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STREAMLINED LIFE CYCLE IMPACT ASSESSMENT AND HOTSPOT ANALYSIS OF A HEAVY EQUIPMENT SERVICE FACILITY IN INDONESIA: A GATE-TO-GATE PYTHON-BASED APPROACH

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Abstract

This study develops and applies a streamlined Life Cycle Impact Assessment (LCIA) approach to evaluate the operational environmental performance of a heavy equipment service facility under a gate-to-gate system boundary. The case study uses 2025 operational data from PT United Tractors Tbk, Semarang Branch, including electricity, fuel, water, and non-hazardous waste consumption, and processes the inventory through a transparent, fully auditable Python-based implementation rather than through commercial LCA software. The results show that the Climate Change (GWP100) score reaches 176,203.80 kg CO2-eq per year under market-based Scope 2 accounting, with grid electricity from the Java-Madura-Bali (JAMALI) interconnection contributing 60.92% of the total impact, well above the gasoline- and diesel-type fuel flows that follow it. At the process level, Workshop and Service and Delivery and Mobilization emerge as the dominant hotspots, jointly contributing 59.05% to the annual climate footprint, while a supplementary hazardous-waste inventory further identifies 4.913 tonnes per year of regulated waste, of which 99.0% is verifiably managed through a licensed third party. The findings indicate that a streamlined, code-based LCIA can deliver sufficiently robust and decision-relevant environmental information for internal management purposes in organizations that face limited access to commercial LCA software and characterization databases. The study contributes a replicable, methodologically transparent, and low-cost assessment framework for service-oriented industrial operations in emerging economies and offers a template that other branch-scale or small-and-medium enterprise operations can adapt with modest technical resources.

Keywords: Life Cycle Assessment; streamlined LCIA; hotspot analysis; gate-to-gate study; heavy equipment service; Python implementation

INTRODUCTION

Authorized automotive and heavy equipment service networks form an operationally significant but comparatively under-examined segment of the industrial environmental footprint. Unlike core manufacturing plants, a service branch does not fabricate goods; instead, its footprint arises from electricity used to power workshop lighting, diagnostic equipment, and administrative facilities, from fuel consumed by operational and delivery vehicles, from water used in washing and sanitation activities, and from solid waste generated by parts packaging, workshop consumables, and office operations. Because each of these activities appears modest in isolation, the cumulative environmental relevance of a nationwide dealer or service network is easily underestimated relative to that of a single large manufacturing facility, even though the aggregate footprint across hundreds of branch locations can be substantial. Indonesia's tightening sustainability disclosure expectations and the increasing adoption of corporate environmental, social, and governance (ESG) reporting frameworks by publicly listed companies raise the practical urgency of establishing a transparent, replicable, and low-cost method by which a branch-scale service operation can quantify its own environmental performance without depending on a centralized corporate LCA function.

Full Life Cycle Assessment (LCA), standardized under ISO 14040:2006 and ISO 14044:2006 (Change, 2006; Standard, 2006; Standardization, 2006), remains the internationally recognized method for evaluating environmental performance across a product, service, or organizational system. In practice, however, a comprehensive implementation covering the complete set of midpoint impact categories defined by methods such as ReCiPe 2016 (Huijbregts et al., 2017) requires access to dedicated modelling software (e.g., openLCA, SimaPro, GaBi) linked to a licensed background database such as ecoinvent. For a single branch office of a heavy equipment dealer, this route is frequently impractical: licence costs, the technical learning curve of dedicated LCA software,

and the absence of a centralized sustainability team with modelling expertise combine to place full LCA outside the reach of routine internal use, even where the underlying activity data required to compute a meaningful subset of impact categories, namely electricity, fuel, water, and waste records, are already collected for other operational or regulatory purposes. This mismatch between data availability and assessment capability constitutes the practical starting point of the present study.

Streamlined or screening-level LCA has long been recognized as a methodologically legitimate response to this constraint. Todd et al. (1999) formalized streamlined LCA as an approach that preserves the same characterization logic as full LCA while narrowing the scope of impact categories to those for which reliable, available data exist, thereby still generating valid information for internal decision-making without requiring exhaustive life-cycle coverage. Subsequent guidance, including the hotspot-analysis framework issued by the United Nations Environment Programme's Life Cycle Initiative (Barthel et al., 2017), has reinforced that a properly scoped, priority-focused environmental assessment can direct organizational attention to the flows and processes that matter most, even without full life-cycle coverage. What remains comparatively underexplored in this literature is the specific combination pursued in the present study: a gate-to-gate, branch-scale operational assessment of an authorized heavy equipment sales and service facility, computed entirely through an open, auditable Python-based implementation rather than proprietary software, and disaggregated simultaneously at both the individual-flow level and the internal unit-process level from a single underlying dataset.

