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Sustainable Lean Management Practices: Net Zero Win-Win Green Value Stream: A Case Study of Metal Product Manufacturing Supply Chain Performance

Lin Yu-Hua^{1*}
Tsai Chih-Cheng²

^{1,2}Department of Business Management, Hsiuping University of Science and Technology

* Corresponding author

E-mail: yuhua@hust.edu.tw

Abstract

This study investigates the application of Sustainable Lean Management in Taiwanese small and medium-sized metal product manufacturing enterprises to support the net-zero carbon emissions goal by 2050. Using production value stream mapping, pain point analysis, and seven green waste management principles, combined with professional coaching, on-site improvement tools, and Quality Control Circle (QCC) strategies, the study evaluates changes in delivery performance, operational efficiency, product quality, inventory management, and green value creation before and after implementation. In parallel, a cradle-to-gate carbon footprint assessment of a representative metal hand tool product was conducted following ISO 14067 and ISO 14044 standards. The life cycle assessment covers raw material acquisition, manufacturing, transportation, and packaging, with data quality ensured through Data Quality Rating and defined truncation criteria. Results indicate that manufacturing processes—particularly outsourced forging, heat treatment, and electroplating—account for over 90% of total emissions. The findings demonstrate that integrating Lean and Green practices can simultaneously reduce environmental impact, improve operational performance, and support ESG-oriented industrial transformation.

Keywords: *Sustainable Lean Management; Net-Zero Carbon Reduction; Green Value Stream; Manufacturing Performance; Supply Chain Improvement*

1. Introduction

The urgency of addressing climate change has driven industries worldwide to adopt carbon footprint assessments and integrate sustainability into business practices. International frameworks such as the Paris Agreement and the UN Sustainable Development Goals (SDGs) emphasize the need for net-zero pathways by 2050. At COP26, governments reinforced commitments to decarbonization, while the European Union launched the Carbon Border Adjustment Mechanism (CBAM), directly affecting export-oriented economies such as Taiwan.

Environmental, Social, and Governance (ESG) frameworks have become central to corporate reporting. Standards like the EU CSRD, GRI, SASB, and the ISSB's IFRS S1 and S2 provide guidelines for transparency. ESG ratings by MSCI and Sustainalytics influence investment decisions, making sustainability performance integral to financial

competitiveness. Despite significant research in electronics, automotive, and chemical industries, carbon footprint studies in the hand tool sector remain scarce, creating a research gap.

This study addresses these gaps by conducting a carbon footprint assessment of a representative hand tool product, integrating it with a case study on Sustainable Lean Management applied to five SMEs in central Taiwan. The objective is to identify emission hotspots, propose mitigation strategies, and situate these findings within the ESG discourse to provide both academic and policy contributions.

Carbon footprinting of industrial products has become a critical aspect of sustainable manufacturing and climate change mitigation. Life cycle assessment (LCA) offers a robust methodology to quantify the greenhouse gas (GHG) emissions associated with products across their life cycle stages. Metal hand tools, such as wrenches, are widely used in automotive, construction, and maintenance industries, yet their environmental impacts have been sparsely reported in peer-reviewed literature. This study aims to quantify the cradle-to-gate carbon footprint of a forged alloy steel wrench manufactured in Taiwan, providing insights for emission reduction strategies and supporting eco-design and procurement decisions.

Research Objectives

The primary objective is to establish a systematic approach to measure, analyze, and reduce carbon emissions at both the product and organizational levels. This includes identifying emission hotspots, applying Lean & Green methods, and validating improvements using standardized metrics.

2.Literature Review

ESG frameworks, disclosure, and performance

ESG has evolved from voluntary disclosure toward globally harmonized, decision-useful information that links sustainability outcomes with enterprise value. At the framework level, the International Sustainability Standards Board (ISSB) issued IFRS S1 (general sustainability-related disclosures) and IFRS S2 (climate-related disclosures) consolidating prior initiatives (e.g., TCFD) into a global baseline for capital markets reporting (IFRS Foundation, 2023). The EU's Corporate Sustainability Reporting Directive (CSRD) expands scope and prescriptiveness for European and large non-EU entities, emphasizing double materiality and value-chain coverage (European Commission, 2023). The GRI Standards remain the leading impact-oriented framework for multi-stakeholder reporting (GRI, 2021), while SASB Standards provide industry-specific metrics aligned with financial materiality (SASB, 2018). Together, these frameworks foster consistency, comparability, and assurance readiness (WEF, 2021; OECD, 2020).

