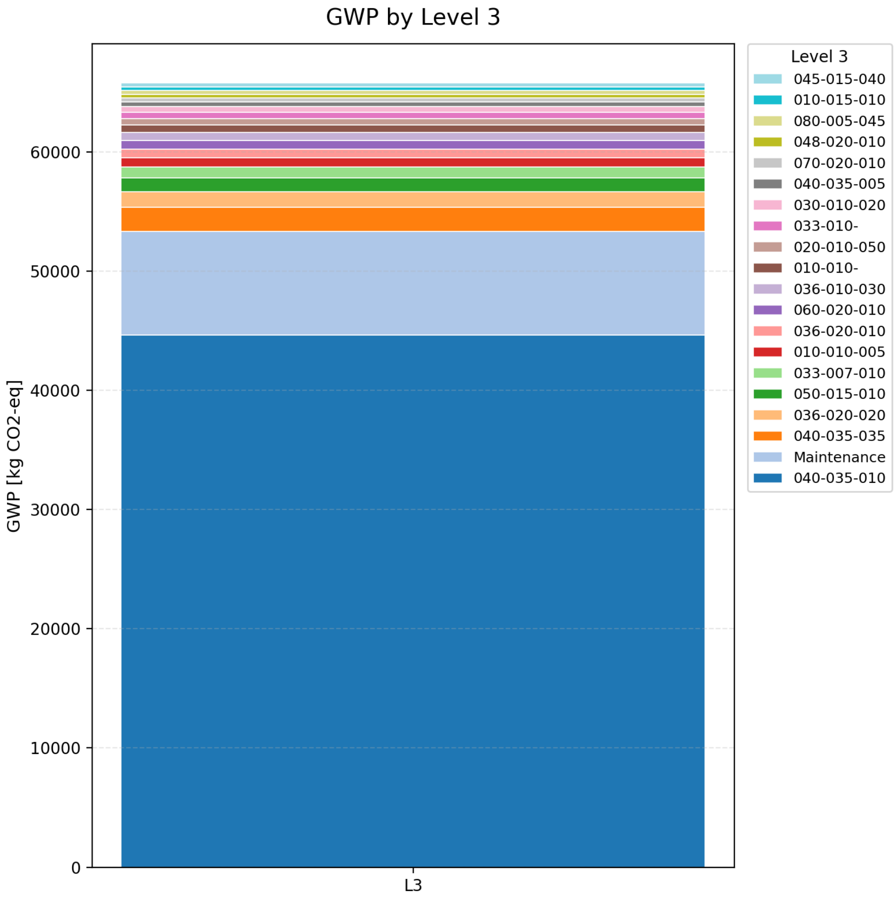

Figure 4.3: A chart showing the 20 largest contributors to GWP at Level 3 (component level), identifying the most impactful individual components.

At Level 3, individual components emerge as the primary drivers of emissions within their respective subsystems. These results suggest that climate impact is not a general property of the vehicle but is instead governed by a few critical hotspots, notably the ESS (040-035-010). This concentration indicates that overall environmental performance is disproportionately sensitive to a small subset of design choices, meaning that strategic interventions in these specific areas could yield significantly higher GWP reductions than widespread changes in low-impact systems.

Together, the three levels illustrate how the identification of hotspots evolves with increasing resolution, from system-level dominance to component-level drivers. At higher levels, entire systems appear dominant, whereas more detailed levels reveal that specific subsystems and components drive the majority of emissions.

In particular, the chassis system (040), including the energy system (040-035) and ESS (040-035-010), consistently dominates the total GWP. This indicates that a small subset of the vehicle structure largely determines overall environmental performance. From a results perspective, this confirms that climate impact is not evenly distributed across the vehicle, but rather governed by a few hotspot elements. Consequently, analysing results at multiple hierarchical levels is essential to avoid both overgeneralisation at higher levels and loss of strategic overview at lower levels.

In addition to the ESS, maintenance-related activities also constitute a major contributor to total GWP across the analysed configurations. Although the ESS remains the dominant hotspot, the consistently high contribution associated with maintenance indicates that lifetime service assumptions and replacement-related activities represent environmentally significant processes within the overall vehicle lifecycle. This highlights that substantial environmental impacts are not exclusively linked to primary production systems, but may also originate from recurring operational and maintenance-related processes throughout the vehicle's lifetime.

4.2 Change and Delta Analysis

This section examines how the environmental performance changes between the baseline and reference configurations by analysing the distribution and magnitude of delta values. While the hotspot analysis identifies where emissions are concentrated, the delta analysis provides insight into where and how changes occur within the system. Together, these perspectives enable a more comprehensive understanding of both the static impact distribution and the dynamic evolution of the system.

Before presenting the illustrative results, the total value of the deltas for the case project was -766 kg CO_2-eq, meaning a reduction in GWP compared to the baseline. Thus, the resulting reference, which serves as the baseline for the new project, has already undergone some reductions.

Figure 4.4 presents all changes in GWP at Level 1.

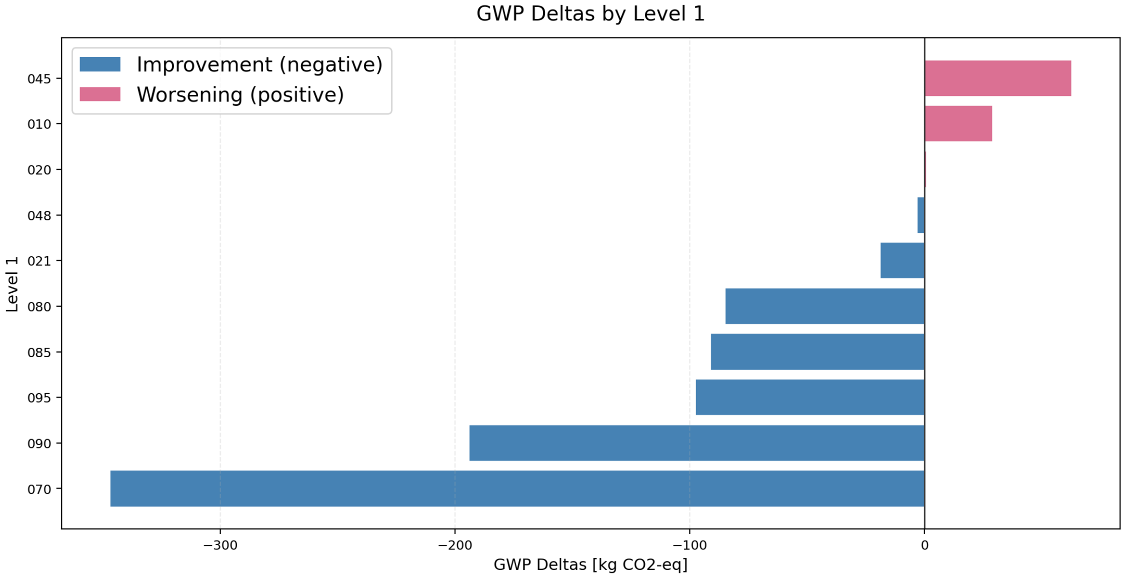

Figure 4.4: Illustration of the changes in GWP in absolute values at Level 1 (system level).

The results in Figure 4.4 show that both positive and negative changes are present, indicating that some systems increase while others decrease in climate impact relative to the baseline. The magnitude of these changes varies considerably, with a small number of systems exhibiting large deviations, while the majority show relatively minor adjustments.

This pattern is further illustrated in Figure 4.5, which shows the distribution of delta magnitudes at Level 1.