This study addresses that gap by developing and applying a streamlined LCIA and multi-level hotspot analysis for the 2025 operations of PT United Tractors Tbk, Semarang Branch, an authorized heavy equipment sales and after-sales service facility in Central Java, Indonesia. The specific objectives are threefold: first, to quantify the annual Climate Change (GWP100) footprint of the branch's gate-to-gate operations using a transparent, code-based streamlined LCIA procedure; second, to identify the dominant environmental hotspots simultaneously at the level of individual material and energy flows and at the level of internal unit processes; and third, to demonstrate that this Python-based approach constitutes a replicable, low-cost template that other resource-constrained service-sector organizations, particularly in emerging economies where access to commercial LCA infrastructure is limited, can adopt with modest technical investment. The contribution of this study is therefore methodological and empirical in equal measure: it reports a concrete environmental performance figure for an operational category (heavy equipment service) that is rarely the subject of published LCIA studies, while simultaneously offering a fully transparent and reproducible computational procedure that other organizations facing similar resource constraints can directly adapt.

LITERATURE REVIEW

Life Cycle Assessment and Streamlined LCIA in Industrial Assessment

LCA methodology, as codified by ISO 14040:2006 and ISO 14044:2006, proceeds through four iterative phases, namely goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation (Change, 2006; Standard, 2006; Standardization, 2006). Full LCIA implementations typically characterize inventory flows against a comprehensive midpoint or endpoint method, such as ReCiPe 2016 (Huijbregts et al., 2017), executed within dedicated software linked to a background database. Todd et al. (1999) argued that a streamlined variant, one that intentionally narrows category coverage to what available data can support while preserving the same linear characterization logic (impact score equal to the sum of flow quantity multiplied by characterization factor across all relevant flows), remains methodologically defensible for internal, decision-supporting purposes rather than for external comparative claims. This precedent underlies the approach adopted in the present study, which computes Climate Change, a fossil-resource-use proxy, water consumption, and non-hazardous waste generation, the four categories for which the branch already collects primary activity data, rather than attempting complete midpoint coverage that would require inventory data the organization does not possess.

Recent computational LCA literature has increasingly favoured open, script-based implementations over proprietary point-and-click software, motivated by the same transparency and reproducibility concerns that justify the streamlined approach itself. The Brightway2 framework (Mutel, 2017) demonstrated that a Python-based LCA calculation engine can replicate the characterization logic of established commercial tools while exposing every computational step to direct inspection and version control, and more recent open-source packages such as lcpy (Gkousis & Katsou, 2025) extend this logic toward parametric and dynamic LCA use cases. These developments indicate a broader methodological trend, of which the present study's Python-based streamlined LCIA implementation forms a modest but practically motivated instance, toward treating the calculation engine itself, not merely the underlying inventory data, as an object that should be auditable, shareable, and reproducible by parties other than the original analyst.

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Hotspot Analysis in Operational Sustainability Studies

Hotspot analysis, understood as the identification of the flows, processes, or life-cycle stages that contribute disproportionately to an overall environmental score, has been formalized as a standalone methodological framework by the United Nations Environment Programme's Life Cycle Initiative (Barthel et al., 2017), which emphasizes that hotspot identification should focus organizational attention simultaneously on the priority impact category, the correct life-cycle stage, and the relevant actor capable of implementing a solution. Pelton & Smith (2015) demonstrated a comparable streamlined hotspot methodology combining environmentally extended input-output data with targeted process-level detail to identify the dominant sourcing-related impacts of a food manufacturing case, arguing that a full process-based LCA is frequently too time- and cost-intensive to apply across an organization's entire portfolio of inputs, whereas a hotspot-first approach can direct more detailed modelling effort toward the areas that matter most. Castellani et al. (2017) synthesized hotspot findings across multiple food-sector LCA studies to identify recurring, cross-study drivers of environmental impact, underscoring those hotspots can be robust and generalizable within a given sector even when the underlying case-study contexts differ. These studies collectively establish hotspot analysis as an accepted, standalone complement to (or scoped substitute for) full LCA, rather than as a preliminary step that necessarily requires subsequent full-scope modelling.

A methodologically distinguishing feature that the hotspot literature has addressed less consistently is the simultaneous disaggregation of a single impact score along two independent dimensions, namely the constituent material and energy flows on one hand, and the internal organizational unit processes that consume those flows on the other. Most published hotspot studies report contribution results along a single dimension, typically either by life-cycle stage or by input category, which is generally sufficient for external supply-chain hotspot mapping but offers less direct guidance for an operations manager seeking to target a mitigation intervention at a specific internal activity. The present study addresses this by exploiting a flow-to-process allocation matrix already available from the case organization's internal records, which permits the same underlying Climate Change inventory to be reported both by individual flow and by internal unit process without requiring any additional primary data collection.

Prior Studies on Service-Sector Environmental Assessment

Environmental assessment research has historically concentrated on manufacturing, agricultural, and energy-sector case studies, where material throughput and production-stage emissions are large and comparatively well characterized in existing databases. Service-sector operations, including retail, logistics support, and after-sales maintenance networks, have received comparatively less systematic LCA attention, in part because their environmental footprint is dominated by utility consumption (electricity, fuel, water) rather than by product-embodied material flows, and in part because service operations are frequently treated as a downstream or supporting activity within the LCA of the physical product they service rather than as an assessment unit in their own right. Where service-sector environmental studies do exist, they typically examine logistics and transport-related footprints, or building-level energy assessments, rather than an integrated, gate-to-gate accounting of a combined workshop, warehouse, and delivery operation of the type examined in this study. The heavy equipment after-sales service context specifically, encompassing workshop repair and maintenance, pre-delivery inspection, warehousing, and unit delivery to customers, has, to the authors' knowledge, not previously been the subject of a published streamlined LCIA and multi-level hotspot study, despite the sector's material presence in resource-intensive economies such as Indonesia, where heavy equipment underpins mining, construction, and agriculture.