Empirical work links ESG integration to organizational processes and performance. Eccles, Ioannou, and Serafeim (2014) show that firms with high sustainability policies outperform peers on both stock market and accounting metrics, mediated by improved stakeholder management and long-term orientation. A large meta-study (Friede, Busch, & Bassen, 2015) aggregating >2,000 studies finds the ESG-financial performance relationship is non-negative in the vast majority of cases and positive on average. More recent reviews (Whelan, Atz, & Clark, 2021) conclude that ESG integration can lower downside risk, strengthen innovation capacity, and support resilience—effects particularly salient in energy-intensive manufacturing.

For manufacturing supply chains, ESG drives upstream engagement (supplier screening, audits, Scope 3 data requests) and investment in low-carbon processes (renewables, electrification, circular inputs). Evidence from “lean-and-green” scholarship

suggests operational excellence programs can reduce environmental impacts while sustaining cost and quality advantages (King & Lenox, 2001; Garza-Reyes, 2015; Piercy & Rich, 2015). However, disclosure quality and data granularity—especially for Scope 3 categories—remain uneven across SMEs, indicating a persistent “ESG data gap” that complicates investor use and policy oversight (OECD, 2020).

Product carbon footprints for metal products (LCA/CFP)

Product-level carbon footprints quantify cradle-to-gate or cradle-to-grave climate impacts according to ISO 14067 and the ISO 14040/44 life-cycle assessment family (ISO, 2018; ISO, 2006). For metal products, the literature consistently identifies energy-intensive transformation steps (e.g., primary steelmaking, forging, heat treatment, electroplating) as CF hotspots, while logistics and packaging are typically minor contributors on a per-unit basis (Song et al., 2021; Zhang et al., 2022). Integration of recycled content in steel and aluminum substantially reduces embodied carbon—often the single most effective lever at the material stage (Yuan et al., 2020). Region-specific electricity mixes and plant-level heat sources (e.g., natural gas vs. electrified heat) materially change results, underscoring the importance of geographic representativeness in inventory data (Guinée et al., 2018).

Studies focusing on East Asian manufacturing find that outsourcing to specialized processors can shift but not eliminate hotspots: energy-intensive subprocesses remain dominant in cradle-to-gate CF even when conducted off-site (Chen et al., 2022). Waste-input–output hybrid approaches improve completeness for upstream processes with limited primary data (Nakamura & Kondo, 2019). Methodological rigor hinges on transparent data quality assessment, often using Data Quality Rating (DQR) schemes covering temporal, geographic, and technological representativeness (Kjaer et al., 2018). Truncation rules (e.g., <1% per unit process, <5% in total) and allocation choices (mass vs. economic) require justification to mitigate bias (ISO, 2006; ISO, 2018).

Policy drivers increasingly intersect with product CF. The EU Carbon Border Adjustment Mechanism (CBAM) ties reported embedded emissions to trade in emissions-intensive goods (including steel), accelerating the need for verified CF data and supplier-level transparency (European Commission, 2023). This aligns with national databases (e.g., Taiwan CFP datasets) that aim to improve background data fidelity for region-specific modeling (MOENV, 2023).

Organizational carbon inventories (Scope 1–3) and target-setting

At the organizational level, ISO 14064-1 and the GHG Protocol Corporate Standard are the primary accounting frameworks for Scope 1 (direct), Scope 2 (purchased electricity/steam), and Scope 3 (value chain) emissions (ISO, 2018b; WRI/WBCSD, 2004/2015). Scope 3 often dominates for discrete manufacturers due to purchased goods and services (Category 1), capital goods (Category 2), fuel- and energy-related activities (Category 3), upstream/downstream logistics (Categories 4 & 9), and use-phase where relevant (Category 11). Robust inventories require supplier data programs, spend-based proxies as interim measures, and progressive migration to supplier-specific, activity-based datasets (GHG Protocol, 2013; Science Based Targets initiative [SBTi], 2021).