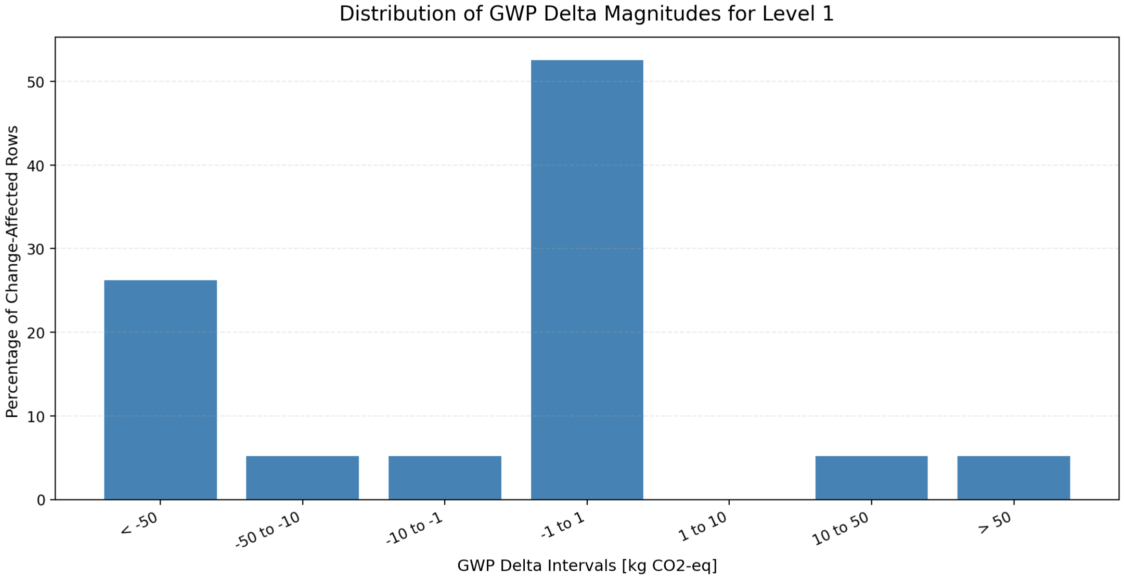

Figure 4.5: A distribution chart showing the magnitude of changes in GWP at Level 1, indicating how most changes are concentrated near zero.

The distribution is characterised by a high concentration of values near zero, combined with a limited number of larger deviations. This suggests that most systems undergo only minor changes, while a small subset of modifications drives the overall difference between baseline and reference configurations.

The aforementioned patterns remain consistent across increasing levels of detail. While the Level 1 results highlight overall changes at the system level, they do not capture how these changes are distributed across subsystems. A more detailed analysis is therefore required to identify where the most significant variations occur.

At the subsystem level, Figure 4.6 shows the corresponding delta results for Level 2, but only for the 20 largest changes due to graph readability concerns.

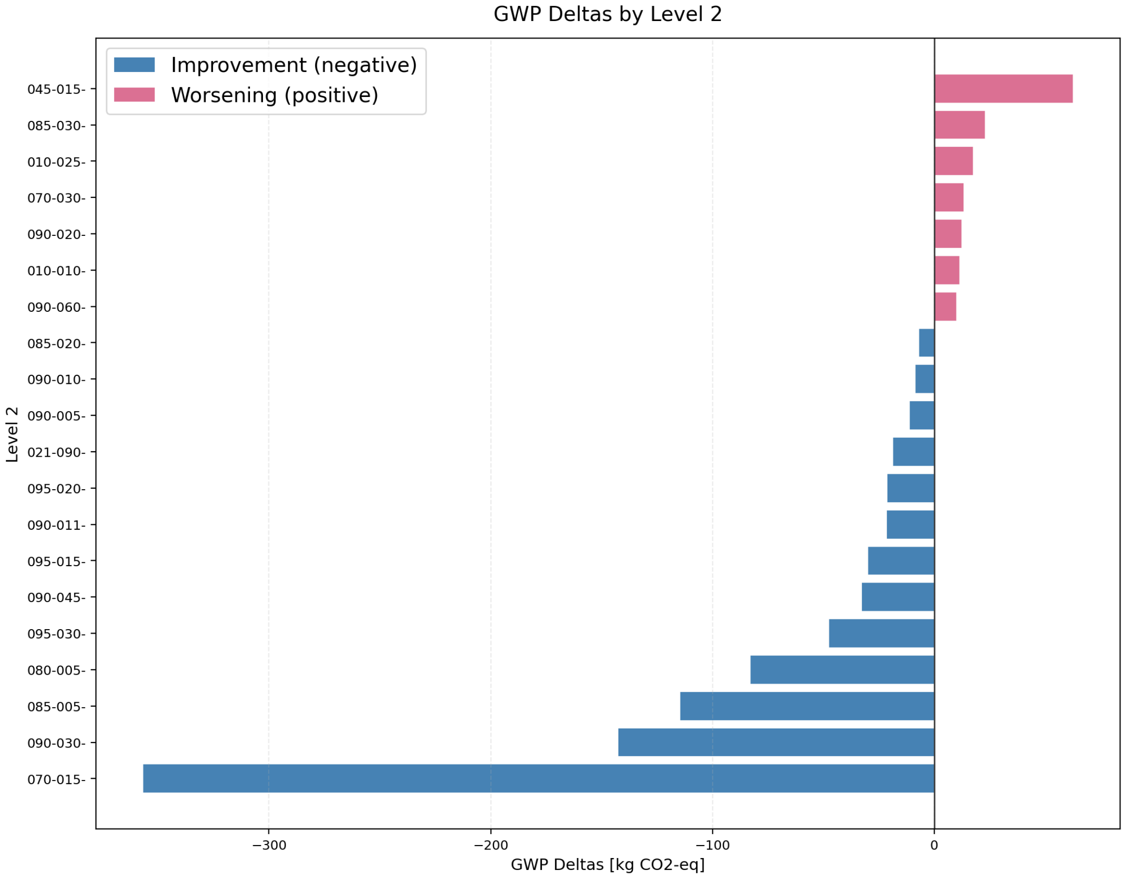

Figure 4.6: An illustration of the 20 largest changes in GWP in absolute values at Level 2, showing variations at the subsystem level.

The increased level of detail reveals a larger number of individual changes, but the overall pattern remains consistent. Most subsystems exhibit small changes, while a limited number contribute disproportionately to the total variation.

Figure 4.7 shows the distribution of delta magnitudes at Level 2.

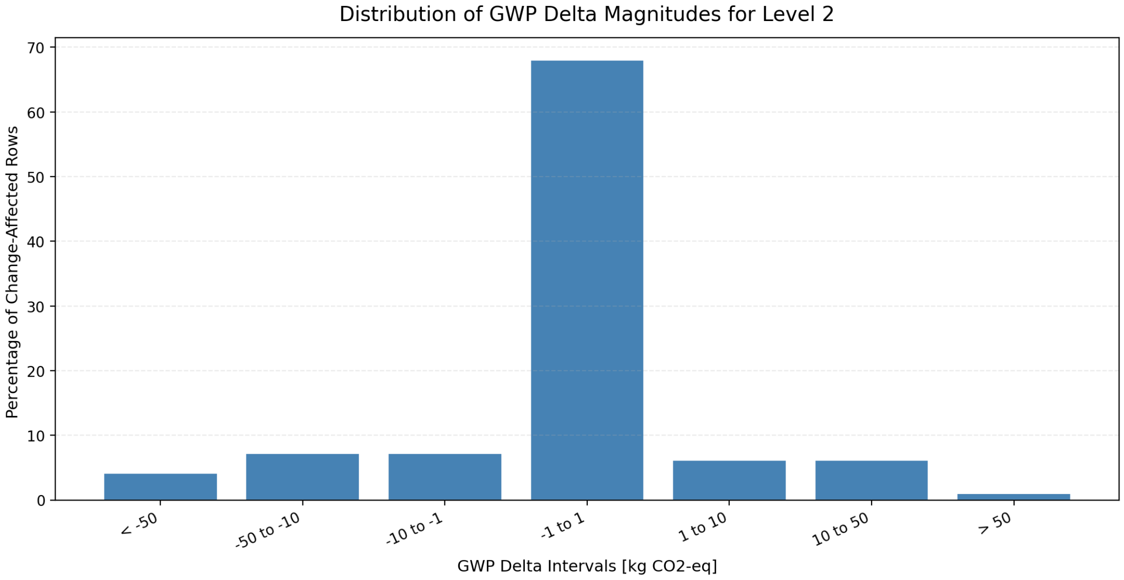

Figure 4.7: A distribution chart depicting the magnitude of changes in GWP at Level 2, highlighting the concentration of low-magnitude changes.

