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LCA FOR MACHINES

Cradle-to-gate life cycle assessment of heavy machinery manufacturing: a case study in Türkiye

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Abstract

Purpose Amidst accelerated industrialization and urbanization, the surge in heavy equipment production, crucial for construction, mining, industry, and transportation, necessitates a comprehensive examination of its environmental implications from a sustainability standpoint. This study aims to scrutinize the environmental impacts of manufacturing forklifts and semi-trailers in Türkiye, employing the life cycle assessment (LCA) methodology.

Methods The life cycle assessment (LCA) methodology is the foundational framework for evaluating the environmental impacts associated with forklift and semi-trailer manufacturing. A cradle-to-gate approach was employed. CCaLC2 software alongside the Ecoinvent 3.0 database and CML LCIA methodology was used.

Results The carbon footprint analysis reveals that the production of a single forklift and semi-trailer generates 10.8 tons CO_2eq. and 24.9 tons CO_2eq. of emissions, respectively. Considering the mass of the machinery, these figures translate to 2.8 ton CO_2eq./ton machinery and 1.57 ton CO_2eq/ton machinery for the forklift and semi-trailer, respectively. These results were found to be consistent with values reported for similar (but not identical) heavy machinery. Notably, the predominant share of environmental impact stems from raw material acquisition for both products, with subsequent contributions from various production stages. Steel utilization emerges as the primary contributor to all environmental impact categories, constituting an average contribution of 75%. Noteworthy exceptions include the acidification potential of forklift production, where the incorporation of the engine emerges as the primary hotspot with a significant 38% contribution.

Conclusions The findings present the environmental footprint associated with forklift and semi-trailer manufacturing, emphasizing the pivotal role of raw material acquisition, particularly steel utilization. Insights derived from this environmental impact assessment provide invaluable guidance for enhancing environmental sustainability. Decision-makers and industry stakeholders can leverage these conclusions to implement targeted measures, such as exploring alternative materials or refining production processes, to mitigate the environmental consequences of resource-intensive heavy equipment manufacturing, aligning with broader sustainability objectives.

Keywords Environmental impacts · Heavy machinery · Forklift · Semi-trailer · Life cycle assessment

1 Introduction

The European Green Deal (EGD) was announced by the European Commission (EC) on December 11, 2019. Its overarching goal is to establish Europe as the first climate-neutral continent with net-zero emissions by 2050. This initiative has significant implications for manufacturing industries within and outside the European Union (EU) (EC, 2019). Specifically, the target of a 55% reduction in greenhouse gas (GHG) emissions by 2030 outlined in the Fit for 55 packages on July 14, 2021,

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levies a significant burden on the European manufacturing industries due to the expansion of the industrial coverage of the European Union Emission Trading System (EU-ETS) (EC, 2021a). Additionally, as part of this package, the EC introduced the Carbon Border Adjustment Mechanism (CBAM), whose main objective is to avoid carbon leakage originating from imports of carbon-intensive products by imposing financial obligations directly on European importers and indirectly on EU trade partners (EC, 2021b). On August 17, 2023, the EC issued the CBAM Implementing Regulation, requiring EU importers to provide quarterly reports on the embedded emissions of selected products from six energy-intensive industries, namely iron and steel, aluminum, cement, fertilizers, electricity, and hydrogen during the transitional period from October 1, 2023, to December 31, 2025 (EC, 2023). According to the regulation, importers will be responsible for paying the designated carbon price at the border, which will be calculated as the price in EU-ETS multiplied by the difference between the embedded emission of the imported product and the default value determined by EC until August 2024. After this transitional period, CBAM coverage would be extended further to cover sectors with high energy intensity and, hence, a high environmental footprint. After this transition period, the scope of CBAM will be expanded to include other sectors, and its effectiveness will be increased.

Türkiye, which directed 40.6% of its exports to the EU in 2022 (TUIK, 2023), is estimated to be one of the most heavily affected countries by these applications. Türkiye, together with the Russian Federation and China, is the country most exposed to the mechanism based on their levels of exports to the EU in selected sectors likely to be included in the CBAM (UNCTAD 2021). According to the World Bank's Relative CBAM Exposure Index, Türkiye ranks 12 th among most exposed countries in aggregate, being 4 th most exposed in electricity, 9 th in fertilizers, 12 th in cement, 17 th in iron and steel, and 20 th in aluminum products (World Bank 2023). Moreover, Acar et al. (2022) have demonstrated that implementing CBAM regulation will have substantial adverse effects on Türkiye's GDP growth until 2030. According to them, Türkiye's GDP in 2030 will decrease by 2.7% and 3.6% when the EU-ETS prices are 30 Euros per ton of CO_2 equivalent (EUR/tCO_2e) and 50 EUR/tCO_2e, respectively. Considering the current EU-ETS price of around 85 EUR/tCO_2e[1] and the estimated near-future price of around 105 EUR/tCO_2e[2] the effect of CBAM on Türkiye's economy will be much more severe. Hence, it is vital for major exporting sectors of Türkiye, particularly the energy-intensive ones, to take the necessary steps to be prepared for the upcoming CBAM and other EGD-related regulations. The first step would be to measure embedded carbon emissions and other environmental footprints of the products that are or will soon be covered by the regulations. Considering the resource and energy-intensive sectors in Türkiye, the manufacture of machinery and equipment not elsewhere classified (NACE -Statistical Classification of Economic Activities in the European Community- 28) and the manufacture of motor vehicles, trailers, and semi-trailers (NACE 29) are crucial. According to the Ministry of Industry and Technology, these subsectors are responsible for 14% and 7.6% of total exports in 2020, ranking 1 st and 5 th, respectively.[3] Among various heavy equipment, the manufacturing of forklifts and semi-trailers is significant. For instance, it was reported that the export of semi-trailers constituted 2.7% of Türkiye's total exports in 2019.[4] Although these subsectors do not have substantial emissions under Scope 1 and Scope 2,[5] their emissions under Scope 3 are relatively high because the primary inputs for these industries are produced in energy- and emission-intensive sectors like iron, steel, and aluminum, which are also within the scope of CBAM regulation.

The Turkish manufacturing industry significantly contributes to the economy through value-added production and export income, particularly in the heavy machinery sector. With the EU's Carbon Border Adjustment Mechanism (CBAM) setting carbon emission benchmarks based on the worst-performing industrial establishments, this study aims to answer the following question: What are the environmental impacts of industrial machinery manufacturing in Türkiye? Additionally, which stages of the production process contribute the most to these environmental impacts?

To address these questions, it is essential to conduct a comprehensive environmental impact assessment of heavy machinery production in Türkiye. This study aims to identify the key stages in the production process that are most responsible for environmental impacts, providing a clearer understanding of where improvements can be made to reduce the overall environmental footprint. Life cycle assessment (LCA) methodology is conducted as a promising tool for thoroughly evaluating products and services throughout their lifetime. The comprehensive process-based dataset of these products is obtained from two anonymous enterprises located in the Adana Hacı Sabancı Organized Industrial Zone, which is one of the most prominent organized

[1] Spot EU-ETS price on 13.10.2023 available at: https://www.eex.com/en/market-data/environmentals/spot. Last accessed on 14.10.2023.

[2] https://www.reuters.com/business/sustainable-business/analysts-raise-eu-carbon-price-forecasts-after-reform-agreement-2023-04-28/. Last accessed on 14.10.2023.

[3] https://www.sanayi.gov.tr/plan-program-raporlar-ve-yayinlar/suresiz-yayinlar Accessed on 14.10.2023.

[4] https://tim.org.tr/files/downloads/Strateji_Raporlari/TIM_Ihracat_2021_Raporu.pdf Accessed on 14.10.2023.