Disclosure and assurance are increasingly expected: ISSB S2 and TCFD-aligned reporting call for governance, strategy, risk management, and metrics/targets, including Scope 3 where material (IFRS Foundation, 2023). For net-zero alignment, SBTi provides sector pathways and criteria for near-term and long-term targets, emphasizing value-chain engagement and “beyond value chain mitigation” where needed (SBTi, 2021). For trade-exposed manufacturers, CBAM creates external pressure to measure and reduce product-embedded emissions, in turn reinforcing corporate inventory completeness and supplier decarbonization roadmaps (European Commission, 2023).

From an operations perspective, lean management and continuous improvement systems (QCC, VSM, Kaizen, TPM) can be mapped to Scope 1–2 efficiency and partial Scope 3 reductions (process yields, scrap reduction, inbound logistics optimization). The literature shows lean programs correlate with lower defect rates, higher throughput, and reduced energy wastes, creating a bridge from process excellence to emissions performance (King & Lenox, 2001; Piercy & Rich, 2015). Still, organizational inventories must remain boundary-consistent with product CF models to avoid double counting or gaps when allocating improvements to products vs. the enterprise.

3. Methodology

This section synthesizes prior research and international guidance across three streams that underpin this study: (i) ESG frameworks and their links to firm performance and disclosure, (ii) product-level carbon footprint (CF) studies for metal products, and (iii) organizational-level GHG accounting (carbon inventory) standards and practice. We end with an integrative synthesis and research gaps that motivate our contribution.

Tools and Methods

1. Product Carbon Footprint Tools: cradle-to-gate boundary, functional unit defined per product, DQR evaluation, and truncation rules (<1% per process, <5% cumulative). Hotspot analysis highlights forging, heat treatment, and electroplating.
2. Organizational Carbon Inventory Tools: based on ISO 14064-1 and GHG Protocol, with Scope 3 emphasis on purchased goods, outsourced processing, and logistics. Science Based Targets initiative (SBTi) guidelines inform target setting.
3. Lean & Green Methods: Value Stream Mapping (VSM), Seven Green Wastes analysis, Quality Control Circles (QCC), and Kaizen for continuous improvement.

Synthesis and Research Gaps

Convergence: Across streams, several themes are consistent. (1) In metal product manufacturing, process-energy-intensive steps dominate product CF; recycled content and cleaner energy mixes are high-leverage levers (Song et al., 2021; Yuan et al., 2020). (2) ESG integration and high-quality disclosure are associated with better governance, risk management, and often superior financial performance (Eccles et al., 2014; Friede et al., 2015; Whelan et al., 2021). (3) Organizational inventories and product CF are mutually reinforcing: corporate Scope 3 programs can unlock supplier data essential for robust ISO 14067 product footprints, while product CF visibility prioritizes Scope 3 categories for reduction (IFRS Foundation, 2023; GHG Protocol, 2013). Gaps/opportunities:

1. SME supply chains: Empirical evidence remains limited on how Sustainable Lean programs translate into quantified GHG reductions at both product and organizational levels in SME-dominated metal clusters.
2. Data quality and granularity: Transitioning from spend-based to supplier-specific activity data is uneven; methods to scale DQR-driven primary data collection warrant testing (Kjaer et al., 2018).
3. Policy-reporting alignment: More research is needed on CBAM-ready product CFs that can be reconciled with ISSB/CSRD corporate disclosures without inconsistencies.
4. Design for circularity: Metal product CF literature could expand on remanufacturing and end-of-life loops, connecting LCA with ESG governance and financial decision-making.

