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FEASIBILITY ANALYSIS AND COMPARATIVE EVALUATION OF SUSTAINABILITY HEAD-TRUCK SYSTEMS USING LIFE CYCLE ASSESSMENT (LCA), TOTAL COST OF OWNERSHIP (TCO), AND ANALYTIC NETWORK PROCESS (ANP) IN THE LOGISTICS OPERATIONS OF PT XYZ

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Abstract

The increasing environmental and operational demands in port logistics require a systematic evaluation of transportation technologies to support sustainable terminal operations. This study analyzes the feasibility of diesel and electric head-truck systems at PT XYZ using an integrated Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and Analytic Network Process (ANP) framework. LCA was conducted to measure environmental impacts such as global warming potential, particulate emissions, and energy use. TCO quantified long-term economic performance through operational energy costs, while ANP synthesized technical, economic, environmental, and social criteria for multi-criteria decision-making. The results indicate that the electric head-truck system has substantially lower environmental burdens across most impact categories and reduces annual operating costs by approximately Rp 550 million per unit. ANP prioritization further shows that environmental (0.432) and economic (0.297) dimensions dominate the sustainability evaluation, resulting in a final preference score of 0.732 for the electric system compared to 0.268 for diesel. These findings demonstrate that electric head trucks offer superior sustainability performance and operational feasibility for port logistics, supporting PT XYZ transition toward low-emission and energy-efficient container-terminal operations.

Keywords: Analytic Network Process; Electric Head Truck; Life Cycle Assessment; Port Logistics; Sustainability; Total Cost Of Ownership

1. Introduction

The increasing complexity of global port logistics demands a transition toward transportation systems that are not only operationally efficient but also environmentally sustainable. Heavy-duty vehicles particularly head trucks used for container hauling represent a critical source of energy consumption and greenhouse gas emissions in port operations. Studies show that the transport sector contributes a major share of total logistics-related emissions, making decarbonization of internal port transport a strategic priority (Rauf & Sari, 2024; Guo et al., 2025). In busy terminals such as PT XYZ, where container throughput and gate-to-yard movements are intensive, improving the sustainability

performance of head-truck operations has become essential to support national and international low-emission port agendas.

Research on sustainable logistics confirms that port systems are undergoing rapid transformation, driven by electrification, digitalization, and infrastructure modernization. Several studies emphasize the importance of integrating renewable energy, shore-side electrification, and electric cargo-handling equipment to reduce the environmental footprint of ports (Ramasan et al., 2025; Wang et al., 2025). Electrification of ground vehicles including automated terminal tractors, yard trucks, and drayage trucks has gained broad recognition as a promising decarbonization pathway with significant potential to reduce local air pollution and improve energy efficiency (Syre & Göhlich, 2023; Li et al., 2024). A growing body of literature confirms that replacing diesel-powered heavy-duty trucks with battery-electric

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alternatives can substantially reduce CO₂ emissions, especially when combined with smart-charging systems and clean electricity sources (Yang et al., 2025; Wenander et al., 2024; Osorio et al., 2022).

From a methodological perspective, Life Cycle Assessment (LCA) has become a key approach to evaluate the full environmental impact of diesel and electric freight vehicles from production to end-of-life (Eduardo et al., 2023; Helena et al., 2023). LCA studies consistently indicate that while electric trucks may exhibit higher upstream impacts related to battery production and mineral extraction, their overall life-cycle emissions remain significantly lower than those of diesel trucks during the operational phase (Forsberg, 2024; Zeng et al., 2024). Complementary studies highlight the importance of Total Cost of Ownership (TCO), demonstrating that electric heavy-duty trucks often yield lower long-term operating costs particularly in energy consumption and maintenance compared to internal combustion engine (ICE) vehicles (Goodarzi et al., 2024; Muller, 2023). This cost advantage becomes increasingly compelling as battery technology improves and electricity markets shift toward cleaner generation mixes (Stephen et al., 2023).