[5] For instance, with respect to Scope 2 emissions, two sectors together are responsible for only 2.1% and 3.7% of total electricity consumption and total natural gas consumption, respectively (MENR, 2021).

industrial zones of Türkiye. It is believed that through an LCA of forklift and semi-trailer manufacturing in Türkiye, not only the environmental impacts of these heavy machinery would be evaluated, but also a hotspot analysis to highlight the potential for improvement for the enterprises under consideration will be provided.

2 Literature review

A comprehensive LCA-related literature review for manufacturing heavy machinery was conducted, considering various equipment, including agricultural machinery, electric motor systems, and construction vehicles by using Web of Knowledge and ScienceDirect databases with the following search keywords: “life cycle assessment, industrial machinery, forklift, trailer, carbon footprint, environmental impact.” Table 1 provides a detailed review of such studies, including the life cycle stages analyzed, the source of inventory, and the location of manufacturing equipment, among others. The use stage has been frequently considered the main hotspot in LCA studies of heavy machinery, as it often accounts for the majority of environmental impacts due to energy consumption and emissions during operation (Ebrahimi et al. 2020; Andersson and Diener 2020). In terms of inventory sources, site-specific data acquisition has been practiced less, which highlights further clarification regarding data from heavy-duty equipment manufacturing. Moreover, within this diverse landscape of LCA research, the specific areas of forklift and semi-trailer manufacturing, especially in the context of Türkiye, remain underexplored. This gap is significant since forklifts are crucial for internal logistics in numerous sectors, and semi-trailers are key elements in the global supply chain, facilitating the transport of a vast range of commodities. The environmental implications of these vehicles, both of which play pivotal roles in material handling and transportation, warrant detailed analysis due to their widespread use and the potential for substantial environmental footprints. Moreover, a lack of transparent inventory datasets related to the manufacturing of heavy-duty equipment is observable.

Given the above, the gap in the LCA literature on forklift and semi-trailer manufacturing in the context of Türkiye offers an opportunity for further research in this regard. Given the significant environmental impacts of heavy machinery provided in Table 1, the comprehensive LCA of forklifts and semi-trailers is environmentally informative, as it not only fills the current gap in the literature but also guides manufacturers and stakeholders toward more sustainable production and operation practices.

These earlier studies collectively utilize life cycle assessment methodologies to evaluate the environmental impacts of various industrial products and machinery, spanning stages such as raw material extraction, manufacturing, usage, and end-of-life. They employ a mix of site-specific and average data sources, emphasizing detailed inventory analysis and broader system-level evaluations. The findings consistently highlight the use stage as the primary

Table 1 Summary of selected literature on LCA of vehicle manufacturing and operation

Product	Life cycle stages evaluated	Source of inventory (average or site-specific)	Main environmental hotspot	Location	Reference
Heavy-duty truck tire	Extraction of raw materials, production, usage, and end-of-life	Site-specific	Use stage	Sweden	Andersson and Diener (2020)
Mining equipment -Boom cylinder -Hydraulic pump	From raw material refinement to assembly, including maintenance	Site-specific	Manufacturing	Japan	Kanazawa et al. (2022)
Induction machine, the externally excited synchronous machine, the permanent magnet synchronous machine, and the synchronous reluctance machine	Manufacturing	Not specified	Motor production	Europe	Schillingmann et al. (2021)
Load boxes	Production, use, and end-of-life	Not specified	Use stage	Brazil	Teixeira et al. (2009)
Wheel loader	Service life of the machine	Average data	Use stage	Europe	Kwak et al. (2012)
Forklift trucks (electric and diesel)	Operation	Site-specific	Use stage	Poland	Fuć et al. (2016)
Construction machinery	Manufacturing, operation, maintenance, end-of-life	Not specified	Use stage	Europe	Ebrahimi et al. (2020)

environmental hotspot for most products, underscoring the significant impacts of operational energy consumption and emissions. Manufacturing also emerges as a key contributor to environmental burdens in specific cases, particularly for complex machinery. The studies demonstrate the importance of targeted interventions, such as optimizing resource use during production and improving energy efficiency during operation, to mitigate environmental impacts.

The literature review revealed that previous studies on heavy machinery manufacturing have primarily focused on generic machinery types or specific components. Moreover, limited site-specific data and lack of focus on machinery manufacturing in Türkiye, particularly forklifts and semi-trailers, leave significant gaps in understanding their environmental impact. This study fills the gap by conducting the first comprehensive LCA of forklift and semi-trailer manufacturing in Türkiye. Using real-world data from manufacturing facilities provides valuable insights into resource use, environmental hotspots, and potential mitigation strategies tailored to local production contexts.

3 Methodology

In this study, an attributional LCA methodology has been implemented in order to investigate the environmental impacts and hotspots related to the manufacturing of forklifts and semi-trailers in Türkiye. The framework of LCA follows the ISO 14040 and ISO 14044 (ISO, 2006), which entails defining goals and scope, gathering inventory data, determining environmental impacts, and interpreting emission results. A schematic view of the system boundaries is shown in Fig. 1. The life cycle modeling in this study is a cradle-to-gate assessment, encompassing the raw material acquisition, production, and transportation stages. In the raw material acquisition stage, inputs are attributed to the unit processes, while the production stage involves all kinds of processing activities conducted in the manufacturing plant. Moreover, the transportation of raw materials to the production location is considered a part of the model. The cradle-to-gate approach was chosen because the primary objective of the study is to evaluate the environmental impacts of manufacturing industrial machinery such as forklifts and semi-trailers in Türkiye, as evident from the title of the paper. The scope includes raw material acquisition, production processes, and transportation to the factory gate. The use and disposal stages (cradle-to-grave) were excluded as they involve numerous variables like usage patterns, maintenance practices, and end-of-life scenarios that are highly uncertain and vary significantly across regions and applications. This boundary aligns with the study's aim of identifying production-stage hotspots and proposing actionable mitigation strategies for manufacturers. By focusing on production, the study provides practical insights for industry stakeholders to improve their operations and reduce emissions.

To implement LCA, CCaLC2 software, an environmental and economic calculation tool developed at the University of Manchester that allows combined economic and environmental impact evaluations of various industrial systems and products, was used. The software has its database in addition to Ecoinvent 3.0 database that contains thousands of datasets from various sectors. A midpoint environmental impact assessment method of CML 2001 was used, following Guinée (2002), and considering the impact categories: carbon footprint (CF), acidification potential (AP), ozone layer depletion potential (ODP), eutrophication potential (EP), photochemical smog potential (POCP), and human toxicity potential (HTP). CCaLC2 was selected for this study due to

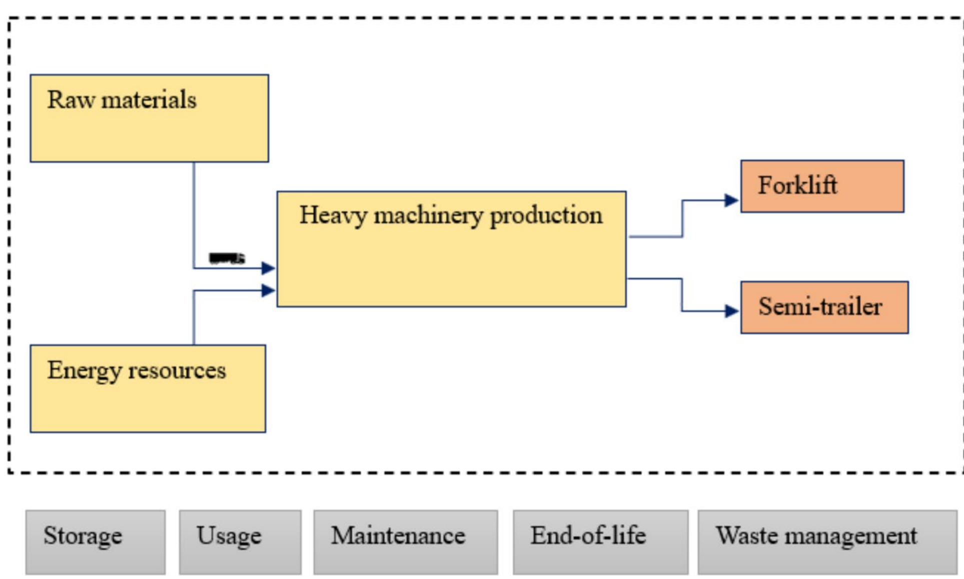


Fig. 1 The overview of the stages included (within the dotted box) and excluded (outside the dotted box) in the life cycles of semi-trailer and forklift