Similar to Figure 4.6, Figure 4.7 strengthens the interpretation of a skewed distribution with a concentration of small values and a tail of larger deviations. This reinforces the observation that changes are not uniformly distributed across the vehicle structure.

At Level 3, the analysis further resolves the changes observed at Level 2, enabling the identification of specific components responsible for the largest deviations. Figure 4.8 presents the 20 largest component-level changes, while Figure 4.9 shows their distribution.

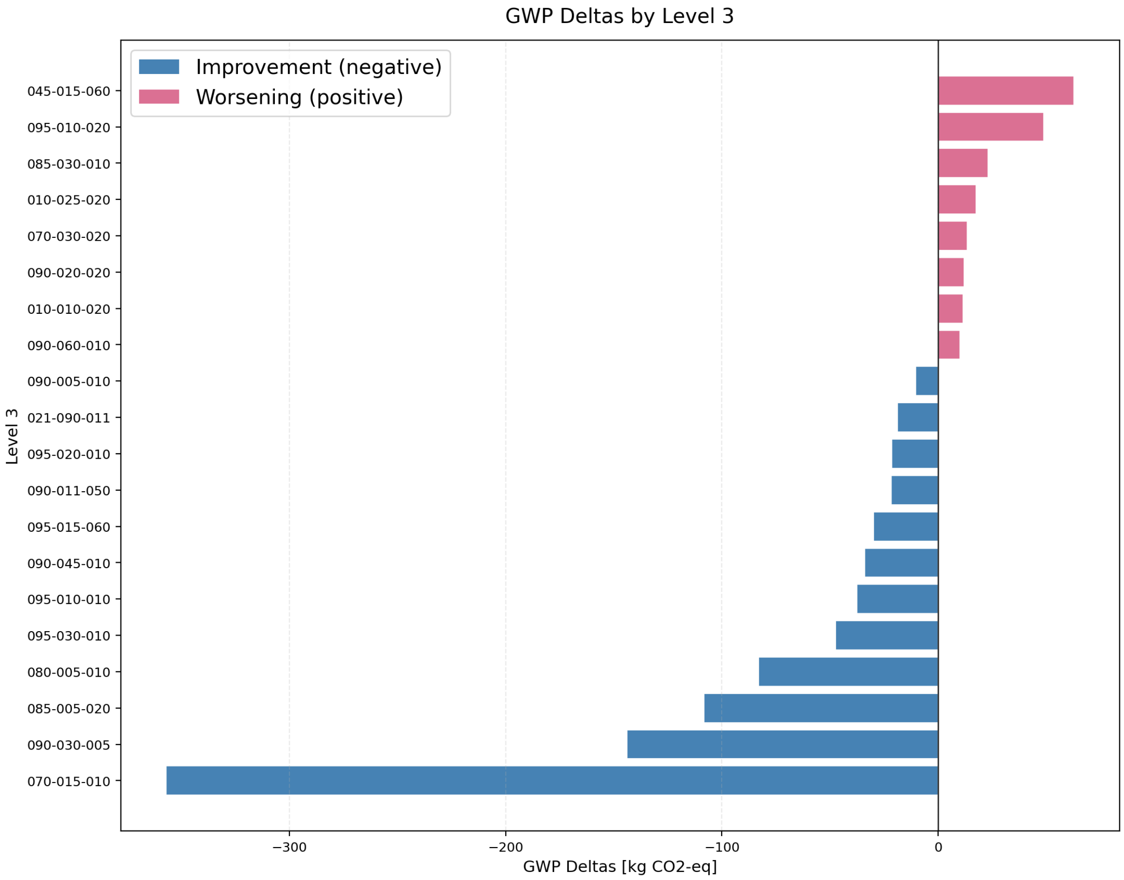

Figure 4.8: A chart illustrating the 20 largest changes in GWP in absolute values at Level 3, highlighting the most affected components.

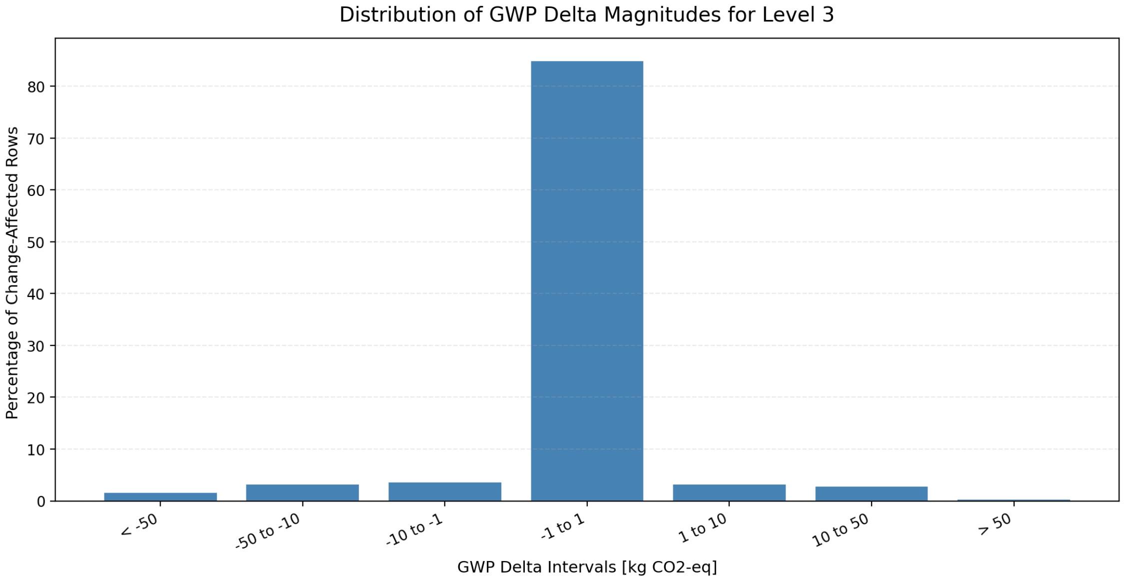

Figure 4.9: A distribution chart showing the magnitude of changes in GWP at Level 3, depicting further concentration on the component level.

The results confirm that a small number of components are responsible for the largest changes in climate impact. This suggests that the overall change between baseline and reference configurations is driven by specific component-level modifications rather than widespread adjustments across the system.

Overall, the delta analysis shows that changes in climate impact are unevenly distributed across the system. While most vehicle elements remain stable, a limited number of modifications drive the majority of the total change. Critically, these large changes do not systematically occur in the high-impact hotspots identified in Section 4.1. This divergence highlights a leverage gap where the systems currently undergoing the most significant changes are not the systems with the highest emissions. This suggests that the current drivers of change are likely functional priorities, such as weight or cost, rather than explicit environmental optimisation.

4.3 Linking Hotspots and Changes

A comparison between the hotspot analysis and the delta analysis reveals a weak alignment between the locations of the highest emissions and the areas where the largest changes occur. While hotspots identify where emissions are concentrated, delta analysis shows where modifications are implemented. This mismatch indicates that high-impact systems are not necessarily the primary focus of ongoing changes. At the same time, the results suggest that changes occurring outside major hotspots may still contribute to emission reductions, particularly when they are easier to implement from a design perspective.

Together, these findings highlight the importance of combining hotspot and delta analyses to capture both the current impact distribution and the direction of system changes.

Figure 4.10 further illustrates the relationship between baseline GWP and net change in GWP for each system.