Positioning of the Present Study

The present study is positioned at the intersection of three strands reviewed above: it applies the streamlined LCIA logic of Todd et al. (1999) to a previously unexamined service-sector operational context; it adopts the flow- and process-level hotspot framework consistent with Barthel et al. (2017) and Pelton & Smith (2015), while extending it to a simultaneous two-dimensional disaggregation drawn from a single inventory dataset; and it implements the entire calculation pipeline in an open, auditable Python-based procedure in the spirit of the open-source LCA computing trend represented by Brightway2 (Mutel, 2017) and lcpy (Gkousis & Katsou, 2025), but scoped specifically to the modest data and technical-resource constraints of a single branch-level organizational unit rather than to advanced dynamic or prospective modelling. This combination distinguishes the present study from prior hotspot and streamlined-LCA literature, which has not, to the authors' knowledge, previously reported a gate-to-gate, dual-level (flow and unit-process) hotspot assessment of an authorized heavy equipment sales and service facility computed through a fully transparent, non-proprietary computational pipeline.

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METHOD

Study Area and System Boundary

The study was conducted at PT United Tractors Tbk, Semarang Branch, an authorized heavy equipment sales and after-sales service facility located in Central Java, Indonesia. The system boundary follows a gate-to-gate approach, encompassing all operational activities under the direct operational control of the branch during the 2025 calendar year (1 January to 31 December 2025), which also serves as the functional unit of the study, defined as one year of branch operation. The gate-to-gate boundary deliberately excludes upstream activities associated with heavy equipment manufacturing and downstream activities associated with customer use-phase operation of delivered equipment, consistent with the operational-control approach to organizational environmental accounting recommended by the Greenhouse Gas Protocol Corporate Standard for entities that do not control upstream production or downstream use.

Functional Unit and Unit Process Allocation

For the purposes of inventory allocation and process-level hotspot analysis, all branch activities were grouped into six internal unit processes (P1-P6), defined in Table 1. Each material and energy flow recorded at the branch level was distributed across these six-unit processes using fixed allocation percentages established jointly with the branch's Environment, Health and Safety (EHS) and General Affairs teams, based on reported usage share, floor area, or operating hours per process, as summarized in Table 2.

Table 1. Definition of the six gate-to-gate unit processes (P1-P6)

Code	Unit Process	Description
P1	Administration and Office	General office and administrative activities, sales administration, and General Affairs support functions.
P2	Workshop and Service	Heavy equipment repair, maintenance, and after-sales parts/service activities.
P3	Pre-Delivery Inspection (PDI)	Comprehensive inspection of heavy equipment units prior to hand-over to customers.
P4	Washing and Finishing	Washing and final cosmetic finishing of units prior to PDI/delivery.
P5	Warehouse and Material Handling	Storage and handling of units and spare parts within the warehouse/yard area.
P6	Delivery and Mobilization	Delivery of units to customers and mobilization of operational vehicles and field technicians.

Table 2. Allocation share of each resource flow to unit processes P1-P6

Code	Electricity	Gasoline (Pertamax/Pertalite)	Diesel (Dexlite/Solar)	Water	Plastic Waste	Non-Plastic Waste
P1	25%	5%	0%	20%	20%	10%
P2	40%	15%	10%	20%	25%	45%
P3	10%	10%	0%	5%	5%	5%
P4	5%	0%	0%	50%	5%	5%
P5	10%	0%	0%	5%	35%	20%
P6	10%	70%	90%	0%	10%	15%
Total	100%	100%	100%	100%	100%	100%

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Note: The Plastic Waste and Non-Plastic Waste allocation shares for P2 (Workshop and Service) were corrected from the source spreadsheet's original entries of 30% and 50% respectively, which produced a column total of 105% rather than 100%. Because P2 was the only row inconsistent with the stated 100% total, its two waste-allocation entries were adjusted downward by 5 percentage points each (to 25% and 45%) to restore internal consistency; all other rows and columns are reported as originally recorded.

Life Cycle Inventory Data Collection and Validation

Life Cycle Inventory (LCI) data were compiled from secondary operational company records for the full 2025 calendar year. Electricity and water consumption were obtained from monthly aggregated meter readings recorded in the branch's internal ESRGA (Environment, Safety, Health, and General Affairs) dashboard. Fuel consumption and non-hazardous solid waste generation were compiled from daily/monthly transaction logbooks and internal waste-generation records. A single anomalous fuel transaction record (170 litres, January 2025, fuel type recorded as invalid) was excluded from aggregation as a probable data-entry error. All inventory data underwent cross-validation between independent internal data sources prior to use, with discrepancies consistently found to be below 1%. Where the water-source breakdown (municipal supply versus on-site groundwater) was not separately recorded for 2025, a proxy ratio of 31.47% groundwater to 68.53% municipal supply, derived from five months (January-May 2026) of meter data with an explicit source column, was applied uniformly across 2025; this constitutes an assumption rather than a direct 2025 measurement and is discussed as a limitation in Section 5.