its integrated features for both environmental and economic assessments, its compatibility with the Ecoinvent 3.0 database, and its ability to model complex systems like heavy machinery manufacturing. Additionally, it is free software, has a user-friendly interface, and has established credibility in academic and industrial LCA studies, making it a suitable choice. While CCaLC2 is robust, resource limitations such as lack of access to alternative tools (e.g., SimaPro, GaBi) or specific regional datasets may introduce uncertainties. These limitations were mitigated by incorporating site-specific data where possible and using widely accepted databases like Ecoinvent. The results remain valid within the defined scope, but future studies could consider comparing results across different tools for additional validation. Another limitation could arise from the narrow impact coverage of CCaLC, but it calculates frequently analyzed impacts such as carbon footprint, acidification, and ozone layer depletion, which was deemed sufficient for this study.

The CML 2001 method was selected because it provides a comprehensive suite of midpoint indicators widely used in LCA studies, particularly for industrial applications. It is compatible with the available data and aligns well with the environmental impacts of interest, such as carbon footprint, acidification potential, eutrophication potential, and human toxicity potential. Categories like water use and land use were not included due to data unavailability and their relatively limited relevance to the heavy machinery production process in this case. The focus was on categories most directly influenced by the manufacturing processes and materials. However, future studies could expand the analysis to include these categories as data availability improves.

3.1 Goals and scope

Life cycle modeling of the production processes in the manufacturing of heavy equipment is conducted for two goals:

(1) Determining the environmental implications associated with the current approach employed for the manufacturing of forklifts and semi-trailers in the city of Adana.
(2) Highlighting the environmental hotspots throughout the production procedures.

The processes in producing utility resources and the manufacturing of heavy equipment collectively constitute the scope of the study. Fig. 2 presents the overview of the system boundary considered for the life cycles of forklifts and semi-trailers.

3.2 Case study

In this study, the heavy equipment production system is modeled based on the operational activities of two manufacturing companies located in the Hacı Sabancı Organized Park in Adana, Türkiye. Manufacturing of the

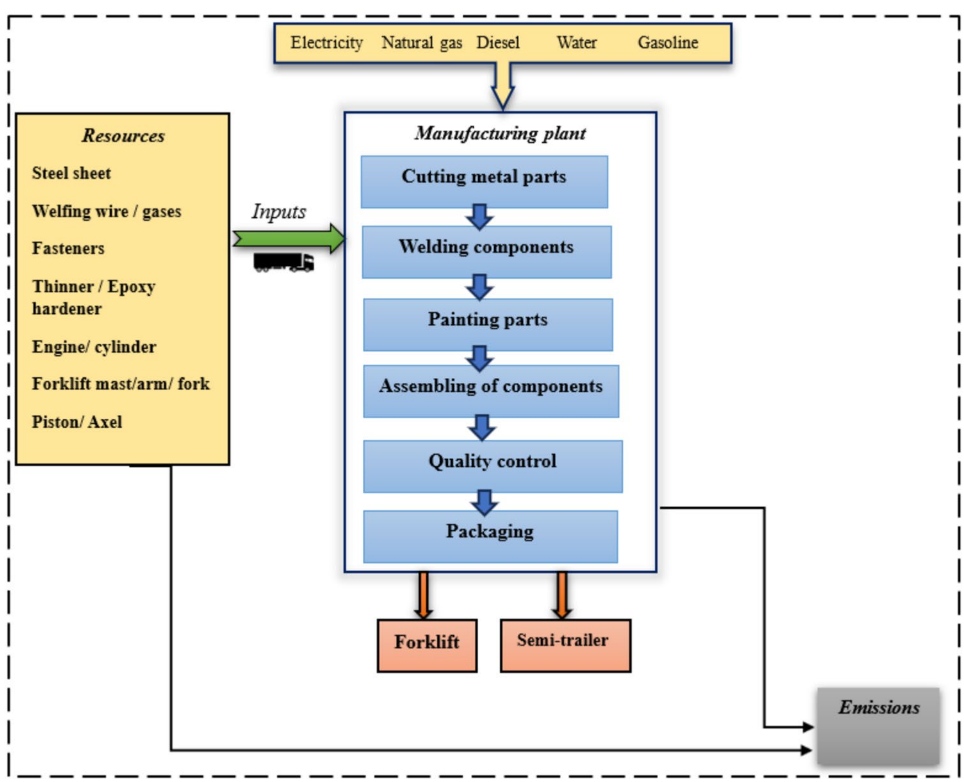


Fig. 2 The system boundary of forklift and semi-trailer production

Fig. 3 View of the forklift (actual image)

Fig. 4 View of a sample semi-trailer (image obtained from the manufacturer)

semi-trailer and lifting equipment constitutes the main business activity of these companies (Figs. 3 and 4). Figures 3 and 4 illustrate a representative schematic view of forklift and semi-trailer considered in the present study. The former is a diesel-based heavy machine capable of lifting average industrial goods and weighing almost 3855 kg, while the latter is a truck section weighing almost 15,876 kg.

The functional units defined in the present study are as follows:

- A 3855 kg forklift was manufactured in Türkiye with the PRODCOM code 28.22.15.13 ($FU_{Forklift}$).
- A 15,876 kg semi-trailer was manufactured in Türkiye with the PRODCOM code 29.20.23.00 ($FU_{Trailer}$).

3.3 Data collection

The data related to the production procedures of forklifts and semi-trailers are collected from the reference companies as a case study for the base year 2022. The emission data of electricity generation in Türkiye is obtained from Atılgan and Azapagic (2016), with the generation mix consisting of natural gas with a share of 22.86%, renewables with a total share of 26.4% (hydro 20.34%, wind 10.64%, geothermal 3.39%, solar 5.14%), coal with a share of 234.63%, waste with a share of 2.88%, and liquid fuels with an approximate share of 0.12%.

Environmental impact data of the two components of the forklift, namely the engine and the wheel, were adopted from Li et al. (2013) and Piotrowska et al. (2019), respectively. This choice was inevitable as no local dataset was available for these inputs. Using generic datasets from different locations is likely to increase the uncertainty of the results. However, in this case, data on these particular inputs was adopted from China and Poland, where electricity generation relies heavily on coal and natural gas, just like in Türkiye. Thus, it was assumed that manufacturing these components abroad would end up causing similar environmental impacts as having these components manufactured in Türkiye. The value-based allocation approach is employed to determine the environmental impacts of multi-output products observed in the company. The energy consumption associated with the manufacturing operations was determined by multiplying the power rating of the machinery used for manufacturing processes by the time it takes for each machine to process the input required for one forklift or trailer.

3.4 Manufacturing system

In the manufacturing plants, various processes are carried out, including cutting steel sheets, bending components, welding parts, painting, and assembling final products. First, the components are cut from steel sheets according to the specifications of the final products. Then, these cut elements undergo the bending process, where components are shaped. Various machines, such as laser cutters, plasma profile devices, and press brakes, are involved in the cutting and bending. Following the production of steel parts, the arc welding process is carried out to attach cut components using welding wires. Joined steel parts then go through the sandblasting process to be polished and smoothed before painting.

The trailers are painted to meet appearance and durability standards. Various painting materials, including epoxy primer and coating components, are used in this stage. Components are then transferred to drying machines, where parts are heated by using hot air guns and a bolting procedure. After the assembly of components, externally produced parts, such as electronic boards, engines, seats, and tires, are mounted onto the semi-finalized structure. Finally, finished forklifts and semi-trailers go through quality control testing to be approved for packaging.