Technological advancements also play an important role in enhancing the feasibility of electric truck deployment in port environments. Digital twins, optimization algorithms, AI-based routing, and real-time simulation frameworks have been shown to significantly improve operational efficiency while reducing energy demand (Su et al., 2024; Yao et al., 2025; Dumetz et al., 2024). Smart infrastructure including managed charging, slow-fast charging coordination, and PV integration has also been proven to mitigate grid-loading challenges, making port electrification more realistic even in aging grid environments (Eriksson, 2025; Ramasan et al., 2025). Meanwhile, research on multimodal and collaborative logistics emphasizes that digital integration, stakeholder coordination, and modern infrastructure planning are essential enablers of large-scale transport decarbonization (Gallo et al., 2024; Ayadi et al., 2024; Amrani et al., 2024).

Despite rapid technological progress, several systematic reviews such as those by Sobczuk (2024), Nicoletti & Appolloni (2024), and Forsberg (2024) reveal persistent gaps in the real-world adoption of sustainable transportation systems. These gaps include limited charging infrastructure, insufficient policy support, social acceptance challenges, and variations in technical performance across different operational contexts. Furthermore, many studies highlight the importance of evaluating sustainability through multi-criteria perspectives integrating environmental, economic, technical, and social aspects to arrive at a more holistic decision-making framework (Ayadi et al., 2024; Li et al., 2024).

Considering these insights, a comprehensive sustainability evaluation of head-truck systems in PT XYZ is needed. Such an evaluation must capture environmental performance through LCA, economic feasibility through TCO, and multi-dimensional decision-making through Analytic Network Process (ANP). This study aims to fill this research gap by providing an integrated assessment of diesel and electric head-truck systems across technical, economic, environmental, and social dimensions, with the goal of supporting PT XYZ strategic transition toward low-emission, efficient, and future-ready port logistics.

2. Research Methodology

This study employs a quantitative comparative approach grounded in sustainability principles to analyze the feasibility of diesel and electric (EV) head-truck systems within the logistics operations of PT XYZ. The research integrates Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and Analytic Network Process (ANP) to provide a comprehensive evaluation of sustainability performance across environmental, economic, technical, and social dimensions. The LCA method assesses environmental impacts such as carbon emissions and energy use throughout the operational phase, while the TCO framework evaluates the total economic cost by considering both investment and long-term operational expenditures. The ANP approach is applied to determine multi-criteria sustainability weightings, allowing the interrelationships among technical, economic, environmental, and social factors to be systematically analyzed. Data were obtained through direct field observations and interviews with the technical and operational divisions of PT XYZ, supported by secondary data including fuel consumption records, maintenance costs, and technical literature on electric head-truck systems in port logistics. These datasets form the basis for the integrated LCA–TCO–ANP analysis used to compare and determine the most sustainable head-truck alternative for port operations.

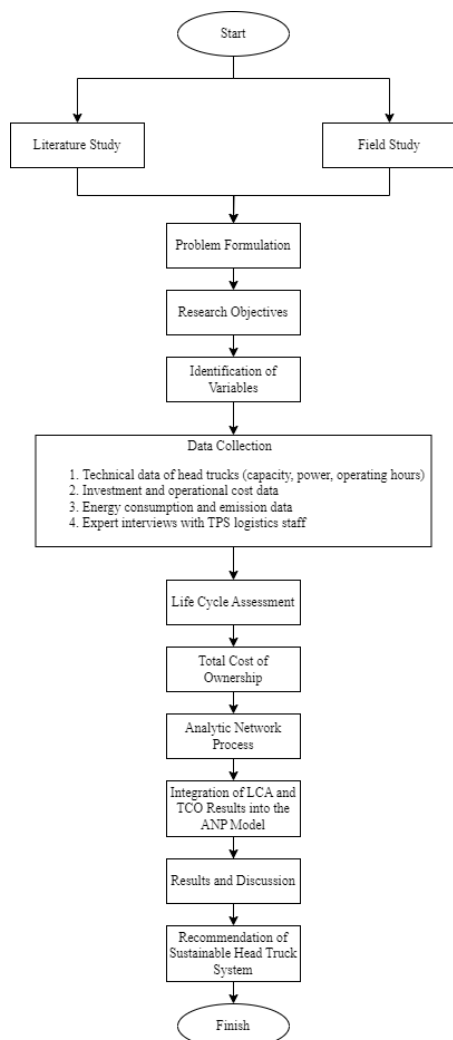


Figure 1. Research framework of the LCA–TCO–ANP approach for the head-truck system at PT XYZ.