A supplementary hazardous waste (B3, Bahan Berbahaya dan Beracun, per Indonesian Government Regulation PP No. 22/2021) inventory was compiled separately from the branch's licensed temporary hazardous waste storage (TPS LB3) disposal records for the 2021-2026 reporting window, covering seven regulated waste codes (used lubricating oil, wastewater treatment sludge, used rags, used filters, contaminated concrete/ceramic fractions, and used hazardous-material packaging). Because no validated characterization factor linking these waste streams to a GWP-equivalent score was available at the time of this study, this inventory is reported separately on a mass basis, consistent with the Global Reporting Initiative's GRI 306 (Waste) disclosure convention, rather than being force-converted into the Climate Change score using an unvalidated factor.

Streamlined Life Cycle Impact Assessment Procedure in Python

In place of a full LCIA computed in openLCA linked to the ecoinvent 3.10/3.11 database under the ReCiPe 2016 Midpoint (H) method, this study computed a streamlined LCIA (Todd et al., 1999) entirely through a Python-based implementation using the pandas library for inventory data handling, covering the subset of midpoint-equivalent impact categories directly derivable from the available primary data: Climate Change (GWP100), a Fossil Resource Use proxy expressed as Cumulative Energy Demand (CED), Water Consumption, and Non-Hazardous Waste Generation. All inventory quantities, emission/characterization factors, and allocation percentages were held in structured pandas' data frames, and the characterization step was executed as a vectorized computation following the standard linear form

$$\text{Impact}_i = \Sigma_j \, (Q_j \times EF_j) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

where Impact_i is the score for impact category i, Q_j is the annual quantity of flow j, and EF_j is the emission or characterization factor of flow j. Every computational step, from raw inventory quantities through characterized impact scores to flow- and process-level hotspot percentages, was executed within a single version-controlled script, so that any reviewer or successor analyst can re-run the identical calculation on the underlying spreadsheet inputs and obtain identical results, a transparency property that a proprietary point-and-click LCA tool does not automatically provide. Table 3 lists the emission factors applied, sourced from the Indonesian Ministry of Energy and Mineral Resources for grid electricity, the branch's internal Tier-2 fuel-emission calculation methodology (validated against IPCC 2006 default ranges for mobile combustion), and literature-based Tier 1-2 proxies for water and waste. Fifteen percent of total 2025 electricity consumption was supplied under a Renewable Energy Certificate (REC) scheme sourced from Cirata hydropower. Following the market-based accounting principle of the GHG Protocol Scope 2 Guidance (Greenhouse Gas Protocol, 2015), this REC-certified share was assigned a Global Warming Potential of zero within the Climate Change category, while remaining fully counted within the Fossil Resource Use/CED category based on its net calorific value, since certification addresses the attribution of GHG emissions rather than the physical energy throughput of the grid.

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Table 3. Emission/characterization factors applied in the streamlined LCIA

Flow	Unit	Factor	Source
Grid electricity (JAMALI)	kg CO2eq/kWh	0.87	Indonesian Ministry of Energy and Mineral Resources (2024)
Pertamax (RON92 gasoline)	kg CO2/L	2.357	Internal ESRGA dashboard calculation (Tier 2)
Pertalite (RON90 gasoline)	kg CO2/L	2.356	Internal ESRGA dashboard calculation (Tier 2)
Dexlite (diesel)	kg CO2/L	1.906	Internal ESRGA dashboard calculation (Tier 2)
Solar blend (Dex + Bio Solar)	kg CO2/L	2.439	Volume-weighted average, 78.3% Dex: 21.7% Bio Solar
Municipal water (PDAM)	kg CO2eq/m3	0.344	Literature proxy, urban water treatment/distribution
Groundwater (deep well)	kg CO2eq/m3	0.10	Literature proxy, deep-well pumping energy
Plastic waste to landfill	kg CO2eq/kg	0.10	IPCC (2006), Vol. 5 (Waste)
Non-plastic waste to landfill	kg CO2eq/kg	1.00	IPCC (2006) Tier 1, Waste Sector

Hotspot Classification Criteria

Environmental hotspots were identified by computing, within the same Python pipeline, the percentage contribution of each individual flow, and separately of each unit process (P1-P6), to the total Climate Change score, and classifying each contribution into one of three priority tiers: High (≥25%), Medium (10-25%), and Low (<10%). Because the underlying allocation structure (Table 2) links each flow to its constituent unit processes, this streamlined approach permits hotspot identification simultaneously at the flow level and at the process level from a single underlying dataset, without requiring a second, independently collected inventory. This dual-level output is a distinguishing feature of the present study relative to conventional single-level LCA hotspot reporting reviewed in Section 2.2 and is intended specifically to support internal decision-makers who need to know not only which resource type dominates the footprint, but also which internal activity is responsible for consuming it.