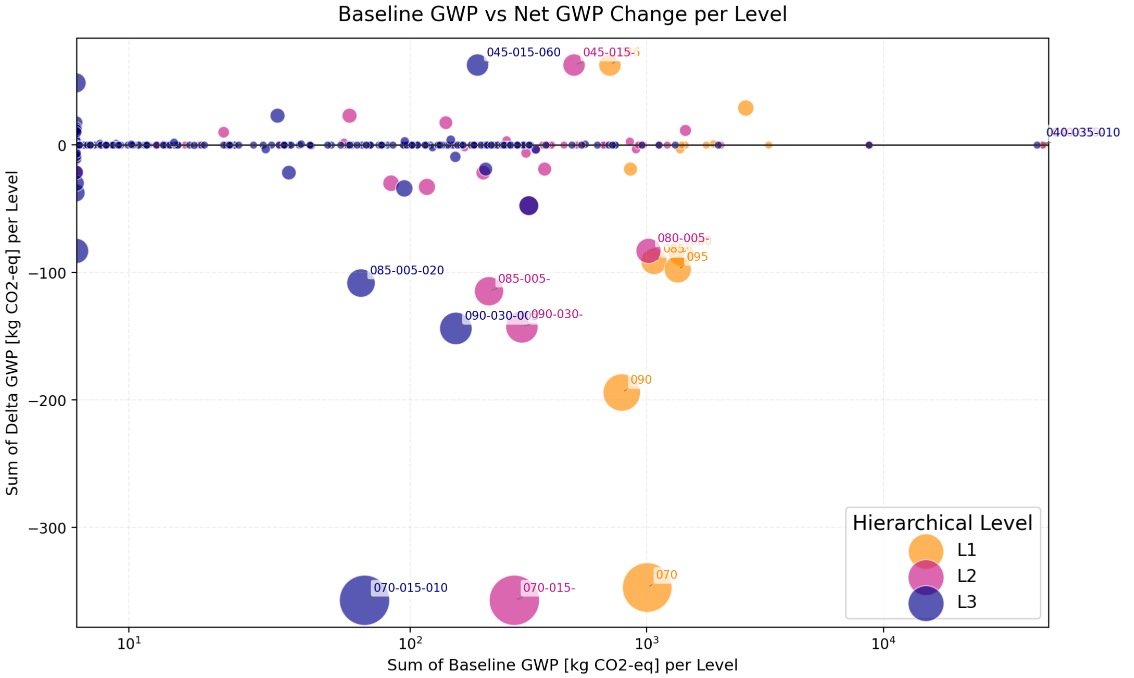

Figure 4.10: A scatter plot illustrating the relationship between baseline GWP and net change in GWP for each hierarchical level, highlighting a non-linear relationship. The size of the points is connected to the absolute value of the delta GWP to maximise chart visibility.

The results show no clear linear correlation between baseline impact and the magnitude of change, as previously discussed. This non-linear relationship serves as a primary analytical finding, revealing that without a structured target-setting mechanism that explicitly links hotspots to project deltas, environmental improvements will remain incidental secondary outcomes rather than intentional design goals.

4.4 Structural Insights from Hierarchical Aggregation

This section examines how the hierarchical structuring of the data influences both the interpretation of results and the identification of environmental impact patterns. By comparing results across different levels of aggregation, it becomes possible to understand how data resolution affects both hotspot identification and change detection. In particular, this analysis provides insight into whether observed patterns are structural and therefore consistent across levels, or artefacts of aggregation.

Figure 4.11 shows the percentage change in GWP at each hierarchical level.

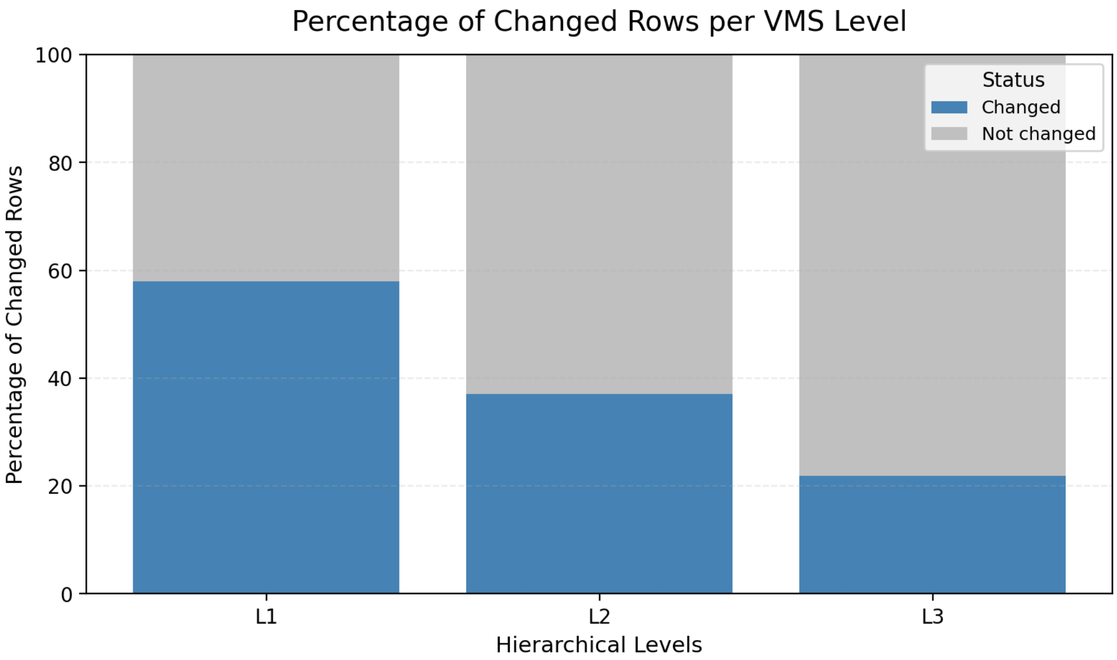

Figure 4.11: A division chart illustrating the percentage of data rows affected by the deltas on all three hierarchical levels. It highlights the importance of studying different levels of granularity.

The results indicate that the magnitude of change varies depending on the level of aggregation, reflecting how impacts are distributed across systems, subsystems, and components. This suggests that aggregation influences not only the representation of results but also the interpretation of relative changes. Thus, Figure 4.11 demonstrates that the interpretation of both hotspots and changes is inherently dependent on the chosen level of aggregation, which should therefore be carefully selected based on the intended use of the results.

From a methodological perspective, these findings demonstrate that the selected aggregation level directly influences which hotspots and changes become visible in the analysis. Consequently, the choice of hierarchical resolution is not merely a presentation decision, but an analytical decision that affects how environmental priorities are identified and interpreted during target setting.

4.5 Sensitivity, Uncertainty and Robustness

The incorporation of project-specific delta values introduces uncertainty into the reference LCA since the project-specific changes are prospective. However, the results indicate that the overall environmental structure of the vehicle remains comparatively stable despite these additions. This is particularly visible at the higher aggregation levels, where the dominant contributors to climate impact remain largely unchanged between the baseline and the reference configuration.