The stages of the research methodology are illustrated in Figure 1, which presents the relationship among the analytical components. The process begins with the collection of technical and operational data for both diesel and electric head trucks, including engine power specifications, energy consumption, load capacity, annual operating hours, and vehicle lifespan. The subsequent stage involves conducting a Life Cycle Assessment (LCA) to evaluate the environmental impacts of both vehicle systems using a cradle-to-grave approach. The LCA model was developed using SimaPro 9.0 software with the ecoinvent database and consists of four main phases: defining the goal and scope, compiling the life-cycle inventory (LCI), performing the life-cycle impact assessment (LCIA), and interpreting the results. The impact categories analyzed include Global Warming Potential (GWP) in kg CO₂-eq, Cumulative Energy Demand (CED) in MJ, and Human Toxicity Potential (HTP) in kg 1,4-DB eq. The LCA results serve as environmental indicators for system comparison. The

next stage, the Total Cost of Ownership (TCO) analysis, calculates the total costs incurred over the vehicle's economic lifetime. The cost components include the initial investment cost (C_{inv}), operating cost (C_{op}), maintenance cost (C_{maint}), energy cost (C_{energy}), and residual value (V_{res}). The total cost is computed using the following equation:

$$TCO = C_{inv} + \sum_{t=1}^n (C_{op,t} + C_{maint,t} + C_{energy,t}) - V_{res}$$

Table 1. Criteria and Sub-Criteria for the Sustainability-Based Feasibility Evaluation of Head-Truck Systems

Dimension	Criteria / Sub-criteria	Indicator	Data Source
Technical	Performance, reliability	Power (kW), operating hours	PT XYZ data
Economic	Investment cost, energy cost, maintenance cost	TCO (Rp/km)	PT XYZ financial reports
Environmental	CO ₂ -equivalent emissions, energy consumption	LCA (SimaPro)	Process inventory
Social	Occupational safety, operator acceptance	ANP questionnaire	Expert interviews

All cost components were converted into Net Present Value (NPV) using a 6 % discount rate. The resulting TCO values were used to assess the economic feasibility and served as inputs to the ANP model under the *economic-impact* criterion. Table 1 summarizes the indicators employed in each sustainability-assessment dimension.

Subsequently, the Analytic Network Process (ANP) was applied to determine the priority ranking of alternative head-truck systems by integrating the LCA and TCO outcomes. ANP was selected because it captures the interdependencies among evaluation criteria. The network model was constructed using Super Decisions 3.0 software and comprised four main criteria: technical, economic, environmental, and social and eight sub-criteria derived from literature reviews and expert consultations. Pairwise comparisons were conducted with five logistics and energy experts from PT XYZ using Saaty's 1–9 scale, and the Consistency Ratio (CR) threshold of ≤ 0.1 was used to validate the reliability of judgments. The final ANP output produced the priority weights for each criterion and the ranking of vehicle alternatives to identify the most sustainable option.

Data validation was performed through triangulation between computed results, company secondary data, and prior studies (Okyerere et al., 2022; Osorio-Tejada et al., 2022; Lalla-Ruiz et al., 2024). The integrated analysis of LCA, TCO, and ANP provided strategic recommendations for a sustainable head-truck system at PT XYZ. The final outputs of this research include quantified environmental impacts (CO₂-eq and

MJ/km), total life-cycle costs (Rp/km), ANP priority weights, and the identification of the most feasible alternative from a sustainability-based decision-making perspective.

3. Results and Discussion

3.1 Life Cycle Assessment (LCA) Results

The Life Cycle Assessment (LCA) was conducted to evaluate the environmental impacts of diesel and electric head trucks during their operational phase (*gate-to-gate*). The assessment was performed using SimaPro 9.0 software with the ecoinvent 3.9 database and the ReCiPe 2016 Midpoint impact method. The functional unit (FU) is 1 km of internal container transport at PT XYZ.