RESULTS AND DISCUSSION

Inventory Summary

Table 4 summarizes the annual 2025 life cycle inventory for PT United Tractors Tbk, Semarang Branch. Total electricity consumption reached 149,161 kWh, sourced entirely from the JAMALI grid interconnection, with a clear upward trend from the first to the second half of the year (July-November monthly values 13,577-14,243 kWh versus January-June values 10,497-11,622 kWh), consistent with increased operational intensity in the second semester. Total fuel consumption across all four recorded types reached 27,772.43 litres, dominated by the two gasoline grades (Pertamax and Pertalite) used for operational vehicle mobilization. Total water consumption reached 2,654.0 m3, and total non-hazardous solid waste generation reached 14,650.74 kg, of which plastic waste accounted for 77.8% (11,395.01 kg).

Table 4. Annual 2025 Life Cycle Inventory summary

Flow	Annual Quantity	Unit
Grid electricity (JAMALI)	149,161	kWh
Pertamax	10,535.72	L
Pertalite	8,502.98	L
Dexlite	4,823.40	L
Solar (Dex + Bio Solar blend)	3,910.33	L
Total fuel (all types)	27,772.43	L
Groundwater (deep well)	1,628.9	m3

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Flow	Annual Quantity	Unit
Municipal water (PDAM)	1,025.1	m3
Total water	2,654.0	m3
Plastic waste to landfill	11,395.01	kg
Non-plastic waste to landfill	3,255.74	kg
Total non-hazardous waste	14,650.74	kg

Streamlined LCIA Results

Table 5 presents the streamlined LCIA results for the four assessed impact categories. The Climate Change (GWP100) score of 176,203.80 kg CO2-eq per year already incorporates the market-based zero-GWP treatment of the 15% REC-certified electricity share described in Section 3.4. For comparison, an alternative accounting scenario in which the entire 149,161 kWh of electricity consumption is treated as unabated JAMALI grid supply (i.e., without the REC market-based adjustment) yields a Climate Change score of 198,277.24 kg CO2-eq per year, 22,073.44 kg CO2-eq (12.5%) higher than the reported result. This comparison is reported transparently because the choice between location-based and market-based Scope 2 accounting materially affects the reported footprint and therefore warrants explicit disclosure alongside the headline figure, consistent with the dual-reporting recommendation of the GHG Protocol Scope 2 Guidance (Protocol, 2015).

Table 5. Streamlined Life Cycle Impact Assessment (LCIA) results, 2025

Impact Category	Value	Unit
Climate Change / GWP100 (market-based, with REC)	176,203.80	kg CO2-eq/year
Climate Change / GWP100 (location-based, without REC)	198,277.24	kg CO2-eq/year
Fossil Resource Use (Cumulative Energy Demand proxy)	1,522,240.77	MJ/year
Water Consumption	2,654.00	m3/year
Non-Hazardous Waste Generation	14,650.74	kg/year
Grid electricity carbon intensity indicator	0.87	kg CO2-eq/kWh

Flow-Level Hotspots

Table 6 and Figures 1-2 present the contribution of each individual flow to the total Climate Change score. Grid electricity is the single dominant hotspot at 60.92%, exceeding the High-priority threshold by more than double. Gasoline-type fuels (Pertamax and Pertalite) jointly contribute 25.43%, falling in the Medium-priority tier individually (14.09% and 11.34% respectively), while diesel-type fuels (Dexlite and Solar blend) jointly contribute 10.86%. All remaining flows, including both waste streams and both water sources, fall below the 10% Low-priority threshold, and the REC-certified electricity share contributes 0.00% to Climate Change by construction of the market-based accounting method applied.

Table 6. Contribution of each flow to the total Climate Change score

Flow	Climate Change (kg CO2-eq)	Contribution (%)	Priority
Grid electricity (JAMALI)	107,346.57	60.92	High
Pertamax	24,832.72	14.09	Medium
Pertalite	19,974.12	11.34	Medium
Dexlite	9,602.31	5.45	Low
Solar (blend)	9,537.32	5.41	Low
Non-plastic waste to landfill	3,255.74	1.85	Low

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Flow	Climate Change (kg CO2-eq)	Contribution (%)	Priority
Plastic waste to landfill	1,139.50	0.65	Low
Municipal water (PDAM)	352.63	0.20	Low
Groundwater (deep well)	162.89	0.09	Low
REC-certified electricity (Cirata hydro, 15%)	0.00	0.00	Low