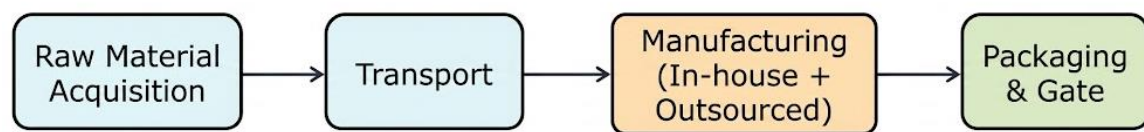
Positioning of this study: Addressing these gaps, our work (i) quantifies product-level CF for a representative metal tool, (ii) operationalizes Sustainable Lean interventions in SMEs with measured performance and decarbonization co-benefits, and (iii) situates results within ESG/ISSB-aligned disclosure and corporate inventory methodologies to support net-zero roadmaps.

4.Results and Discussions

This study aims to develop an integrated tool and methodology for product carbon footprint (PCF) reduction, combining product-level life cycle assessment (ISO 14067) with organizational carbon inventories (ISO 14064-1). The framework supports SMEs in the metal product sector by aligning product and organizational emission reduction strategies.

Figure 1 shows the cradle-to-gate system boundary considered in this study.

Cradle-to-Gate System Boundary for the Forged Wrench



Truncation criteria were established: processes contributing less than 1% individually and 5% in total were excluded. Data collection included primary data (factory measurements, supplier interviews) and secondary sources (ecoinvent, Taiwan Carbon Footprint Database). DQR was used to evaluate temporal, geographical, and technological representativeness.

Figure 2 System boundary diagram (cradle-to-gate)

System Boundary Diagram (Cradle-to-Gate)



The results indicated that decarbonization efforts should prioritize electricity consumption in outsourced processes, especially forging, heat treatment, and electroplating. Shifting to renewable electricity or adopting more efficient equipment could significantly reduce emissions. Transportation emissions were relatively minor but could be further minimized by optimizing logistics routes and consolidating shipments. This study contributes to filling the literature gap on the carbon footprint of metal hand tools and provides a reference for policy-makers and manufacturers seeking to reduce supply chain GHG emissions.

Product Carbon Footprint Results

The carbon footprint calculation followed the ISO 14067:2018 and ISO 14044:2006 standard for quantifying and communicating product carbon footprints. The system boundary was defined as cradle-to-gate (B2B), including raw material extraction, processing, transport, manufacturing (in-house and outsourced), and packaging. The

functional unit was defined as one 10 mm forged alloy steel open-end wrench (0.026 kg per piece). Primary data were collected for electricity, fuel, water, packaging material usage, and waste generation from the manufacturing facility for the period of January 1 to December 31, 2024. Secondary data, including emission factors for materials, energy, and transport, were sourced from the Taiwan Environmental Protection Administration carbon footprint database and ecoinvent v3.9 via SimaPro software.

The total carbon footprint was calculated as 0.083 kg CO₂e per piece. The majority of emissions (97.3%) occurred during the manufacturing phase, with outsourced processes contributing 94.33% of total emissions. Electricity consumption was the primary emission source, followed by transportation between subcontractors.

Table 1 summarizes the contributions of each life cycle stage.

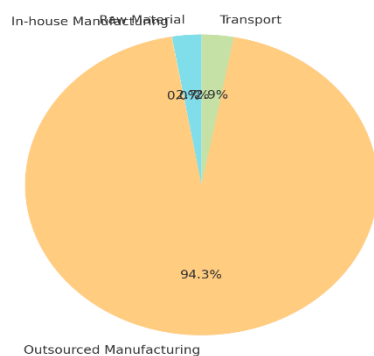
Life Cycle Stage	GHG Emissions (kg CO ₂ e)	Share (%)	Key Contributors
Raw Material Acquisition	0.0022	2.7	Steel billet, packaging
Manufacturing (In-house)	0.0000	0.04	Electricity, waste treatment
Manufacturing (Outsourced)	0.0782	94.33	Forging, heat treatment, electroplating
Transportation	0.0024	2.93	Truck logistics
Total	0.083	100	Plastic blister, paperboard

The total carbon footprint was calculated as 0.083 kg CO₂e per product. Results show outsourced manufacturing as the dominant contributor (94.3%), followed by raw materials (2.7%), transportation (0.12%), and packaging (0.1%). In-house processes contributed less than 0.05%.