Table 2 presents the required average inventory of input resources to the production system under study, where the averages are calculated over the 1-year production activities of the plant. As seen in the table, the most significant contributions of mass are made by engines and steel in the case of forklifts, whereas steel and welding wires have the highest share of mass for semi-trailers.

3.5 Waste management

Various waste streams, including processing effluents and solid residues, are observed in the semi-trailer manufacturing plant. Wastewater and steel scraps generated from the cutting procedure and empty metal boxes in the welding and painting processes are transferred to recycling plants for further treatment. Therefore, emissions from waste management are excluded from calculations in the present study.

4 Results and discussion

The LCA results of the forklift and semi-trailer are unveiled in Figures 5 and 6, respectively. The findings (Figures 5 and 6) show that emissions generated in the raw material stage contribute significantly to all impact categories more than emissions generated in the production and transportation stages, demonstrating the resource-intensive nature of forklift and semi-trailer manufacturing.

Table 2 The inventory of forklift and semi-trailer manufacturing

Resources	Units	Quantity per $FU_{Forklift}$	Quantity per $FU_{Trailer}$	Dataset
Steel sheet	kg	3040	7859	User-defined*
Welding wire	kg	78	121.13	User-defined*
Welding gas total	kg	546.2	80.94	Oxygen
Nitrogen	kg	-	0.54	Argon, liquid, at plant
Oxygen	kg	531	37.9	Carbon dioxide
Argon	kg	12.2	34.9	
Carbon dioxide	kg	3	7.6	
Thinner	kg	9	66.3	Methyl ethyl ketone
Epoxy primer hardener	kg	0.2	2.3	User-defined*
Acrylic paint	kg	0.7	10.5	User-defined*
Fasteners (bolt, washer, nut M16, clamp)	kg	34.1	902	User-defined*
Buckle (32–34 MM)	kg	10	-	User-defined*
Shipping strap (34MM)	kg	9	32	User-defined*
Electricity (cutting, painting, assembling and packaging)	kWh	836	1299	User-defined*
Natural gas	m^3	8	17.4	Natural gas, burned in industrial furnace > 100 kW
Diesel (transportation)	l	2	16	Diesel
Gasoline (transportation)	l	6	10.4	Gasoline
Lubricant oil	kg	14.6	28	Lubricating oil
Water	m^3	4.3	6.9	Deionized water
Engine	kg	400	-	User-defined*
Cabin mat	kg	2	-	User-defined*
Steering wheel	kg	1	-	User-defined*
Armchair	kg	3	-	User-defined*
Wheel	kg	40	-	User-defined*
Axel	kg	160	-	User-defined*
Hydraulic arm	kg	16	-	User-defined*
Piston	kg	30	-	User-defined*
Fork	kg	50	-	User-defined*
Mast	kg	150	-	User-defined*