Figure 4.12 illustrates the comparison between the baseline and reference GWPs

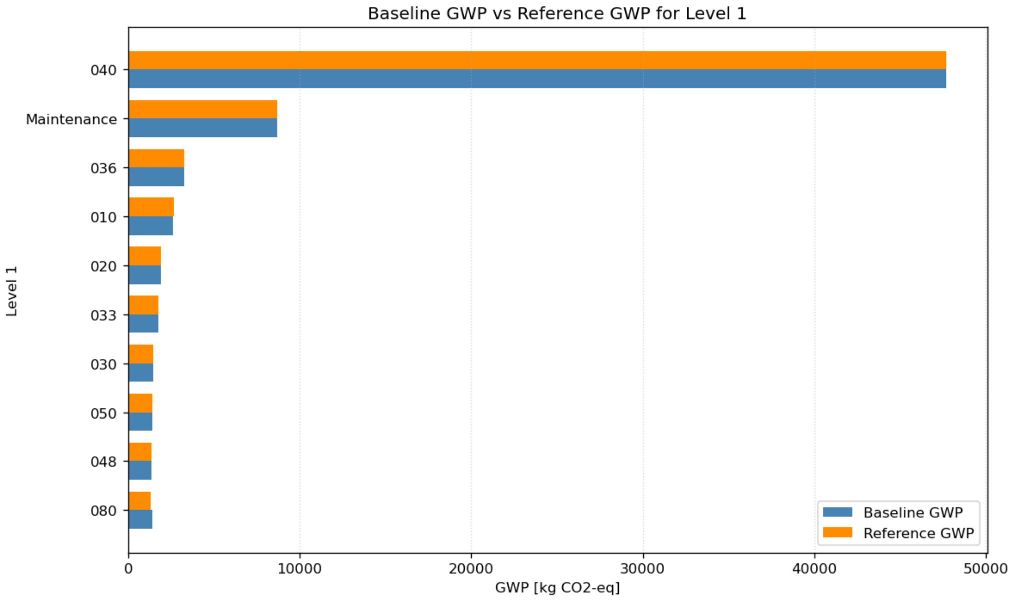

Figure 4.12: Comparison of the baseline GWP and the reference GWP across Level 1 systems, illustrating how project deltas modify the reference minimally in comparison to the baseline, while largely preserving the main hotspot structure.

Figure 4.13 depicts the top rank changes between the baseline and the reference cases.

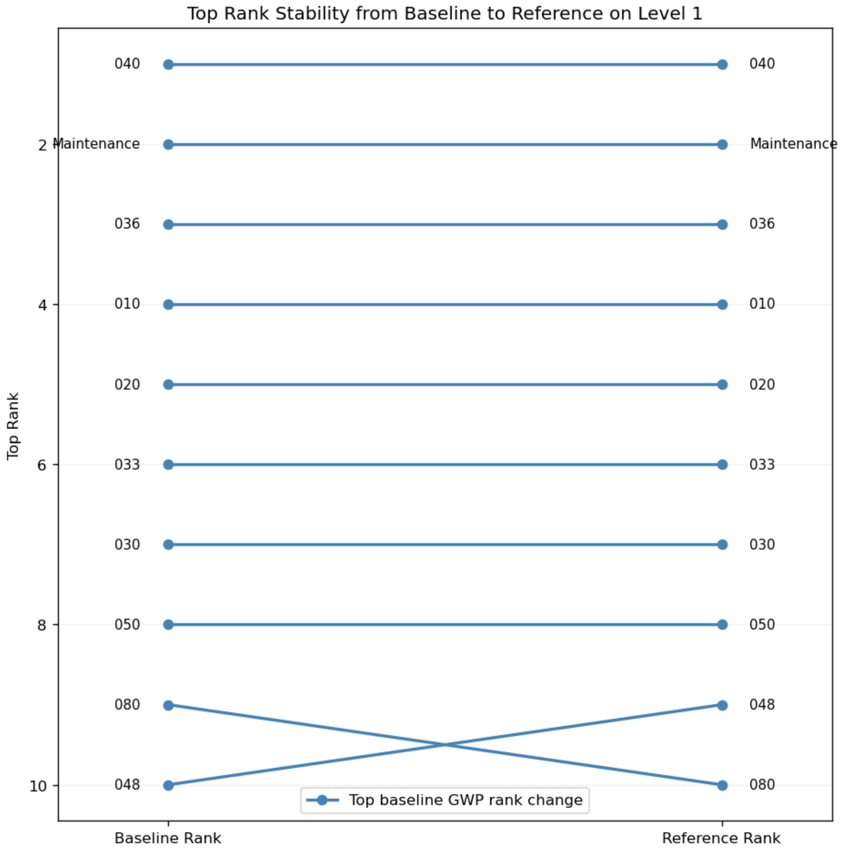

Figure 4.13: Top GWP rank comparison between baseline and total GWP contributions at Level 1, illustrating that the main hotspot ranking remains largely stable after incorporating project-specific delta values.

Figures 4.12 and 4.13 demonstrate that the main hotspot ranking is only marginally affected after incorporating the project deltas. In particular, the ESS remains the dominant contributor to total GWP across both configurations. This suggests that the overall hotspot structure is relatively robust even when prospective assumptions are introduced. Consequently, the methodology appears sufficiently stable for early-phase target setting, where the primary objective is to identify major impact contributors and support strategic prioritisation rather than establish exact environmental impact values.

Figure 4.14 illustrates the contributions of the total absolute GWP delta values.

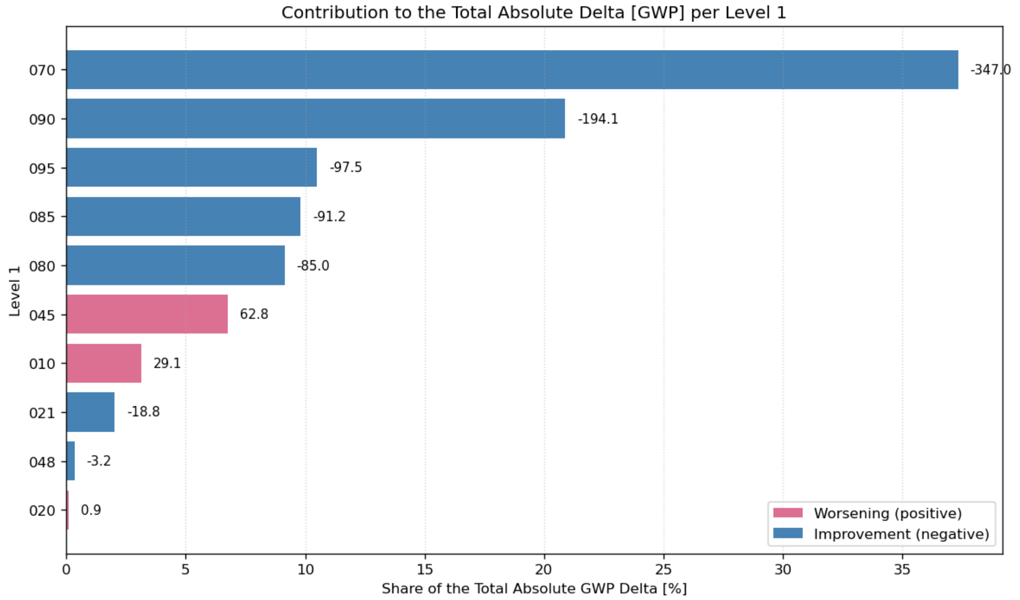

Figure 4.14: Contribution of Level 1 systems to the total absolute GWP delta, showing that a limited number of systems account for most of the total change between the baseline and reference configurations.

Figure 4.15 shows the absolute GWP deltas at level 2, highlighting the percentual distribution per delta.

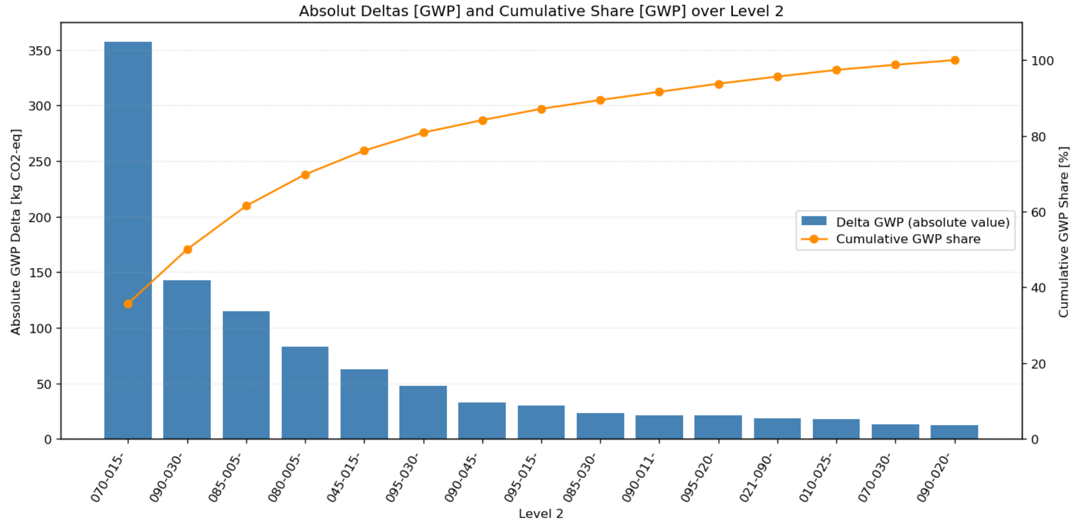

Figure 4.15: A Pareto chart of the 20 largest absolute GWP deltas at Level 2, showing that a limited number of subsystems account for a large share of the total absolute change in GWP.