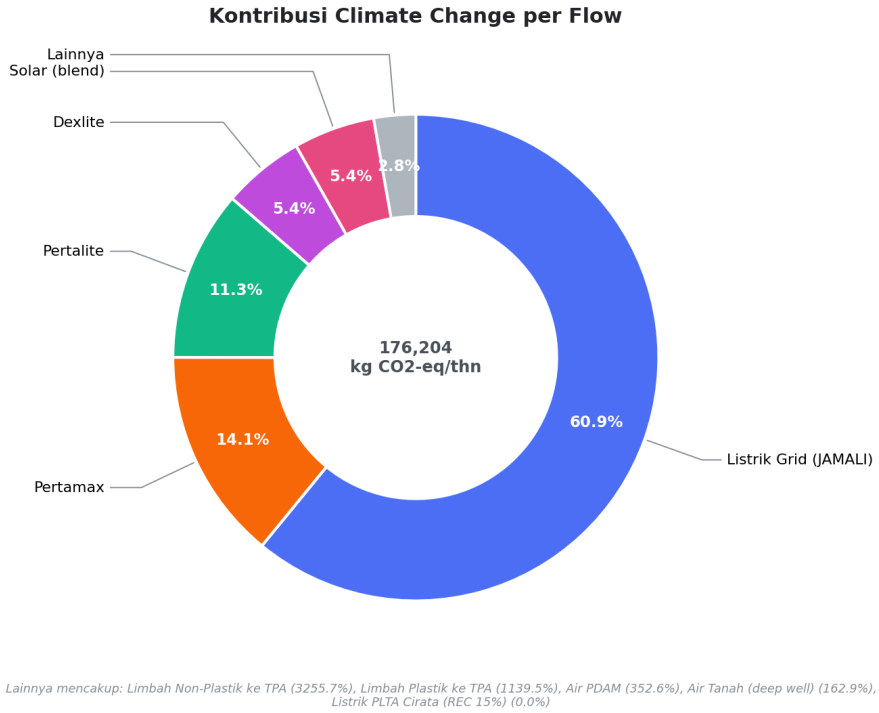


Figure 1. Contribution of each flow to the total Climate Change score

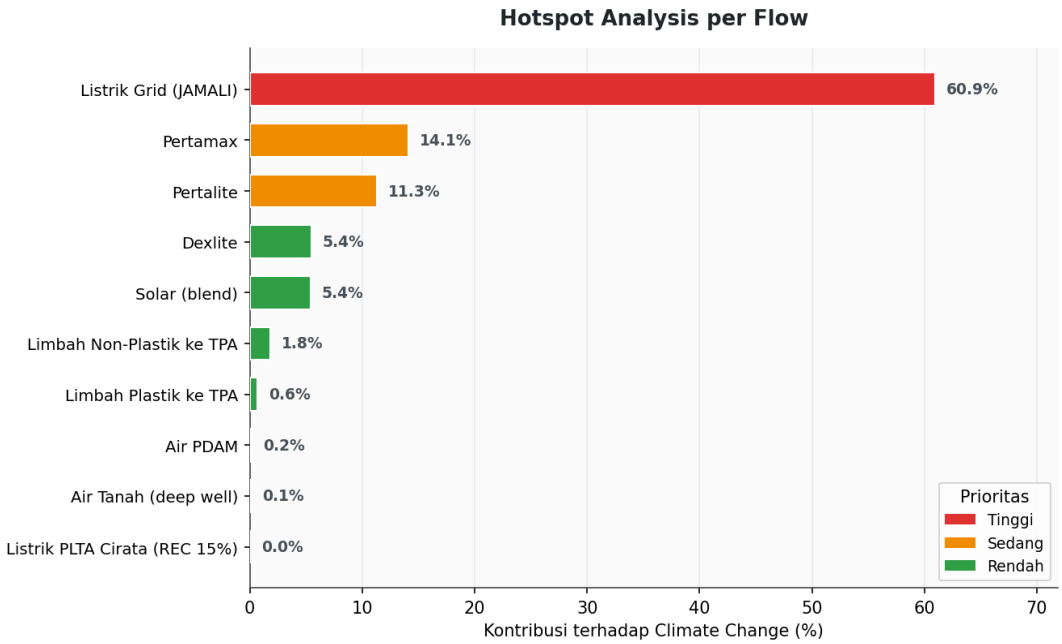


Figure 2. Flow-level hotspot analysis, classified by priority tier

Process-Level Hotspots

Table 7 and Figure 3 disaggregate the same total Climate Change score by unit process (P1-P6), made possible by the allocation structure summarized in Table 2. Workshop and Service (P2) and Delivery and Mobilization (P6) are jointly identified as High-priority process hotspots, together accounting for 59.05% of the total footprint, while Administration and Office (P1) fall in the Medium-priority tier. The remaining three processes (Pre-Delivery Inspection, Warehouse and Material Handling, and Washing and Finishing) each fall below the 10% Low-priority threshold. This two-level disaggregation, obtainable from a single underlying dataset without additional data collection, allows mitigation attention to be targeted at specific operational processes rather than applied uniformly across the facility.

Table 7. Contribution of each unit process to the total Climate Change score

Unit Process	Climate Change (kg CO2-eq)	Contribution (%)	Priority
P2: Workshop and Service	55,370.28	31.42	High
P6: Delivery and Mobilization	48,678.07	27.63	High
P1: Administration and Office	37,176.80	21.10	Medium
P3: Pre-Delivery Inspection (PDI)	15,215.34	8.64	Low
P5: Warehouse and Material Handling	14,176.22	8.05	Low
P4: Washing and Finishing	5,587.09	3.17	Low