*Further details are found in the Supplementary Material

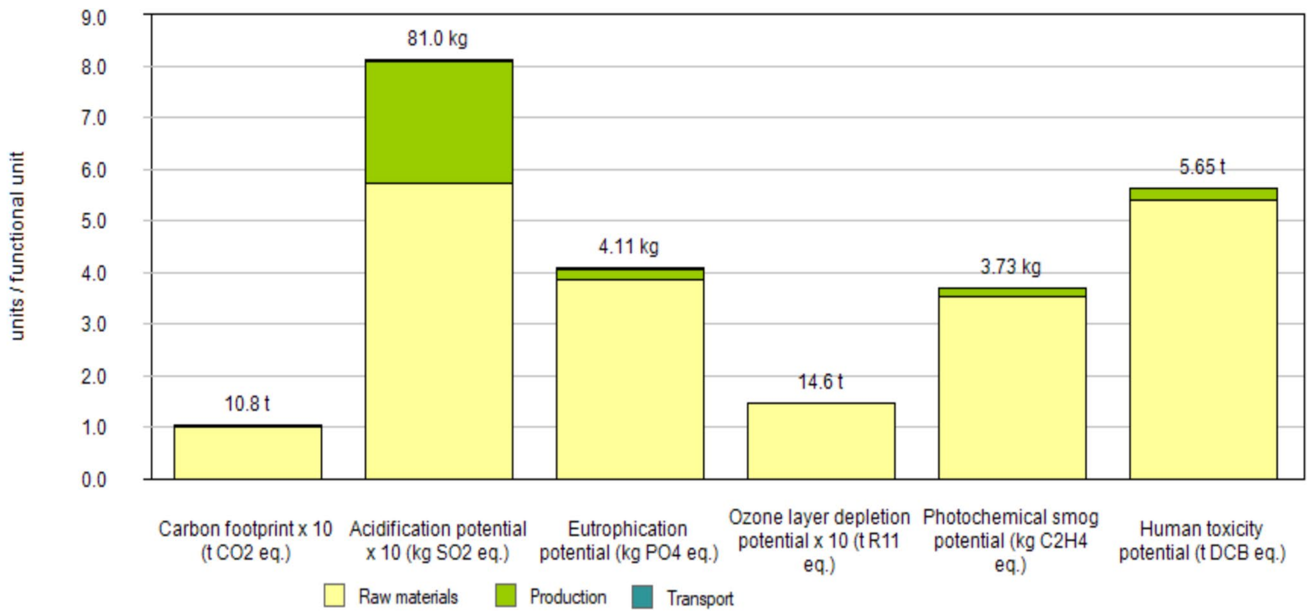


Fig. 5 The environmental impacts of $FU_{Forklift}$

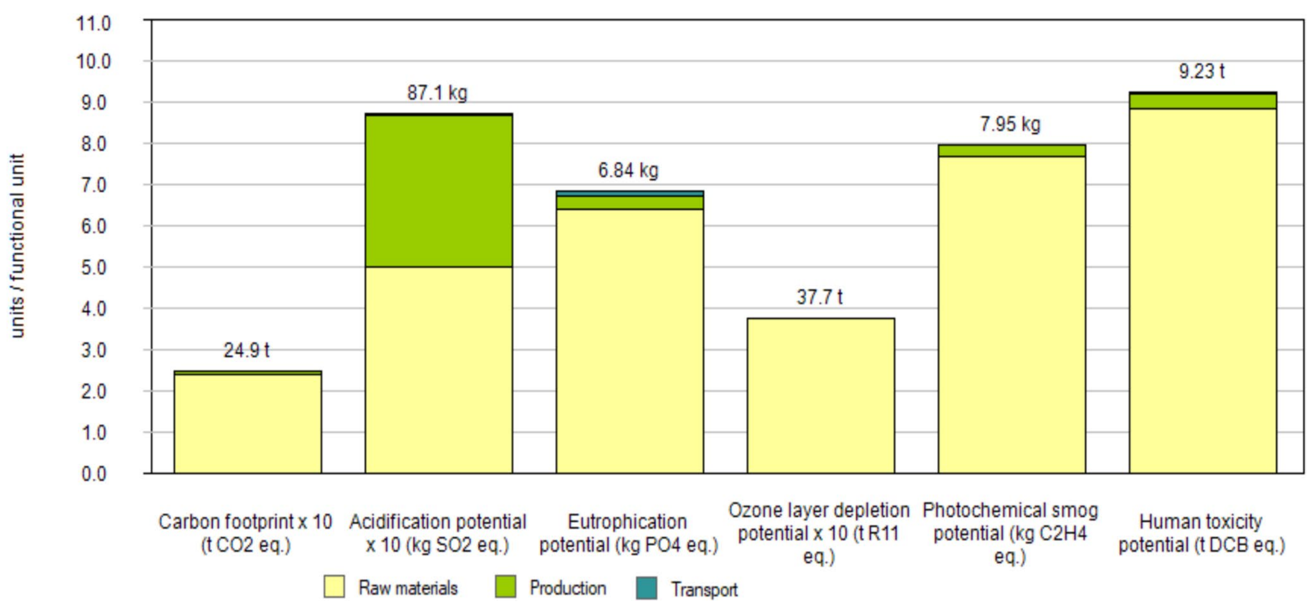


Fig. 6 The environmental impacts of $FU_{Trailer}$

Moreover, the CF result of the semi-trailer (Figure 6) indicates that producing a semi-trailer can cause 24.9 tons CO_2eq./$FU_{Trailer}$. Manufacturing of a forklift resulted in 10.8 tons of CO_2eq./$FU_{Forklift}$. Regarding the AP category, average emissions are respectively calculated as 81 kg SO_2eq./$FU_{Forklift}$ and 87 kg SO_2eq./$FU_{Trailer}$. On average, the production of 1 forklift generates 4.11 kg PO_4eq., 14.6 tons R11eq., 0.0037 tons C_2H_4eq., and 5.65 tons DCBeq. while the production of 1 semi-trailer generates 6.84 kg PO_4eq., 3.73 tons R11eq., 7.95 kg C_2H_4eq., and 5.65 and 9.23 tons DCBeq. in EP, ODP, POCP, and HTP categories, respectively. Compared with the studies reviewed in Table 1, raw material supplied in none of the LCA studies where the boundary included the use stage was highlighted as an environmentally polluting stage, as the contribution of the use stage to the environmental impact categories is generally higher.

4.1 Contribution of the product's life cycle stages to the carbon footprint

CF contributions associated with raw material acquisition, transportation, energy use, and direct emission in the production stage of forklift and semi-trailer are compared in Fig. 7. Evidently, raw material supply is the major contributor to CF in both forklift and semi-trailer production with a share roughly around 96%. The raw materials used for the semi-trailer emits 24 tons CO_2eq., surpassing the corresponding forklift production value by 10.3 tons CO_2eq. The second highest contribution to the carbon footprints of both products is associated with energy use during production, reaching 0.735 and 0.465 tons CO_2eq. for one semi-trailer and one forklift, respectively. Transportation of raw materials and direct emissions has the lowest shares in CF of semi-trailer (0.6%) and forklift (0.5%) production. It should be noted that Figures 5 and 6 only show the contribution of the main stages (raw material, production, and transportation), while Figure 7 provides information on the contribution of sub-production stages such as energy, packaging, and direct emissions.

The significant contribution of the raw material stage to all impact categories can be attributed to the high energy intensity and resource demand of steel production, which constitutes a substantial portion of the material composition in forklifts and semi-trailers. This finding aligns with studies such as Andersson and Diener (2020) and Scania (2021), which similarly emphasize raw material production as a major environmental hotspot due to its intensive energy use and emissions. However, it differs from studies like Ebrahimi et al. (2020), where the use stage dominated the environmental impacts. These differences highlight the importance of context, as our cradle-to-gate approach places greater focus on manufacturing and material extraction rather than operational phases. This analysis underscores the critical need for sustainable material selection and process optimization to minimize life cycle impacts.

4.2 Contribution of the input flows to the environmental impact categories

The contributions of input resources to the impact categories for forklift and semi-trailer production are shown in Figs. 8 and 9, respectively. In these figures, "steel components" refer to pieces such as pipes, steel sheets and sections, armchairs, pistons, wheels, axles, forks, fasteners, and hydraulic arms. "Painting materials" consist of paint, thinner, paste, and hardener. The highest shares of all impact categories for both products are from steel components, except for the AP category of forklift production, where the engine contributed the most due to its complexity. In the CF category of forklift production, contributions of steel components and engines were found to be 84.60% and 9.89%, respectively. On the other hand, in the CF category of semi-trailer production, steel components are the major contributor with a 93.50% share, followed by electricity consumption with a 2.71% share. In the AP category of the forklift, the engine is the major contributor, with a 37.29% share, followed by steel components (34.10%) and electricity consumption

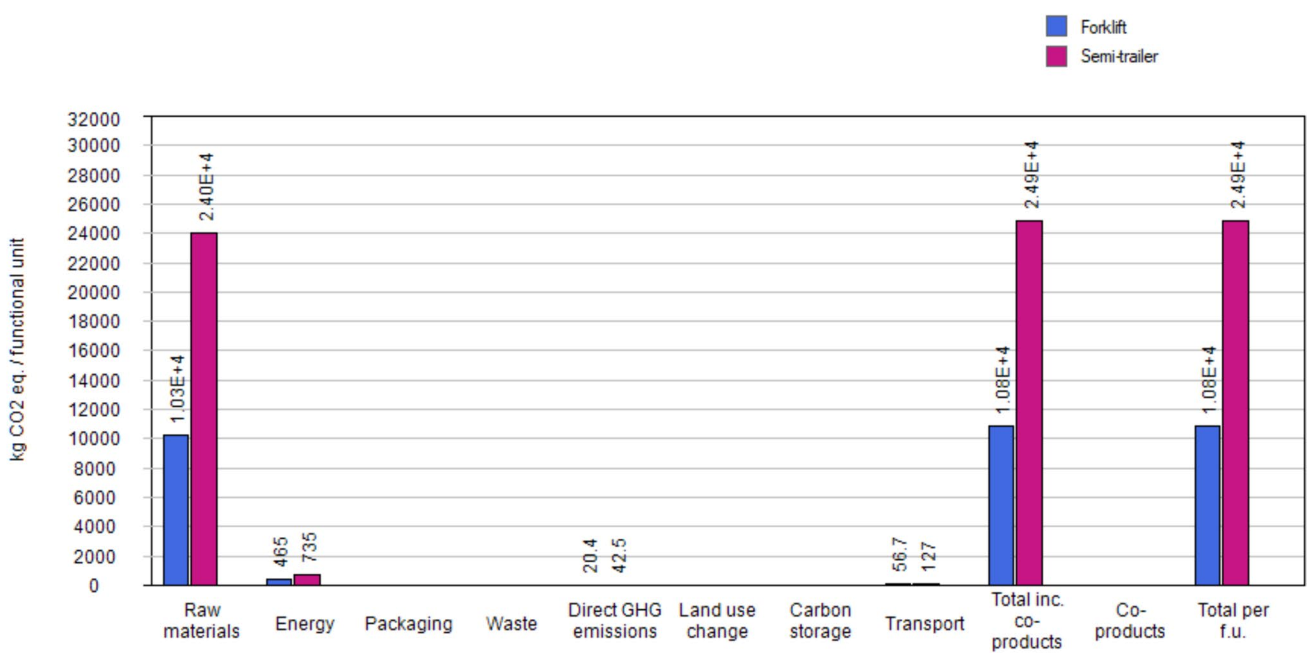


Fig. 7 Contributions of different life cycle stages to the carbon footprints of forklift and semi-trailer

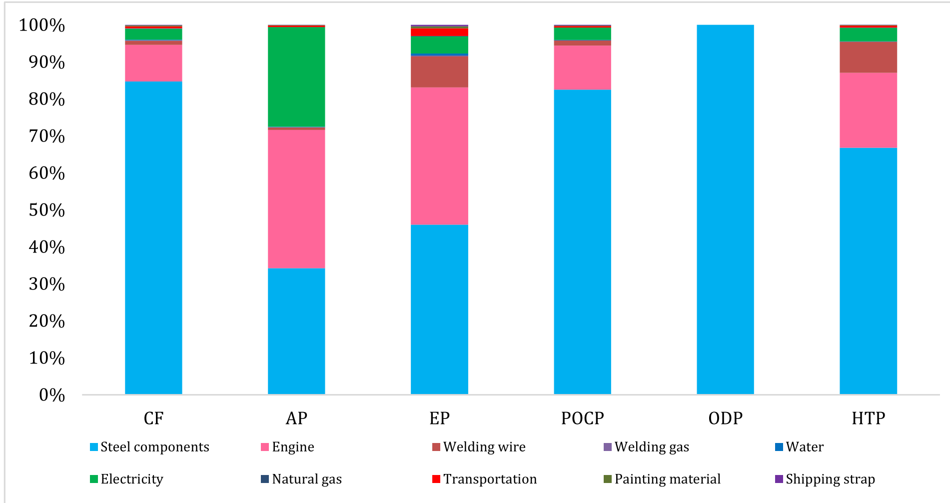


Fig. 8 Contribution of input resources of forklift production to the impact categories