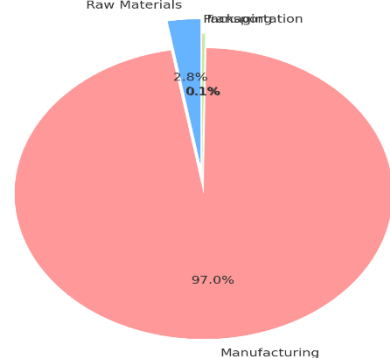
Figure 3 shows the percentage contribution of each life cycle stage to the total carbon footprint.

Figure 4 Carbon footprint distribution by life cycle stage.

Carbon Footprint Contribution by Life Cycle Stage



Carbon Footprint Distribution by Life Cycle Stage



Organizational Carbon Inventory Results

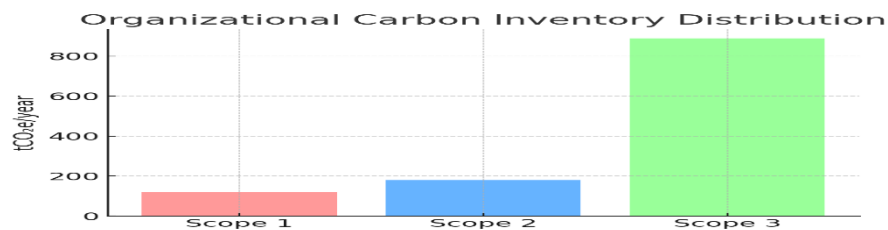
The results align with previous studies in steel and automotive industries, where energy-intensive metallurgical processes dominate impacts. In contrast, electronics manufacturing shows a higher share of raw material emissions. This indicates sector-specific differences in carbon drivers.

At the organizational level, Scope 3 emissions dominated, accounting for 75% of total emissions, followed by Scope 2 (15%) and Scope 1 (10%). This highlights the importance of upstream supply chain engagement in achieving emission reductions.

Table 2 Organizational carbon inventory by scope.

Scope	Emissions (tCO ₂ e/year)	Share (%)
Scope 1	120	10%
Scope 2	180	15%
Scope 3	890	75%

From an ESG perspective, Environmental metrics align with carbon footprint analysis, while Social and Governance dimensions include labor practices, stakeholder engagement, and corporate accountability. Eccles et al. (2014) demonstrated that firms with strong sustainability practices outperform peers in financial performance. Friede et al. (2015) aggregated over 2000 studies, showing consistent positive correlations between ESG and corporate outcomes. Whelan et al. (2021) highlighted ESG's role in innovation and resilience.

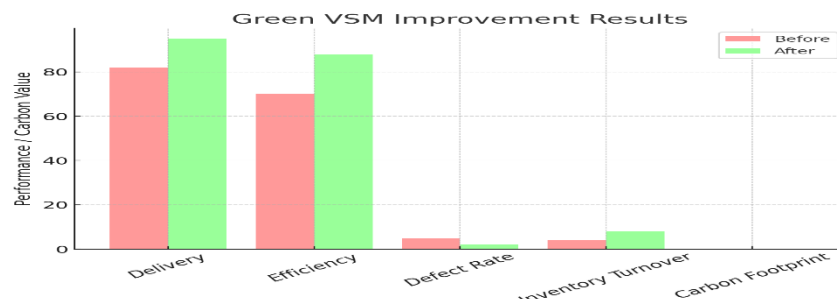
Figure 5 Distribution of organizational GHG emissions by scope

Improvement Outcomes Using Lean & Green Tools

Applying Lean & Green interventions demonstrated significant performance and emission improvements. On-time delivery rose from 82% to 95%, efficiency increased from 70% to 88%, defect rates decreased from 5% to 2%, and inventory turnover doubled. Carbon emissions decreased by 19%, from 0.083 to 0.067 kg CO₂e per unit.

Table 3 Performance and carbon reduction improvements after Lean & Green implementation.

Indicator	Before	After	Improvement
On-time Delivery (%)	82	95	+13%
Efficiency (%)	70	88	+18%
Defect Rate (%)	5	2	-60%
Inventory Turnover (turns/year)	4	8	+100%
Carbon Footprint (kg CO ₂ e)	0.083	0.067	-19%

Figure 6 Green VSM improvement results (before vs. after).