At the same time, the results indicate that the project-specific changes are highly concentrated within a limited number of systems and subsystems. As illustrated in Figures 4.14 and 4.15, a relatively small share of the hierarchical structure (systems, sub-systems or components) accounts for a large proportion of the total absolute delta GWP. Furthermore, Figure 4.11 in Section 4.4 shows that a substantial share of the rows remain unaffected by project-specific modifications. Together, these observations indicate that many parts of the baseline configuration remain stable throughout the development process, while uncertainty and variability are concentrated within a smaller subset of modified systems and components.

This concentration effect has important methodological implications. Since the majority of the environmental structure remains unchanged, the baseline LCIA retains significant explanatory value even after the inclusion of prospective project data. The methodology, therefore, enables targeted updating of environmentally relevant areas without requiring complete reassessment of the full vehicle configuration. Such an approach is particularly relevant in early-phase industrial contexts, where data availability and project maturity are limited.

The uncertainty associated with the methodology is primarily linked to the project deltas rather than the baseline LCIA itself. While the baseline configuration is based on comparatively mature and high-coverage production data, the project-specific updates rely on assumptions regarding future component configurations, supplier selections, material compositions, and technology maturity. Additional uncertainty originates from differences in data structure and standardisation between sustainability tool outputs.

Despite these uncertainties, the methodology demonstrates a sufficient level of robustness for its intended application. The objective of the reference LCA is not to predict future environmental performance with high precision, but rather to support early-phase environmental target setting through structured hotspot identification and change analysis. In this context, the preservation of the overall hotspot structure and the concentration of changes within a limited number of systems suggest that the methodology can provide decision-relevant guidance even under conditions of incomplete and evolving data.

5

Discussion

This chapter discusses the results presented in Chapter 4 within a broader methodological, industrial, and environmental context. While the previous chapter focused on presenting and analysing the results, this chapter extends the interpretation by relating the findings to existing literature, industrial product development practices, and the overall research objectives of the thesis.

The discussion focuses particularly on the implications of the developed methodology for early-phase environmental target setting under conditions characterised by uncertainty, evolving product definitions, and limited data maturity. In addition, the chapter reflects on the methodological trade-offs, limitations, and generalisability of the proposed approach, as well as its potential role in supporting sustainability integration within industrial decision-making processes.

5.1 Interpretation of Hotspots in a Broader Context

The hotspot analysis presented in Section 4.1 demonstrates that climate impact is highly concentrated within a limited number of systems, particularly the ESS and the maintenance system. This concentration has direct implications for early-phase environmental decision-making. Rather than attempting to optimise the entire vehicle uniformly, efforts can instead be strategically focused on a limited number of high-impact systems and components. Such prioritisation supports a more efficient allocation of engineering and analytical resources, which is particularly important in early development phases characterised by limited data availability and high uncertainty.

The relatively large contribution associated with maintenance further illustrates the importance of adopting a broader lifecycle perspective during early-phase environmental target setting. While electrification-related systems such as the ESS dominate total GWP, the results indicate that recurring maintenance and replacement activities also contribute substantially to the overall environmental profile. This suggests that environmentally relevant development decisions may extend beyond primary component design towards aspects such as durability, service intervals, component lifetime, and maintenance strategies.

At the same time, the finding that the ESS contributes the largest share of GWP is consistent with previous studies on both heavy-duty and passenger BEVs, which commonly identify battery systems as dominant contributors to manufacturing-related emissions [19]. According to Simons and Azimov in *Comparative Life Cycle Assessment of Propulsion Systems for Heavy-Duty Transport Applications* [19], Lithium-ion (Li-ion) battery electric trucks exhibit substantially higher manufacturing-related GWP compared to both ICE and Fuel Cell (FC) alternatives. Their results indicate that battery production alone can account for up to 30% of total manufacturing-related GWP within truck production. Since the study applies a similar cradle-to-gate system boundary, these findings are highly comparable to the results obtained in this thesis.

High emissions associated with the ESS should therefore not be interpreted as an isolated observation, but rather as a systematic characteristic of BEV production systems. However, it is important to acknowledge that the use phase is excluded from the present study. This is the phase where BEVs generally demonstrate their environmental advantages, often outperforming ICE vehicles over the full life cycle. This is illustrated in *A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels* by the International Council on Clean Transportation (ICCT) [15]. Their results show that heavy-duty BEVs can achieve at least 65% lower GHG emissions than equivalent ICE vehicles over the full vehicle life cycle, including fuel and electricity production, vehicle operation, and end-of-life treatment.

A similar pattern has also been observed for passenger BEVs. As presented by Joris Šimaitis et al. in *Battery electric vehicles show the lowest carbon footprints among passenger cars across 1.5–3.0°C energy decarbonisation pathways* [18], battery electric passenger cars generally exhibit higher embodied emissions during production than ICE vehicles, primarily due to energy-intensive battery manufacturing. Nevertheless, these higher manufacturing emissions are often compensated for during the use phase, depending on factors such as electricity grid composition and energy decarbonisation pathways [18].

Overall, the findings place the results of this study within a broader research context, confirming that battery-related emissions constitute a major hotspot within BEV production systems. At the same time, the discussion highlights the importance of interpreting cradle-to-gate results within the context of the broader vehicle life cycle, particularly when environmental target setting is conducted during early product development phases.

5.2 Linking Hotspots and Changes - Implications for Target Setting

The results presented in Chapter 4 reveal a weak alignment between identified hotspots and the locations of the largest changes within the system. While the previous chapter established this relationship empirically, this section focuses on interpreting its implications for environmental target setting and product development processes. In particular, the results indicate that hotspot magnitude and change magnitude do not necessarily coincide and should therefore be evaluated jointly.

This misalignment has important implications for environmental target setting. From an analytical perspective, effective emission reductions require that changes occur within the identified hotspots. However, the observed pattern suggests that many implemented or proposed changes are located outside the most environmentally impactful areas of the system. As a result, the overall potential for reducing total GWP may not be fully realised despite ongoing development activities. This further suggests that focusing exclusively on implemented changes may overlook the systems with the greatest reduction potential.

The observed pattern also suggests that development decisions are primarily driven by other functional priorities, such as product costing, load capacity, performance, or similar engineering considerations, rather than environmental aspects alone. Consequently, emission reductions may occur as secondary effects of decisions motivated by cost or performance improvements. This highlights a broader structural challenge related to integrating sustainability into early-phase product development. If environmental considerations are not aligned with the primary drivers of change, their influence on design decisions may remain limited. As a result, even well-identified hotspots may not be prioritised unless they overlap with other functional objectives.

At the same time, an exclusive focus on hotspots also presents limitations. Although targeting the largest emission contributors is analytically reasonable, it may not always be practically feasible or optimal from a product development perspective. Opportunities for emission reductions that are easier to implement, for example through material substitutions influencing both cost and weight, may be overlooked if they fall outside the primary hotspots. A strictly hotspot-driven approach therefore risks neglecting feasible improvements that could still contribute meaningfully to overall emission reductions while simultaneously supporting other engineering objectives.