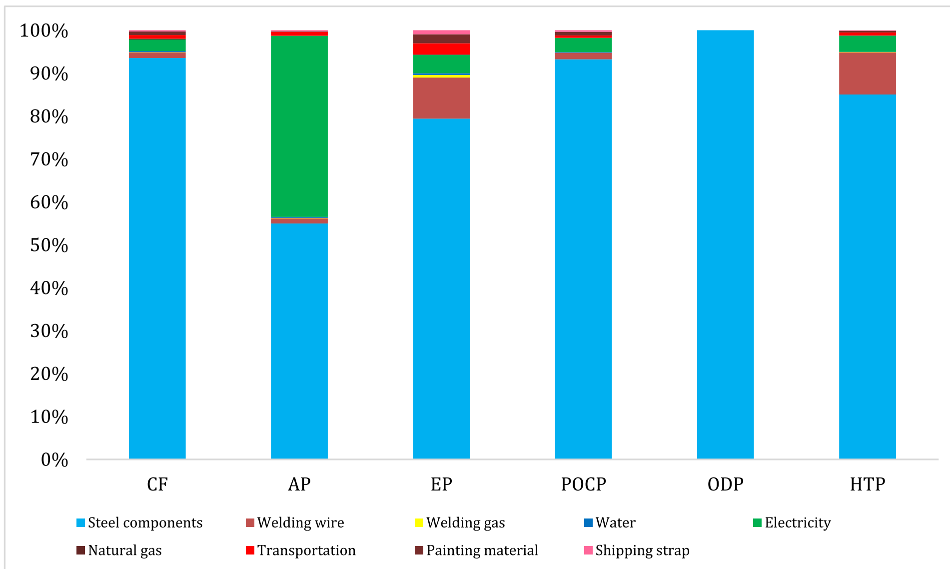


Fig. 9 Contribution of input resources of semi-trailer production to the impact categories

(26.88%). In semi-trailer production, steel components contribute 54.60%, whereas electricity consumption's contribution is 41.90% in the AP category, as shown in Fig. 9. Regarding the EP category, the second highest contributors are the engine (36.70%) in forklift and welding wire (9.60%) in semi-trailer production. In the POCP, ODP, and HTP categories, steel components are the predominant contributors in both forklift and semi-trailer productions. Finally, for both products, consumption of natural gas is the least contributor to all impact categories (with an average share of 0.05%), except for the CF category, where consumption of welding gas contributed the least (an average of 0.07% contribution).

In Figures 8 and 9, the term "steel components" encompasses all inputs directly related to the use of steel in the production process, including steel sheets, fasteners such as bolts, washers, and nuts, buckles, shipping straps, and structural components of the forklift and trailer such as the engine, axel, hydraulic arm, piston, fork, mast, and wheel (specific to the forklift). The term "painting material" aggregates inputs associated with the painting process, which include thinner, epoxy primer hardener, and acrylic paint. This categorization was adopted to reduce visual clutter and enhance readability in the figures while ensuring that key inputs were represented accurately. A detailed breakdown of these inputs is found in Table 2.

Differences in the contributions of input resources across impact categories stem from variations in material intensity and resource characteristics. For instance, the significant contribution of steel components to global warming potential reflects the carbon-intensive nature of steel production, which dominates the environmental profile for certain machinery types. Variations in electricity use between different machinery types are attributed to differences in manufacturing processes, machine sizes, and operational requirements. Equipment with extensive welding or machining processes typically exhibits higher electricity consumption, leading to disparities in environmental impact.

4.3 Comparison of heavy equipment manufacturing in terms of carbon footprint and energy

Table 3 compares the manufacturing of various gross-weight freight machinery and relevant components from the LCA perspective. In the table, only the life cycle stages of freight vehicles in CF, from the primary raw material supply to the manufacturing stage of previous studies, are considered. In order to be able to make an accurate CF comparison between different heavy-duty equipment, results are presented in terms of tons CO_2eq. per ton of machinery.

The highest CF is observed for manufacturing Quayside cranes with 5.28 tons CO_2eq. per ton machine (Wen et al. 2017). In quayside crane manufacturing, large crude steel consumption was highlighted as one of the main hotspots. Similarly, in diesel construction machine manufacturing, almost 70% of the machine's weight is made of steel, while cast iron and rubber rank second and third most used materials by quantity. Moreover, the highest share of CF for the diesel construction machine comes from the functional group components such as frame chassis, loader, and wheels, collectively constituting more than 70% of the machine's total mass.

Having studied an internal combustion engine truck with 7448 kg weight in a study conducted by Wolff et al. (2020), the production of chassis was highlighted as the main contributor to the total CF, and steel, with more than 50% consumption, was the predominant material, followed by iron with almost 20% consumption. Scania (2021) reported that the CF of manufacturing a diesel-based truck is 27.5 tons CO_2eq. of which 2.5 tons CO_2eq. was associated with manufacturing different parts, assembling processes, and inbound logistics. The highest contribution to the manufacturing of diesel trucks was found to be raw material extraction and refining. A regionalized LCA of a crawler excavator was carried out by Ebrahimi et al. (2020). They found out that the operation phase was the primary environmentally incompatible phase of the product's life cycle, and exhaustion of non-energetic resources during manufacturing and maintenance was critical. Considering the LCA of a conventional heavy-duty truck conducted in Wanniarachchi (2022), the highest share of GWP was related to the chassis.

Taking the CF result of Table 3 into account, the CF result of the forklift assessed in this study is comparable. The predominant contributor to the CF result of forklift manufacturing was steel consumption, which is in line with other studies. It should be mentioned, however, that despite the intensive use of resources during the production stage of heavy-duty machinery in the aforementioned studies, the operation phase has been regarded as the predominant life cycle hotspot of such machines.

In addition, some studies are carried out on the environmental impact evaluation of various components associated with heavy machinery, for instance, the manufacturing of exterior panels of a heavy truck, which is made of self-reinforced polyethylene terephthalate (SrPET) with 0.0107 tons CO_2eq. per ton panels by Poulikidou et al. (2016). The authors noted that using SrPET instead of composite glass fiber in the exterior panels could result in a 25% reduction in environmental impacts. The coating process was also identified as the main hotspot in the production phase of panels, with more than 60% contribution to the potential effects of global warming. The CFs of load

Table 3 Comparison of heavy-duty equipment in terms of CF

Heavy-duty machinery	CF per machine production (tons CO_2eq./ton machine)	Reference
Quayside crane	5.28	Wen et al. (2017)
Diesel excavator	1.99	Khan and Huang (2023)
Grader	2.44	Ebrahimi et al. (2020)
Crawler excavator	1.31	Ebrahimi et al. (2020)
Wheel loader	2.31	Ebrahimi et al. (2020)
Heavy-duty truck	2.3	Wolff et al. (2020)
Diesel-based truck	3	Scania (2021)
Conventional diesel truck	1.8	Wanniarachchi (2022)
Diesel-based delivery truck	1.29	Zhao et al. (2016)
Forklift	*2.8*	*Present study*
Heavy components		
2 exterior panels of a truck	0.0107	Poulikidou et al. (2016)
Semi-trailer	*1.57*	*Present study*
Load box of a semi-trailer	3.4	Teixeira et al. (2009)

box manufacturing made of wood, steel, and a three-layer synthetic (TLS) related to a semi-trailer were compared by Teixeira et al. (2009). The TLS panel was found to have a better CF result (5.11 tons of CO_2eq. per ton box produced). However, the authors emphasized that manufacturing TLS panel load boxes had a greater impact than manufacturing other panels. Considering the semi-trailer manufacturing in the present study, a better CF result was observed compared to the TLS panel, even though more than 90% of the CF result of the semi-trailer was associated with steel consumption.