The Life Cycle Inventory (LCI) model consists of energy input (diesel or electricity), lubricating oil, tire wear, and maintenance activities, while the outputs include carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter (PM_{2.5}). The initial LCI data used in SimaPro for both systems are presented in Table 2.

Table 2. Life Cycle Inventory (LCI) of Diesel Head Truck per 1 km Operation

Process	Input	Qty	Unit	Output	Qty	Unit
STS Crane Operation	market for electricity, medium voltage {ID}	3.50	kWh	container handling, STS crane	1.00	move
Shuttle Transport – Diesel	transport, freight, lorry 16-32t, EURO5 {RER}	0.80	km	shuttle transport, diesel	1.00	leg
RTG Operation – Diesel	market for diesel, low-sulphur {RER}	0.998	kg	container stacking, RTG diesel	1.00	move
	market for lubricating oil {GLO}	0.00020	kg	—	—	—
Maintenance	maintenance, heavy duty vehicle, processing {GLO}	0.00100	p·km	—	—	—
Tyre Wear	light commercial vehicle tyre production {GLO}	0.00001	unit	—	—	—
Lubricant	market for lubricating oil {GLO}	0.00085	kg	waste oil	0.00085	kg

Table 3. Life Cycle Inventory (LCI) of Electric Head Truck per 1 km Operation

Process	Input	Qty	Unit	Output	Qty	Unit
STS Crane Operation	market for electricity, medium voltage {ID}	3.50	kWh	container handling, STS crane	1.00	move
Shuttle Transport – Electric (EV)	market for electricity, medium voltage {ID}	1.20	kWh	shuttle transport, electric	1.00	leg

Process	Input	Qty	Unit	Output	Qty	Unit
	market for electricity, medium voltage {ID} (charger loss)	0.04	kWh	—	—	—
	market for lubricating oil {GLO}	0.00017	kg	—	—	—
E-RTG / RMG Operation – Electric	market for electricity, medium voltage {ID}	6.00	kWh	container stacking, E-RTG	1.00	move
Maintenance	maintenance, passenger car, electric, processing {GLO} (proxy EV)	0.00050	p·km	—	—	—
Tyre Wear	light commercial vehicle tyre production {GLO}	0.00001	unit	—	—	—
Lubricant	market for lubricating oil {GLO}	0.00017	kg	waste oil	0.00017	kg

The inventory data presented in Table 2 & 3 represent the initial Life Cycle Inventory (LCI) before simulation in SimaPro. The model was executed in SimaPro 9.0 using the ecoinvent 3.9 database and the ReCiPe 2016 Midpoint (H) impact assessment method. After running the simulation, the software generated environmental impact results across several analytical levels: Characterization, Damage Assessment, Normalization, Weighting, and Single Score. The Characterization step quantifies the impact in physical units (e.g., kg CO₂-eq, MJ, kg 1,4-DB eq). The Damage Assessment stage groups these impacts into major damage categories (Human Health, Ecosystem Quality, and Resource Scarcity). The Normalization and Weighting steps convert them into comparable scores to identify dominant categories, while the Single Score represents the overall environmental burden for each head-truck system. The resulting LCIA outputs are discussed in the following section.

1) Diesel Head-Truck System

The overall process network generated by SimaPro for the diesel system is shown in Figure 2. It represents all upstream and operational flows contributing to total environmental impacts.

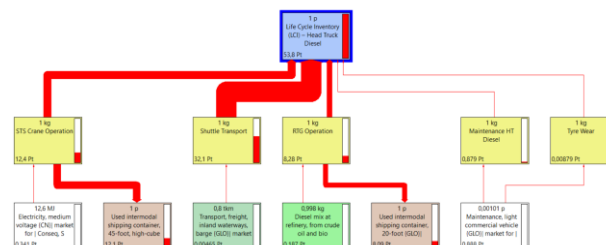


Figure 2. Overall process network of the diesel head-truck system.