Taken together, these observations suggest that neither hotspot prioritisation nor change-driven development alone is sufficient. Instead, meaningful emission reductions require an alignment between environmental hotspots, feasible technical solutions, and broader functional priorities such as cost, performance, and manufacturability. In practical terms, this implies that sustainability-related targets should be formulated in a way that intersects with existing engineering and business decision criteria, enabling environmental considerations to function as a co-driver rather than as a separate constraint.

Furthermore, the hierarchical structure of the analysis enables this relationship to be identified at different levels of resolution. While system-level analysis highlights overall environmental priorities, component-level analysis allows for the identification of more specific intervention points where changes can be both impactful and practically feasible. This reinforces the value of combining hotspot and delta analyses as complementary tools for supporting early-phase environmental decision-making. The reference LCA approach developed in this thesis enables such a combined perspective by linking baseline environmental impact with project-specific changes across multiple hierarchical levels.

Overall, the results demonstrate that neither hotspot analysis nor delta analysis alone is sufficient to guide effective environmental improvements. Instead, their combined interpretation provides important insight into both the environmental impact distribution and the realised development changes within the system. Bridging the gap between these two perspectives therefore represents both a key challenge and a key opportunity for improving the integration of sustainability into industrial product development processes. Effective environmental target setting consequently requires a combined evaluation of both impact magnitude and change potential rather than relying on either perspective independently.

5.3 Limitations

While the previous sections demonstrate the analytical usefulness of the methodology for identifying hotspots and interpreting project-driven changes, these findings must also be considered in relation to the limitations and uncertainties inherent to early-phase industrial sustainability assessments. Understanding these limitations is important both for interpreting the results appropriately and for evaluating the broader applicability of the methodology.

A first limitation relates to temporal alignment between datasets. The temporal reference of the sustainability tool data used for deriving delta values do not always fully correspond to the temporal reference of the baseline LCIA. This introduces uncertainty in the calculated differences between baseline and reference configurations. Nevertheless, within the context of early-phase environmental target setting, such discrepancies were considered acceptable. The methodology is intended to support indicative decision-making under uncertain conditions rather than provide exact predictive results. In this regard, the approach represents a practical alternative to conducting complete prospective LCAs, which are often infeasible due to limited time, data maturity, and resource availability.

A second limitation concerns the representativeness of the included project data. One project initially considered for inclusion was excluded due to outdated and unreliable information. Although this improved the overall consistency and analytical robustness of the dataset, it also reduced the diversity of the included cases. Since delta values are central to defining the differences between baseline and reference configurations, unreliable project data could have introduced disproportionate influence on the results and reduced the validity of the analysis. The exclusion therefore reflects a methodological trade-off between representativeness and analytical reliability.

A third limitation concerns the baseline LCIA itself. The baseline was derived from a BoM extracted at a specific point in time, while later updates indicated that a notable share of the components had undergone some form of change. These changes may range from minor adjustments to more substantial modifications such as material substitutions or component replacements. Although a detailed reassessment of all changes was outside the scope of this thesis, the observed variation indicates that the baseline configuration itself contains a degree of uncertainty. Maintaining a continuously updated baseline would likely improve reliability, but would also require repeated LCIA modelling, which conflicts with the objective of developing a time-efficient methodology suitable for early-phase applications.

A fourth limitation is related to the maturity and standardisation of industrial sustainability workflows. The methodology relies on sustainability tool outputs that are not fully standardised across projects, resulting in differences in structure, resolution, and data completeness. This affects interoperability between datasets and limits the degree of automation achievable within the workflow. Although the semi-structured Power Query approach provided sufficient flexibility for handling these variations, the limitation remains important for future scalability and industrial implementation.

Finally, the studied case represents a context where market maturity and technology maturity are not fully aligned, as discussed in Section 2.2. The market conditions surrounding the studied system are comparatively mature, while parts of the underlying technology are still evolving. This mismatch affects both uncertainty and transferability, since methodological performance and observed patterns may differ under other maturity conditions. Consequently, while the methodological structure itself may be transferable, the resulting outcomes remain dependent on the specific industrial and technological context in which the methodology is applied.

Taken together, these limitations highlight the broader challenge of conducting environmental assessments in early-phase industrial product development, where uncertainty, incomplete information, and evolving system definitions are unavoidable. The results should therefore be interpreted as indicative rather than exact, supporting decision-making and target setting rather than definitive environmental quantification.

This further reinforces that methodological applicability in industrial contexts often depends more on usability, transparency, and robustness under uncertainty than on achieving maximum analytical precision.

5.4 Methodological Reflections and Generalisation

The methodology developed in this thesis demonstrates that combining baseline LCIA data with structured delta values provides a feasible approach for constructing reference LCAs during early project phases. A key strength of the methodology lies in its ability to balance methodological robustness with industrial applicability. By grounding the reference in an existing baseline LCIA, the methodology retains consistency and traceability, while the use of delta values enables the integration of prospective project information without requiring a complete prospective LCA for each development project.

In this context, the primary contribution of the methodology is not the elimination of uncertainty, but rather the establishment of a structured and transparent framework capable of supporting environmental decision-making under uncertain conditions. In industrial product development, where complete product definitions rarely exist during early project phases, the ability to identify environmentally significant systems and changes becomes more important than achieving exact environmental performance estimates.

At the same time, the methodology remains dependent on the quality, maturity, and structure of the available input data. The sustainability tool outputs used in this study were not fully standardised across projects, resulting in differences in structure, resolution, and completeness. Consequently, a flexible and semi-structured data-handling approach was required, limiting the degree of automation achievable within the workflow. This reflects a broader industrial challenge, where sustainability assessments often need to operate under evolving data structures and incomplete information.

The methodology should therefore be interpreted as a pragmatic trade-off between analytical precision and practical applicability. While the resulting assessments are associated with uncertainty and do not achieve the level of detail obtainable through a complete LCA, such comprehensive assessments are generally infeasible during early development phases due to limitations in time, data maturity, and resource availability. Within this context, the methodology provides a sufficiently robust basis for early-phase environmental target setting and decision support.

The methodology is furthermore generalisable primarily through its workflow structure and decision logic rather than through the specific numerical results generated in this study. The transferable aspect is therefore the structured process of integrating retrospective baseline information with prospective project-specific changes. Consequently, the methodology may be applicable to other industrial projects where comparable baseline LCIA data and structured delta information are available.

Regarding implementation, Power Query was selected in this study due to the non-standardised nature of the available sustainability data. This provided the flexibility required to accommodate project-specific variations and iterative adjustments throughout the workflow. However, this flexibility comes at the expense of scalability. As the number of projects and datasets increases, the semi-structured nature of the workflow becomes increasingly time-consuming and more difficult to maintain efficiently.

In contrast, a script-based implementation, for example using Python, could improve scalability, repeatability, and cross-functional integration between sustainability, product costing, and load capacity workflows. However, the current lack of standardised input data limits the practical feasibility of such an implementation within the present industrial context.

The methodology therefore reflects a broader trade-off between flexibility and scalability. Within the scope of this thesis, flexibility was prioritised in order to accommodate evolving and partially unstructured sustainability data. Given the intended use of the methodology within early-phase industrial target setting, this flexibility was considered more important than achieving a fully automated but less adaptable solution.

Looking forward, increased standardisation of sustainability data outputs could enable more automated and scalable implementations while retaining the conceptual strengths of the methodology. Such developments could improve both efficiency and usability across a broader range of industrial product development projects.

5.5 Implications for Future Projects and Method Development

Based on the findings of this thesis, future work should focus on improving both data quality and methodological efficiency while further strengthening the integration of sustainability considerations into existing product development processes.

One important area for future development is the integration of more detailed material information into the methodology. Incorporating data related to RC and SOC would enable more comprehensive and actionable environmental assessments. While this thesis primarily focuses on GWP, the inclusion of RC data could support more precise identification of emission reduction opportunities within identified hotspots, for example, by evaluating the feasibility of increasing recycled material shares in high-impact components. Similarly, although SOC is not directly linked to climate impact, its integration could support a broader environmental perspective by enabling the identification of material-related environmental hotspots. This could facilitate more informed decisions regarding material substitutions, regulatory compliance, and long-term sustainability strategies. Together, these additions could strengthen the methodology's ability to support multi-dimensional environmental target setting.