It should also be acknowledged that the variation between the CF scores presented in Table 3 can partially be attributed to the fact that geography can significantly affect environmental impacts. To be more precise, the electricity mix, the type of fossil fuel used for thermal energy supply, and transportation distances could be quite different from location to location, and these variations can lead to considerable changes in the environmental impacts.

The electricity consumption results during the manufacturing stage of heavy-duty equipment are presented in Table 4. It should be noted that data regarding electricity use was not provided in all studies; thus, the comparison of electricity use was narrowed down to limited case studies.

Considering the results, forklifts demonstrated higher electricity use than equipment studied in Wolff et al. (2020). Considering the internal combustion engine studies in Wolff et al. (2020), the electricity use data was obtained from the literature, while the provision of such data related to quayside cranes was site-specific data. On the other hand, electricity consumption for manufacturing exterior panels of a heavy-duty vehicle made of SrPET was significant (Poulikidou et al. 2016). The authors mentioned that the electricity use of fiber production is based on the ELCD database (European Life Cycle Database), while compression and molding process energy use is based on their estimation. What is derived from Table 4 is that (A) limited manufacturing data related to various heavy equipment are available, which hinders regional environmental impact comparison between machinery, and (B) manufacturing of forklifts can be considered to be an electricity-intensive process.

Notably, the carbon footprint findings in this study are lower than those reported in analyses conducted in China. This discrepancy can be linked to the higher environmental impact of the Chinese electricity grid, which relies heavily on coal, compared to the relatively lower carbon intensity of electricity in the regions analyzed in this study. Limitations such as reliance on average data in some cases and the exclusion of upstream processes are also acknowledged to provide a balanced perspective and facilitate a nuanced interpretation of the findings.

4.4 Environmental impact reduction scenarios

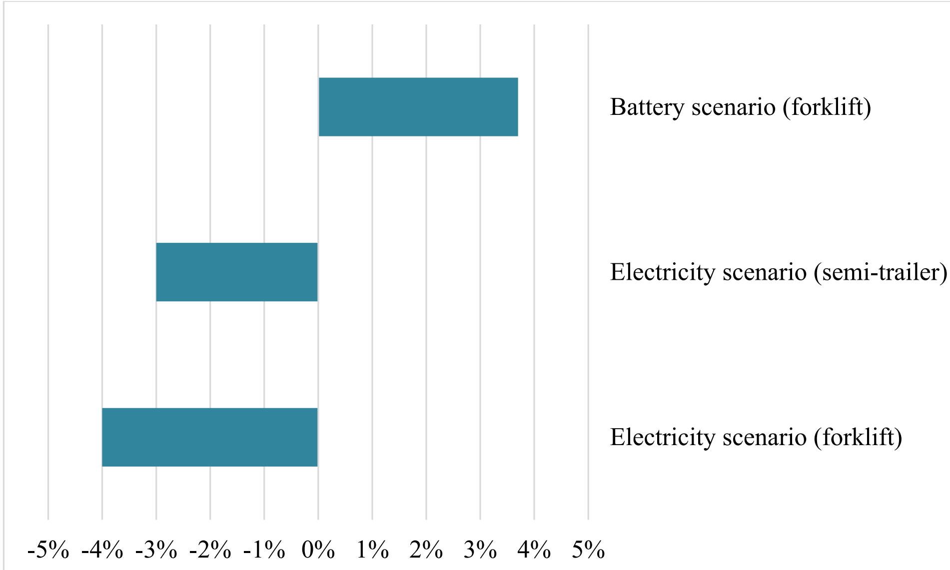
In conjunction with identifying the major hotspots in the present study, the influence of two alternative scenarios on the environmental impact results of considered equipment was investigated. Considering the significance of the CF category, the results of considering such scenarios were calculated for the CF category. The consumption of electricity during the production stage is one of the major hotpots. Considering the electricity mix in Türkiye (with more than 70% reliance on fossil fuel sources), an improvement to the share of renewable energies is the main assumption in the energy scenario. In this context, an increase to the share of hydro, solar, and wind energies (Gumus 2024) in the total electricity mix generated in Türkiye in 2023 was adopted (5.7% for solar, 10.7% for wind, and 19.7% hydro).

On the other hand, the contribution of diesel engines to the CF result of forklifts was approximately 10%, making it the second highest contributor to the CF category. In line with the electrification trend of vehicles, including heavy equipment, switching from a diesel-based forklift to an electric forklift is assumed to be the second scenario. In this context, it is assumed that the electric forklift will be equipped with a lithium-ion battery (48 V/540 Ah). The GWP of an electric battery production was obtained from (Scania 2021), considering 74 kg CO_2eq/kWh of installed battery capacity. The results of CF changes associated with the consideration of electricity and battery scenarios are depicted in Figure 10. Expectedly, switching to an electricity mix with a higher share of renewable energies led to a

Table 4 Comparison of heavy-duty equipment in terms of electricity use during manufacturing

Heavy-duty machinery	Electricity use per machine production (kWh/ton machine)	Location	Reference
Quayside crane	46	China	Wen et al. (2017)
Heavy-duty truck	98.7	Europe	Wolff et al. (2020)
Forklift	*216.8*	*Türkiye*	*Present study*
Heavy components			
2 exterior panels of a truck	2900	Europe	Poulikidou et al. (2016)
Semi-trailer	*81.8*	*Türkiye*	*Present study*
Load box of a semi-trailer	55.1	Brazil	Teixeira et al. (2009)

Fig. 10 Percentage change to CF results associated with different scenarios



reduction in CF, while switching to an electric battery was found to increase the CF result by almost 3.7%. The latter result is in line with other LCA studies, where the production of vehicle batteries was highlighted as environmentally less favorable (Balboa-Espinoza et al. 2023; Koroma et al. 2022, Scania 2021). Further analysis regarding the applicability of switching to an electric battery in the reduction of CF related to the operation of the forklift is outside the scope of the present study since the use stage was excluded from our system boundaries.

The scenario analysis provides critical insights into the feasibility, trade-offs, and broader implications of adopting alternative strategies, such as changes in the electricity mix and increased reliance on battery usage, in the context of industrial machinery manufacturing. While shifting to a cleaner electricity mix shows clear potential for reducing environmental impacts, the battery usage scenario presents a more complex picture, with the analysis indicating a net negative impact.

The adverse environmental outcomes associated with the battery scenario stem primarily from the production phase of batteries, which is highly resource- and energy-intensive. The extraction and processing of critical materials, such as lithium, cobalt, and nickel, contribute significantly to global warming potential (GWP), acidification potential (AP), and resource depletion categories. Furthermore, the energy requirements of battery manufacturing, often linked to fossil-fuel-intensive electricity grids in supplier regions, amplify these impacts.

Despite these challenges, battery technology offers opportunities for emission reductions in the operational phase of machinery by replacing fossil fuel–based energy sources. However, the benefits are heavily dependent on the lifecycle conditions, particularly the electricity mix used during production and operation. For instance, transitioning to renewable energy in battery production and machinery operation could mitigate many of the adverse impacts observed.

The scenario analysis highlights important trade-offs, such as balancing the environmental costs of battery production against its potential to decarbonize operations. To address these challenges, potential solutions include optimizing battery recycling processes, improving energy efficiency in manufacturing, and advancing research into alternative, less resource-intensive battery chemistries. Additionally, promoting circular economy principles, such as reusing and repurposing batteries, could reduce the demand for virgin materials.

By critically reflecting on these scenarios, this study underscores the need for a systemic approach to sustainability, considering both upstream and downstream effects. It also emphasizes that transitioning to cleaner technologies must be accompanied by advancements in supply chain practices and energy systems to ensure long-term environmental benefits.