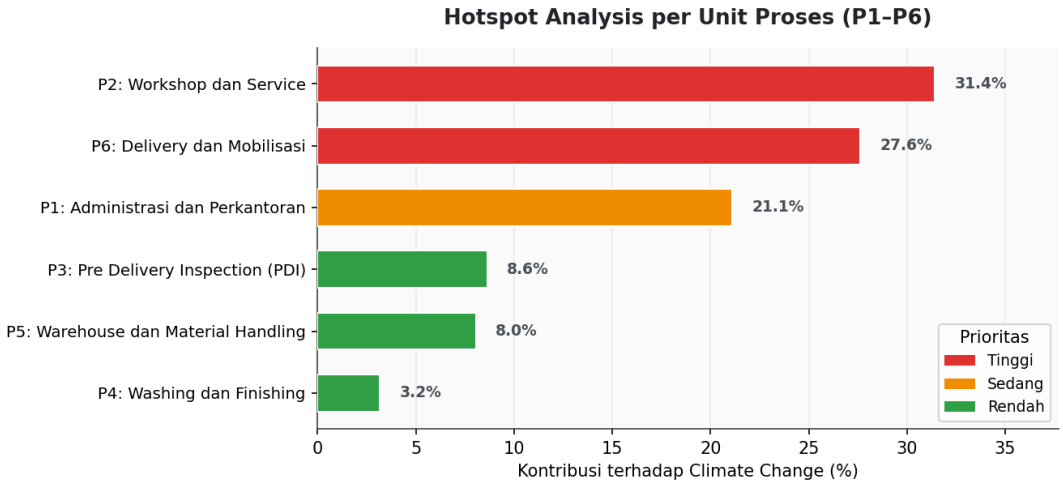


Figure 3. Process-level hotspot analysis (P1-P6), classified by priority tier

Supplementary Hazardous Waste Profile

Table 8 reports the supplementary hazardous waste (B3) inventory compiled from the branch's licensed temporary storage (TPS LB3) disposal records. Total regulated hazardous waste generation across the reporting window reached 4.913 tonnes, dominated by used lubricating oil (76.1%) and wastewater-treatment sludge (18.3%). Compliance monitoring indicates that 4.863 of 4.913 tonnes (99.0%) had been verifiably transferred to a licensed third-party processor (PT Indo Cakra Semesta) under a tracked Ministry of Environment and Forestry (KLHK) manifest, with only 0.050 tonnes remaining in on-site storage at the time of reporting, indicating a regulation-compliant waste chain rather than an unmanaged accumulation. Because no validated characterization factor was available to convert this heterogeneous waste stream into a GWP-equivalent score, it is reported on a mass basis following the GRI 306 (Waste) disclosure convention rather than being merged into the Climate Change result in Table 5; nonetheless, its mass exceeds the non-hazardous waste stream reported in Table 4 by a factor of approximately 335, indicating that it is a materially significant flow that future characterization work should prioritize (see Section 6).

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Table 8. Hazardous waste (B3) inventory by waste code, cumulative reporting window

Waste Code	Waste Type	Quantity (tonnes)	Share of Total B3
B105d	Used lubricating oil (hydraulic, engine, gear)	3.7384	76.1%
B108d	Wastewater treatment plant (WWTP) sludge	0.9000	18.3%
B110d	Used rags	0.1700	3.5%
—	Used oil (separate internal log category)	0.0500	1.0%
B109d	Used filters	0.0250	0.5%
B354-3	Concrete/ceramic fraction containing hazardous residue	0.0250	0.5%
B104d	Used hazardous-material packaging (jerry cans, tins)	0.0050	0.1%
Total	—	4.9134	100.0%

Discussion

Interpretation of Dominant Impact Drivers

The results establish an unambiguous hierarchy of environmental drivers for the branch's gate-to-gate operations. Grid electricity alone contributes more than three-fifths of the annual Climate Change score, a share that exceeds the combined contribution of all four fuel types by a factor of more than two. At the process level, this same dominance is echoed in Workshop and Service, the unit process that both houses the electricity-intensive diagnostic and repair equipment and receives the largest single electricity allocation share in Table 2 (40%), and in Delivery and Mobilization, the unit process that receives the overwhelming majority of gasoline and diesel allocation (70% and 90% respectively). The convergence of the flow-level and process-level results, both independently pointing toward the same two underlying activities (grid-supplied electricity use in the workshop, and vehicle fuel use in delivery and mobilization), strengthens confidence that these are genuine operational hotspots rather than artefacts of the allocation assumptions in Table 2, since the two levels of disaggregation are consistent with each other despite being computed through different allocation pathways within the same dataset.

Why Electricity and Fuel Dominate the Footprint

The dominance of grid electricity over fuel and other flows is explained jointly by the emission factor structure in Table 3 and by the underlying energy mix of the JAMALI interconnection. At 0.87 kg CO2-eq/kWh, the JAMALI grid factor reflects a generation mix still substantially reliant on coal-fired capacity, which is markedly higher than grid carbon intensities reported for electricity systems with a larger renewable or gas-fired share. Because the branch's total annual electricity consumption (149,161 kWh) is large relative to its total fuel consumption when both are expressed on a common carbon basis, even a moderate improvement in electricity carbon intensity, whether through additional renewable energy certificate procurement, on-site solar generation, or national grid decarbonization, would translate into a proportionally larger reduction in the branch's total footprint than an equivalent percentage improvement in fuel efficiency. This asymmetry is a direct, quantifiable consequence of the streamlined LCIA results rather than a general assumption, and it illustrates a broader implication for similarly structured service operations in Indonesia and other JAMALI-connected regions: as long as the national grid retains its current carbon intensity, electricity-consuming activities will tend to dominate the footprint of comparable branch-scale operations regardless of the specific service sector involved, simply because the grid factor is high relative to most liquid-fuel alternatives on a per-unit-of-delivered-energy basis.