Another important area for future development concerns the standardisation of sustainability tool outputs. As discussed in Section 5.4, the current lack of standardisation introduces variability in data structure, resolution, and completeness, limiting both comparability and the potential for automation. Increased standardisation would not only improve the robustness and consistency of the assessments, but also enhance the practical usability of sustainability tools within industrial organisations. Since sustainability functions are still developing in many industrial contexts, including the studied case, the establishment of consistent data structures and user-oriented workflows is important for enabling broader organisational adoption and effective decision support.

From a methodological perspective, increased standardisation would also enable a transition from the current semi-structured Power Query workflow towards a more automated and scalable script-based implementation, for example using Python. As discussed in Section 5.4, such an implementation could improve scalability, reproducibility, and cross-functional integration between sustainability, product costing, and load capacity workflows. In addition, increased automation could support the application of the methodology across a larger number of projects while reducing the need for manual data handling and restructuring.

More broadly, the findings of this thesis suggest that future methodological development should not focus solely on improving analytical precision, but also on strengthening the organisational integration of sustainability within existing engineering and decision-making processes. As highlighted in Section 5.3, environmental target setting becomes more effective when sustainability considerations are aligned with existing functional priorities and development workflows.

Ultimately, the long-term objective is to develop a methodology that is not only transparent and sufficiently robust for early-phase applications, but also scalable, adaptable, and integrated into existing industrial product development processes. Achieving this will require continued improvements in data quality, standardisation, workflow integration, and organisational alignment surrounding sustainability-related decision-making.

5.6 Answering the Research Questions

This section synthesises the findings of the study in relation to the three research questions by integrating the methodological, analytical, and organisational insights discussed throughout Chapters 4 and 5. Collectively, the findings demonstrate both the feasibility and the practical limitations of constructing reference LCAs for early-phase product development using combined retrospective and prospective data.

The first research question addressed how retrospective baseline data can be combined with prospective sustainability data to support environmental assessment in early-phase product development. The results demonstrate that this can be achieved by using baseline LCIA outputs as a stable reference point and incorporating structured delta values representing project-specific changes. As discussed in Section 4.2, this approach enables the modelling of prospective scenarios without requiring complete product definitions. The methodology thereby bridges the gap between data-rich retrospective assessments and uncertain future configurations, providing a practical solution for early-phase applications where traditional LCA approaches are often infeasible.

The second research question concerned the methodological choices and associated limitations of the proposed approach. The study adopts an attributional LCA framework combined with hierarchical aggregation and a delta-based update mechanism. As discussed in Section 5.3 and 5.4, these methodological choices reflect a deliberate trade-off between analytical precision and practical applicability. While the methodology does not achieve the level of precision associated with complete LCAs, it enables structured and repeatable assessments under industrial constraints characterised by limited data availability, evolving product definitions, and time pressure. The main limitations concern data quality, temporal alignment, and a lack of standardisation in sustainability tool outputs. Although these limitations affect both robustness and scalability, they are also closely connected to the realities of early-phase industrial product development.

The third research question examined how the developed methodology supports environmental target setting in the early project phases. The results demonstrate that the combined use of hotspot analysis and delta analysis provides a structured basis for such target setting. As demonstrated in Section 4.1, hotspot analysis identifies systems and components associated with the largest environmental impacts, while delta analysis, presented in Section 4.2, identifies where project-driven changes are occurring. However, as discussed in Sections 4.3 and 5.2, these two perspectives are not inherently aligned. This misalignment indicates that identifying environmental hotspots alone is insufficient for enabling effective emission reductions, since implemented changes are often governed by other engineering and business priorities such as cost, performance, and load capacity.

Consequently, the methodology supports environmental target setting not only by identifying high-impact systems, but also by revealing the relationship between environmental impact and realised development changes. This enables a more informed and practically grounded approach to target setting, where sustainability considerations can be aligned with existing engineering and decision-making processes. By combining analytical structure with organisational relevance, the methodology contributes to bridging the gap between environmental assessment and practical industrial implementation.

Overall, the research questions are addressed through the development and application of a methodology that enables structured, flexible, and decision-relevant environmental assessments during early-phase product development. While limitations and uncertainties remain, the study demonstrates that meaningful support for sustainability target setting can still be achieved under conditions characterised by incomplete data and evolving product definitions.

6

Conclusion

This thesis aimed to develop a transparent, repeatable, and industrially applicable methodology for constructing reference LCAs to support environmental target setting during early-phase heavy-duty truck development. The work addressed the methodological challenge of combining retrospective baseline LCIA data with prospective project-specific information under conditions characterised by incomplete product definitions, evolving technologies, and limited data maturity.

The developed methodology combines an existing baseline LCIA with structured delta values representing project-specific changes. Through this approach, a reference LCA can be constructed without requiring a complete prospective LCA for each new development project. The methodology thereby provides a practical alternative for early-phase environmental assessment, where time constraints, limited data availability, and uncertainty often make full LCAs infeasible.

A central contribution of the thesis is the demonstration that meaningful environmental assessments can still support decision-making despite these constraints. Rather than attempting to eliminate uncertainty, the methodology establishes a structured and transparent framework capable of operating under uncertain industrial conditions. In this context, the primary value of the methodology lies in its ability to support environmental target setting, hotspot identification, and decision-relevant analysis during phases where environmental influence is high but information maturity remains limited.

The case study implementation demonstrated that climate impacts are highly concentrated within a limited number of systems, particularly the ESS in BEVs. At the same time, the analysis revealed a weak alignment between identified hotspots and the locations where project-driven changes were occurring. This finding represents one of the key analytical insights of the thesis, as it suggests that development activities are primarily driven by other engineering and business priorities, such as cost, load capacity, and technical performance, while sustainability improvements often occur as secondary outcomes.

Consequently, the study highlights that effective environmental target setting requires more than simply identifying environmental hotspots. Meaningful emission reductions depend on the extent to which sustainability considerations can be integrated into existing engineering and organisational decision-making structures. The combined use of hotspot analysis and delta analysis therefore provides an important analytical perspective by simultaneously identifying both where impacts are concentrated and where development changes are actually occurring.

From a methodological perspective, the thesis also demonstrates the importance of balancing analytical robustness with industrial applicability. The resulting methodology should not be interpreted as a replacement for complete LCAs, but rather as a pragmatic and decision-oriented complement adapted to early development phases. Within this context, usability, transparency, repeatability, and adaptability become more important than achieving maximum analytical precision.

At the same time, the study identified several limitations affecting both robustness and transferability. These include uncertainties related to temporal alignment between datasets, variations in baseline configurations, limited standardisation of sustainability tool outputs, and the evolving maturity of industrial sustainability workflows. Furthermore, the methodology was developed within a specific industrial context characterised by partially mature market conditions combined with evolving technologies, which may influence applicability in other contexts.

Despite these limitations, the thesis demonstrates that structured and actionable sustainability assessments can be performed even under conditions of uncertainty and incomplete information. The work therefore contributes both a practical industrial methodology and a broader conceptual perspective on how environmental assessment can support early-phase product development.

Looking forward, future development of the methodology would benefit from improved standardisation of sustainability datasets, increased integration of material-related sustainability information such as RC and SOC, and more automated data-handling workflows. Such developments could improve scalability, interoperability, and integration with other industrial functions while retaining the methodological strengths demonstrated in this thesis.

Overall, the thesis contributes to bridging the gap between environmental assessment and practical industrial implementation. By combining retrospective baseline LCIA data with prospective project-specific updates within a structured and flexible framework, the methodology enables environmental target setting to become more integrated into industrial product development processes despite uncertainty, evolving technologies, and incomplete data.

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