5 Summary

This part directly addresses the research questions outlined at the beginning of this study. For the first question, "What are the environmental impacts of industrial machinery manufacturing in Türkiye?" the analysis reveals significant contributions to global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) across all assessed processes. The primary drivers of these impacts are the production and processing of steel components, which dominate the material composition of forklifts and trailers.

Steel-related processes contribute heavily to GWP due to the carbon-intensive nature of steel production and the energy requirements of welding and assembly operations. Acidification and eutrophication potentials are similarly influenced by raw material processing and energy consumption emissions. Furthermore, the electricity grid mix in Türkiye, which relies on a combination of fossil fuels and renewable energy sources, plays a critical role in determining the carbon footprint of these manufacturing processes. Addressing the second question, "Which stages of the production process contribute the most to these environmental impacts?" the findings consistently point to the raw material stage as the predominant contributor across all impact categories. This is attributed to the high energy demands of steel production and the associated emissions. For instance, steel sheet production alone accounts for the majority of emissions in both the forklift and trailer manufacturing processes, as reflected in the life cycle inventory results. In contrast, the transportation and assembly stages exhibit relatively lower contributions to environmental impacts partly due to their limited energy consumption and the localized nature of production logistics. These observations align with existing literature on industrial machinery manufacturing, highlighting the upstream stages, particularly raw material extraction and processing, as critical environmental hotspots.

This study underscores the importance of sustainable material sourcing, improving energy efficiency in raw material production, and transitioning to lower-carbon electricity sources. By addressing these critical intervention points, the environmental footprint of industrial machinery manufacturing in Türkiye can be significantly reduced. These findings not only provide a comprehensive assessment of environmental impacts but also identify actionable pathways for enhancing sustainability in the manufacturing sector.

6 Conclusion

This study provides the first detailed life cycle assessment of industrial machinery manufacturing in Türkiye, focusing on the raw material acquisition, production, and transportation stages. The findings reveal that the raw material stage is the predominant contributor to all assessed environmental impact categories, with significant emissions observed for both semi-trailer production (24.9 tons CO_2eq per unit) and forklift production (10.8 tons CO_2eq per unit). Steel consumption emerged as the key hotspot, accounting for 93.50% of the emissions in semi-trailer production and 84.60% in forklift production. Additionally, the production stage contributed substantially to the carbon footprint (CF), primarily through electricity use, with 0.735 tons CO_2eq for semi-trailer and 0.465 tons CO_2eq for forklift manufacturing. These findings underscore the resource- and energy-intensive nature of heavy equipment manufacturing in Türkiye and highlight the critical role of material sourcing and energy use in determining the overall environmental impact.

Two scenarios are developed to explore potential mitigation strategies: transitioning to an electricity mix with a higher share of renewable energy and substituting diesel engines with electric batteries in forklifts. The electricity scenario demonstrated a notable reduction in CF for both forklifts and semi-trailers, emphasizing the importance of renewable energy adoption in reducing the environmental burden of manufacturing. However, the battery scenario resulted in an increased CF for forklift production, primarily due to the resource- and energy-intensive nature of battery manufacturing, particularly the extraction and processing of critical materials such as lithium and cobalt. These findings highlight the importance of considering trade-offs when evaluating emission reduction strategies and suggest that integrating cleaner electricity sources and optimizing battery production processes will be critical for achieving long-term sustainability.

The study's results directly impact compliance with international environmental standards such as the Carbon Border Adjustment Mechanism (CBAM). Identifying key hotspots, such as steel production and electricity use, provides actionable guidance for aligning industrial processes with CBAM requirements. Industry stakeholders can adopt material efficiency practices, such as increasing the use of recycled steel and exploring alternative, less carbon-intensive materials to reduce dependency on virgin raw materials. Transitioning to renewable energy sources and investing in cleaner production technologies can further mitigate emissions associated with the energy-intensive stages of manufacturing. Process innovations to improve energy efficiency and minimize resource wastage are also essential for achieving sustainability goals.

Policymakers are crucial in facilitating these transitions by developing regulatory frameworks that incentivize sustainable manufacturing practices. Providing subsidies for renewable energy integration, offering tax benefits for using recycled materials, and promoting adopting advanced technologies can accelerate the industry's shift toward more sustainable practices. Additionally, training programs to enhance industry's technical capacity will ensure manufacturers are well-prepared to meet international environmental standards and compete effectively in global markets.

The findings of this study extend beyond Türkiye and have far-reaching implications for the heavy machinery sector and environmental sustainability at large. By pinpointing major environmental hotspots, such as steel consumption and electricity use, this research provides actionable insights that can guide sustainability efforts across the industry. The focus on localized data ensures that the findings are relevant to Türkiye's industrial context while offering a model for similar assessments globally. From an environmental sustainability perspective, this study supports global efforts to decarbonize industrial processes, reduce resource dependency, and transition toward a circular economy. Highlighting actionable strategies for emission reduction, the research emphasizes the critical need for systemic changes in manufacturing practices to achieve broader environmental goals. By applying a midpoint-level assessment across six environmental impact categories, this study offers a multi-dimensional view of the environmental burdens associated with heavy machinery production. Beyond reaffirming known hotspots, the results emphasize the importance of material choice, design strategies, and regional energy profiles in shaping environmental performance. The use of primary data from local manufacturers also contributes to improving LCA relevance in the context of developing economies.

Despite its contributions, the study has several limitations that should be addressed in future research. One major limitation is the reliance on outdated electricity data for Türkiye, which may not accurately reflect the current grid mix or renewable energy contributions. Future analyses should integrate updated and region-specific electricity data to capture the environmental impacts of energy use better. Additionally, secondary data were used for specific components, which may not reflect the actual manufacturing processes and materials used in the specific context of Türkiye. Primary data collection through on-site assessments and direct industry collaborations is essential for improving data accuracy and reliability. Furthermore, this study excluded the use and end-of-life phases from its scope. Future research should expand the system boundaries to include these phases, enabling a comprehensive cradle-to-grave assessment. Specific impacts such as land use, water footprint, or abiotic resource depletion could be evaluated to provide a holistic view of environmental performance. Incorporating social and economic dimensions, such as worker safety and operational costs, could further enrich the analysis and offer a multi-dimensional perspective on sustainability. As part of a larger project focusing on circular economy applications, this study serves as the LCA foundation upon which further analyses will be built. In a separate forthcoming publication, we explore end-of-life scenarios, material recovery potentials, and ecodesign-based interventions using the same case studies. This division of content was intentional to avoid redundancy and ensure thematic clarity between publications. Nonetheless, the potential for integrating circular economy strategies into life cycle thinking is acknowledged, and the present study lays the groundwork for such future analyses.

To sum up, this study advances LCA practice by demonstrating how disaggregated impact analysis can reveal component-level opportunities for environmental improvement. These insights can inform manufacturers, suppliers, and policymakers in their efforts to reduce the environmental footprint of industrial products through smarter material sourcing, process optimization, and design for longevity. Future research could extend this work through cradle-to-grave modeling and comparative assessments using updated LCIA methods and regionalized databases.

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Data availability The data generated or analyzed during this study are available upon reasonable request. Researchers interested in accessing the data for academic or verification purposes may contact the corresponding author at gorkem.uctug@ieu.edu.tr to request the dataset.

Material and code availability The study does not involve the creation of new materials or code. Therefore, there are no specific materials or code associated with this research. The analyses and findings are based on established methodologies, and any relevant information is provided in the manuscript.

Declarations

Ethics approval This study does not involve human subjects, animals, or any sensitive data. As such, ethical approval was not required for the research. All applicable legal and ethical standards have been strictly adhered to throughout the study.

Consent to participate Participants' informed consent was not applicable for this study, as it did not involve human subjects. The research focused on the life cycle assessment of heavy machinery manufacturing and did not require the collection of personal or identifiable information.

Competing interests The authors declare no competing interests.

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