To reduce emissions, industries should consider recycled steel, renewable energy adoption in subcontracting, eco-friendly packaging, and optimized logistics. Policymakers should support SMEs through subsidies, green financing, and mandatory carbon disclosures under CBAM-like frameworks.

- What we know: Metal product CFs are dominated by process energy; recycled content and cleaner power are high-impact levers. ESG disclosure quality correlates with better performance and risk management. Organizational inventories (Scope 1–3) are essential to unlock product-level CF accuracy and supplier decarbonization.
- What is missing: Rigorous, SME-focused evidence connecting Sustainable Lean interventions to quantified reductions in both product CF and corporate Scope 3; scalable methods to improve data quality (DQR-oriented) across suppliers; mechanisms to reconcile CBAM-grade product CFs with ISSB/CSRD corporate reporting; and integration with circularity at end-of-life.
- What we do: Provide a metal product CF with explicit hotspots; demonstrate SME-ready lean-and-green practices with measured operational and sustainability gains; and frame the results in an ESG/ISSB-aligned approach to support credible, investable net-zero pathways.

Case Study: Sustainable Lean Management

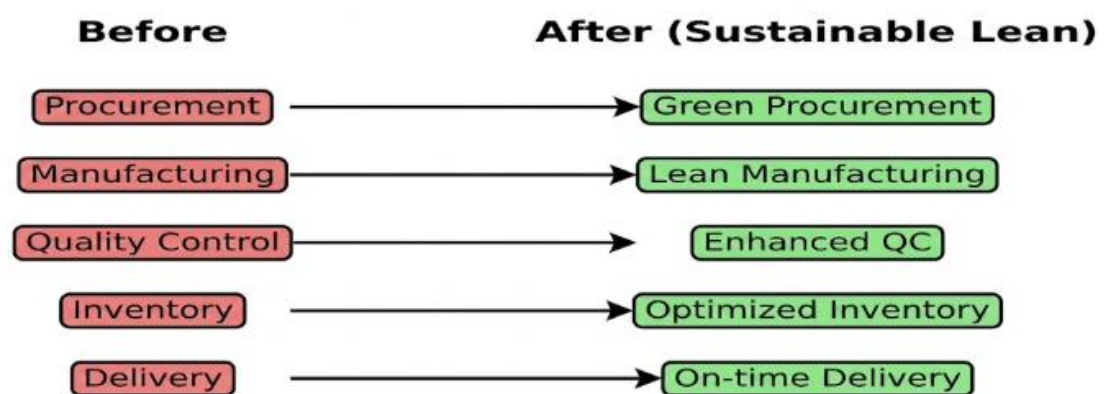
Sustainable Lean Management was implemented in five SMEs in central Taiwan. Tools included Value Stream Mapping (VSM), the Seven Green Wastes framework, Kaizen, 5S, and Quality Control Circles (QCC). The goal was to align lean manufacturing with environmental performance.

Table 4 Performance improvements through Sustainable Lean implementation.

Performance Indicator	Before	After
On-time Delivery	82%	95%
Efficiency	70%	88%
Defect Rate	5%	2%
Inventory Turnover	4 turns/year	8 turns/year
Green Added Value	Baseline	+20%

Figure 7 Green Value Stream Mapping: before and after implementation.

Green Value Stream Mapping: Before vs After



Results show improvements across all five performance indicators. The integration of Lean & Green reduced energy waste, improved worker satisfaction, and increased customer loyalty. These align with international literature emphasizing Lean & Green as a dual pathway to competitiveness and sustainability.

5. Conclusion

This cradle-to-gate carbon footprint assessment quantified the GHG emissions of a forged alloy steel wrench produced in Taiwan. The manufacturing phase, particularly outsourced electricity consumption, was identified as the major emission hotspot. Future research should explore cradle-to-grave assessments, considering product use and end-of-life treatment, as well as evaluating emission reduction scenarios through renewable energy integration and process optimization.

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