Methodological Implications of the Python-Based Approach

Beyond the substantive findings, this study's Python-based streamlined LCIA implementation carries a methodological implication for organizations facing constraints similar to those described in Section 1. Every characterization and hotspot-classification step in this study was executed as an explicit, inspectable computation on structured tabular data rather than through a proprietary software interface, meaning that another analyst, whether an internal successor, an external auditor, or a researcher at a comparable organization, can reproduce the exact reported

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figures given only the underlying spreadsheet inputs and the calculation script. This transparency addresses a specific practical barrier identified in Section 1: many organizations already collect the primary activity data (electricity bills, fuel logs, water meter readings, waste manifests) required for a streamlined assessment of this kind but lack a modelling pathway that does not require a paid software licence. The approach demonstrated here shows that a modest technical investment, namely a data analyst competent in a general-purpose scripting language such as Python and access to publicly available emission-factor references, can substitute for a commercial LCA licence for the specific, narrower purpose of streamlined climate-impact and hotspot assessment, even though it cannot substitute for the full multi-category, life-cycle-wide coverage that a licensed LCA platform and background database provide.

Comparison with Related Studies

The present findings are broadly consistent with the streamlined and hotspot-analysis literature reviewed in Section 2, while also clarifying how the present case differs from it. Consistent with the hotspot-analysis framework advanced by Barthel et al. (2017), the results confirm that a small number of flows and processes account for the large majority of the impact score, in this case two flows (grid electricity and gasoline-type fuel) and two processes (Workshop and Service, and Delivery and Mobilization) together explaining the substantial majority of the footprint, mirroring the general finding in hotspot studies across other sectors that environmental impact tends to concentrate rather than distribute evenly across an organization's activities. Unlike the food-sector streamlined hotspot studies of Pelton & Smith (2015) and Castellani et al. (2017), which addressed upstream sourcing and supply-chain-level hotspots, the present study identifies operational, on-site hotspots within a gate-to-gate boundary, reflecting the different nature of a service-sector case relative to a product manufacturing or agricultural supply chain. The Python-based computational approach adopted here is more modest in scope than dedicated open-source LCA frameworks such as Brightway2 (Mutel, 2017) or lcpy (Gkousis & Katsou, 2025), which are designed for dynamic, prospective, or parametric LCA across complex product systems; the present study instead demonstrates that even a comparatively simple, custom-built script, without a general-purpose LCA computing framework, is sufficient to deliver a defensible streamlined LCIA and dual-level hotspot output for a single organizational unit, which may be the more realistic starting point for many resource-constrained organizations than adopting a full LCA computing framework.

CONCLUSION

This study developed and applied a streamlined Life Cycle Impact Assessment and multi-level hotspot analysis, implemented entirely through a transparent Python-based procedure, to quantify the 2025 gate-to-gate environmental performance of PT United Tractors Tbk, Semarang Branch. The annual Climate Change score reaches 176,203.80 kg CO2-eq under market-based Scope 2 accounting (198,277.24 kg CO2-eq under location-based accounting), with JAMALI grid electricity (60.92%) identified as the dominant flow-level hotspot and the combined Workshop-Service and Delivery-Mobilization unit processes (59.05% combined) identified as the dominant process-level hotspots. A supplementary hazardous-waste inventory further identifies 4.913 tonnes per year of regulated waste, 99.0% of which is verifiably managed through a licensed third party, indicating a compliant waste-management chain alongside the Climate Change results.

Theoretically, the study extends the streamlined LCIA and hotspot-analysis literature into a previously unexamined service-sector context, namely authorized heavy equipment sales and after-sales service, and demonstrates that a single flow-to-process allocation dataset can support simultaneous two-level hotspot disaggregation without additional primary data collection. Practically, the study offers organizations with limited access to commercial LCA software and background databases a replicable, code-based template for producing a defensible, decision-relevant environmental footprint estimate using data they are likely already collecting for other operational purposes, and the study's clear identification of electricity and vehicle fuel as the dominant drivers gives such organizations a concrete, evidence-based starting point for prioritizing mitigation attention rather than treating all operational flows as equally deserving of intervention.

This study is subject to several limitations that also define directions for future research. First, the streamlined scope covers four impact categories rather than the full midpoint set defined by methods such as ReCiPe 2016; future work should extend the framework toward full openLCA/ecoinvent modelling where licence access permits, to test whether the flow- and process-level hotspot rankings reported here remain stable once a broader set of impact categories is considered. Second, the water-source split, and several emission factors rely on literature-based or proxy-period assumptions rather than direct 2025 measurement, as detailed in Section 3.3; future studies at this and

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comparable facilities should prioritize closing these specific data gaps. Third, no validated characterization factor was available to convert the supplementary hazardous-waste inventory into a GWP-equivalent score; developing such a factor for the specific waste streams identified in Table 8 would allow this materially significant flow to be integrated into the primary Climate Change result rather than reported separately. Fourth, because this study addresses a single branch of a single company, replicating the same Python-based streamlined LCIA and hotspot procedure at other branches or comparable service-sector organizations would help establish whether the specific hotspot pattern identified here, electricity dominance reinforced by a carbon-intensive national grid, generalizes across the sector or is specific to this case.

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