Annual EV operating cost:

$$C_{EV,year} = C_{EV,day} \times 360 \dots \dots \dots (4)$$

$$C_{EV,year} = 717,003.77 \times 36 = 258,121,357.56 \text{ Rp/year}$$

The resulting annual operational savings from switching to EV are:

$$\text{Annual Savings} = C_{diesel,year} - C_{EV,year} \dots \dots \dots (5)$$

$$\text{Annual Savings} = 808,108,992 - 258,121,358$$

$$\text{Annual Savings} = 549,987,634.44 \text{ unit per year}$$

$$\text{Annual Savings} = \text{Rp } 549,987,634.44 \text{ per unit per year}$$

This corresponds to a 68% reduction in annual energy cost, highlighting the significant economic advantage of the EV system even without full CAPEX information.

Table 4. Annual Operating Cost Comparison of Diesel and EV Head Trucks

Component	Formula	Diesel	EV
Daily Energy Cost	$Q \times P$	Rp 2,244,747.20	Rp 717,003.77
Monthly Energy Cost	$C_{day} \times 30$	Rp 67,342,416	Rp 21,510,113
Annual Energy Cost	$C_{day} \times 360$	Rp 808,108,992	Rp 258,121,358
Annual Savings	$C_d - C_{ev}$	—	Rp 549,987,634

The TCO evaluation demonstrates that the electric head-truck system reduces annual operational expenditure by nearly Rp 550 million per unit, indicating a strong economic justification for electrification. Over a 7–10-year operating life, these savings accumulate into several billion rupiah per unit, reinforcing the EV system's financial feasibility in port logistics operations.

3.3 Analytic Network Process (ANP) Results

The Analytic Network Process (ANP) was applied to integrate the Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) findings into a unified multi-criteria decision framework. Experts from PT XYZ evaluated the alternatives based on four sustainability dimensions technical, economic, environmental, and social each consisting of two sub-criteria. Pairwise comparison judgments were provided using Saaty's 1–9 scale in the SuperDecisions software. The comparisons indicate that the environmental and economic dimensions play the most dominant roles, followed by technical and social aspects. Diesel scored slightly higher on technical criteria due to perceived performance and reliability advantages, while EV dominated economic, environmental, and social dimensions. SuperDecisions generated the normalized and limiting supermatrices, resulting in the priority weights shown in Table 5.

Table 5. Summary of ANP Weights and Final Priority of Alternatives

Dimension	Weight	Sub-Criteria	Sub-Criteria Weight (Local)	Global Weight	Diesel Priority	EV Priority
Technical	0.174	Performance	0.67	0.116	0.612	0.388
		Reliability	0.33	0.058	0.655	0.345
Economic	0.297	Operating Cost (TCO)	0.86	0.255	0.121	0.879
		Investment Cost	0.14	0.042	0.780	0.220
	0.432	GWP (LCA)	0.78	0.337	0.084	0.916

Dimension	Weight	Sub-Criteria	Sub-Criteria Weight (Local)	Global Weight	Diesel Priority	EV Priority
Environmental		Energy Consumption	0.22	0.095	0.105	0.895
Social	0.097	Safety	0.66	0.064	0.311	0.689
		Acceptance	0.34	0.033	0.271	0.729
Final ANP Priority	—	—	—	—	0.268	0.732

Table 5 clearly shows that the environmental dimension holds the highest weight (0.432), driven mainly by the Global Warming Potential (GWP) sub-criterion, which alone contributes a global weight of 0.337. This reflects the operational context of PT XYZ, where emissions and energy consumption are critical considerations. The economic dimension ranks second (0.297), with Operating Cost (TCO) dominating Investment Cost. This outcome aligns with the TCO results, where the EV head-truck demonstrates substantial yearly savings of approximately Rp 550 million per unit.

The technical dimension carries a moderate weight (0.174), where diesel shows an advantage in performance and reliability. However, these technical benefits are not sufficiently strong to offset diesel's poor environmental and economic performance. The social dimension has the lowest weight (0.097), yet EV still outperforms diesel in safety and operator acceptance.

In terms of alternative ranking, the EV head-truck achieves a dominant final priority score of 0.732, significantly higher than the diesel alternative at 0.268. This strong preference for EV is driven by its superior performance in the economic and environmental dimensions, particularly with near-zero tailpipe emissions (LCA) and drastically lower operational costs (TCO). Even though diesel has a marginal technical advantage, the magnitude of EV's benefits in other dimensions decisively outweighs it.

Overall, the ANP results confirm that the electric head-truck is the most sustainable and feasible alternative for PT XYZ, providing long-term environmental and economic advantages while also maintaining positive social attributes.

3.4 Integration of LCA–TCO–ANP Results

The integration of Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and Analytic Network Process (ANP) provides a holistic evaluation of the sustainability performance of diesel and electric (EV) head-truck systems in PT XYZ operations. Each method contributes a different analytical perspective: LCA captures environmental impacts across multiple midpoint categories; TCO quantifies long-term financial implications through operational energy expenditure; and ANP synthesizes these environmental and economic results with technical and social considerations to produce an overall sustainability ranking. When combined, the integrated framework highlights strong

methodological convergence that consistently positions the electric head-truck as the superior alternative.

LCA results demonstrate that the diesel system generates significantly higher environmental burdens across all major impact categories, particularly Global Warming Potential, particulate emissions, and fossil resource use. The EV system shows reductions in CO₂ emissions, particulate matter (PM_{2.5}), and overall environmental damage, with remaining impacts concentrated primarily on upstream electricity generation. These environmental advantages are reinforced by the TCO results, which show that the EV system reduces annual operating energy costs by approximately Rp 549 million per unit a 68% improvement compared to diesel. Over a standard 7–10-year operational lifespan, this cost reduction translates into multi-billion-rupiah savings, strengthening the economic rationale for EV adoption.

The ANP model synthesizes these environmental and economic findings with expert judgements across technical and social dimensions. The environmental dimension receives the highest weight (0.432), followed by economic performance (0.297), reflecting PT XYZ's increasing emphasis on emission reduction, energy efficiency, and long-term operational cost control. While diesel scores moderately higher in technical criteria—primarily due to perceptions of engine reliability and familiarity these advantages are insufficient to offset the EV system's strong environmental and economic performance. Consequently, ANP outputs rank the EV head-truck as the most preferred option with a final priority score of 0.732, far surpassing diesel at 0.268.

Overall, the integrated LCA–TCO–ANP framework shows strong consistency across all evaluation layers. Environmental impact reduction and economic savings emerge as the dominant factors influencing sustainability feasibility, both of which strongly favor the electric head-truck system. The ANP model confirms that, even when technical and social aspects are incorporated, the EV system remains the most sustainable and feasible option for implementation in PT XYZ internal transport operations. This integrated analysis provides robust evidence to support strategic decision-making toward electrification and low-emission port logistics.

4. Conclusions

This study aimed to evaluate the feasibility and sustainability performance of diesel and electric (EV) head-truck systems at PT XYZ using an integrated LCA–TCO–ANP framework. The combined analytical approach demonstrates that the electric head-truck system provides clear advantages aligned with the study's objectives across environmental, economic, technical, and social dimensions.

The main scientific finding is that the EV head-truck delivers substantially lower environmental impacts, particularly in global warming potential, particulate emissions, and fossil resource use, confirming its superiority in reducing the ecological footprint of internal container transport operations. From the economic perspective, the EV system results in significant operational cost savings, with an annual reduction of approximately Rp 550 million per unit, providing strong financial justification for fleet electrification. The multi-criteria integration using ANP further reinforces these findings: despite diesel exhibiting a slight advantage in technical attributes, the EV system achieves the highest overall sustainability priority (0.732), driven primarily by its environmental and economic benefits.

In summary, the integrated assessment conclusively identifies the electric head-truck as the most feasible and sustainable alternative for PT XYZ. Future research may expand this evaluation by incorporating full life-cycle investment and maintenance data for EV fleets, analyzing grid decarbonization scenarios, and assessing long-term infrastructure readiness to support large-scale electrification in port logistics.

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