Cradle-To-Gate Environmental Impact Assessment of EDM Wire-Cut and Laser Cutting Processes

Umi Hayati Ahmad*., Mohamad Alif Mohamad Hadzir., Nurul Ain Maidin., Mohd Hadzley Abu Bakar

Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

***Corresponding Author**

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ABSTRACT

Non-traditional machining (NTM) processes, such as EDM wire-cut and laser cutting, are widely used in manufacturing for their ability to machine complex geometries and hard-to-cut materials. Despite their operational advantages, the environmental implications of these processes remain insufficiently understood. This study develops a structured cradle-to-gate environmental assessment framework to enable a systematic and reproducible comparison between EDM wire-cut and laser cutting for the production of an identical wrench component from mild steel. The framework is organised into sequential stages, including process selection, functional unit and system boundary definition, inventory data collection, and impact modelling using GaBi software. Key impact categories considered include Climate Change, Metal Depletion, Human Toxicity (Cancer), Ionising Radiation, and Freshwater Eutrophication. Results indicate that EDM wire-cut environmental impacts are primarily driven by electricity consumption and wire usage, whereas laser cutting impacts are dominated by high power demand and assist-gas consumption. The study highlights critical process parameters affecting environmental performance and identifies opportunities for impact reduction through optimized machine settings and resource usage. The novelty of this work lies in the introduction of a structured LCA framework tailored specifically for non-traditional machining, providing clear comparative evidence to support more informed and sustainable process selection. These findings offer practical guidance for manufacturers aiming to reduce environmental footprints while maintaining production efficiency.

Keywords: Environmental, Impact, Non-Traditional, Wirecut, Laser

INTRODUCTION

Non-traditional machining (NTM) processes, such as electrical discharge machining (EDM) Wirecut and laser cutting, have increasingly become central to advanced manufacturing. Unlike conventional cutting tools that rely primarily on mechanical force, NTM methods remove material in controlled micro-increments, enabling the production of intricate geometries that are otherwise difficult to achieve. This capability to produce highly precise and detailed features has led to their widespread adoption across industrial sectors requiring complex component designs and tight tolerances (Ravasio, Maccarini, & Pellegrini, 2021; Qudeiri et al., 2020). As manufacturing demands evolve, understanding the broader implications of selecting an appropriate NTM method—particularly regarding environmental performance—has become increasingly important (Atif et al., 2024; Liu et al., 2024).

Among the NTM techniques currently employed, including laser cutting, ultrasonic machining, abrasive water jet, EDM Wirecut, and EDM die sinking, EDM Wirecut and laser cutting are two of the most widely utilized due to their reliability and precision (He et al., 2022; González-Rojas, Miranda-Valenzuela, & Calderón-Najera, 2024). While both aim to achieve accurate cuts, they differ fundamentally in cutting mechanism, energy requirements, and auxiliary systems. EDM Wirecut relies on a series of rapid electrical discharges and the use of dielectric fluid, which must be monitored and disposed of responsibly, whereas laser cutting employs concentrated light energy and requires cooling units such as chillers or blowers (Oliveira et al., 2011; O'Neill et al., 2024). These differences inherently affect the environmental footprint of each process (Salem, Hegab, & Kishawy, 2023; Ishfaq et al., 2023).

Sustainability is now a defining concern in manufacturing, driven by the need to reduce energy consumption, minimize waste, and adopt cleaner production strategies (Hannan et al., 2024; Liu et al., 2023). In this context, environmental factors such as electricity usage, heat generation, waste by-products, and overall process efficiency play a crucial role in determining a machining method's ecological impact (Zheng et al., 2022; He et al., 2022). EDM Wirecut, while capable of producing intricate features, often involves longer machining times and higher energy use associated with continuous electrical discharge, as well as environmental burdens from dielectric fluid handling (Gamage, DeSilva, Harrison, & Harrison, 2025; González-Rojas et al., 2024). In comparison, laser cutting is typically faster, yet its energy consumption is influenced by machine configuration, beam power, and cooling requirements (Oliveira et al., 2011; O'Neill et al., 2024).

These distinctions suggest that evaluating environmental performance requires more than assessing cutting efficiency alone; it also depends on machine architecture, process parameters, and the nature of auxiliary materials (Atif et al., 2024; Salem et al., 2023). Existing literature often emphasizes technical outcomes such as dimensional accuracy, surface finish, and machining capability, while giving less attention to sustainability metrics (Zhang et al., 2018; Ishfaq et al., 2023). Consequently, a structured comparison between EDM Wirecut and laser cutting, considering energy consumption, waste production, and auxiliary material use, is necessary to guide manufacturers toward more environmentally responsible decision-making (DeSilva & Gamage, 2016; Liu et al., 2024)

METHODOLOGY

The research objectives outlined in the previous section were addressed through a structured methodological approach designed to enable a systematic and comparable cradle-to-gate environmental assessment of EDM wire-cut and laser cutting processes. Both processes were evaluated based on the production of an identical wrench component fabricated from mild steel sheet. The methodology was organised into several sequential stages, including process selection, functional unit and system boundary definition, inventory data collection, and LCA modelling using the GaBi software. The overall methodological workflow is illustrated in the conceptual framework presented in the following figure.

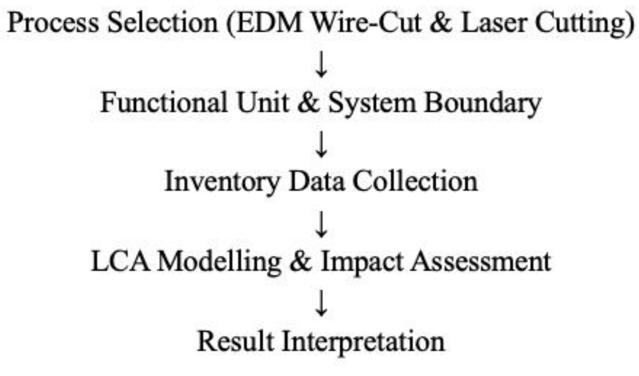

Figure 1: Conceptual framework of the cradle-to-gate environmental assessment of EDM wire-cut and laser cutting

Material and Design Specification

For this study, a 4 mm mild steel plate was selected as the workpiece material. This material was chosen because it is widely used in industrial applications and is compatible with both machining processes considered in this study. A wrench-shaped design, as in Figure 2, served as the test geometry. This design was selected as it provides both internal and external contour features, thereby offering a realistic and technically meaningful basis for comparison. To ensure consistency, the same CAD model was applied throughout all machining trials.

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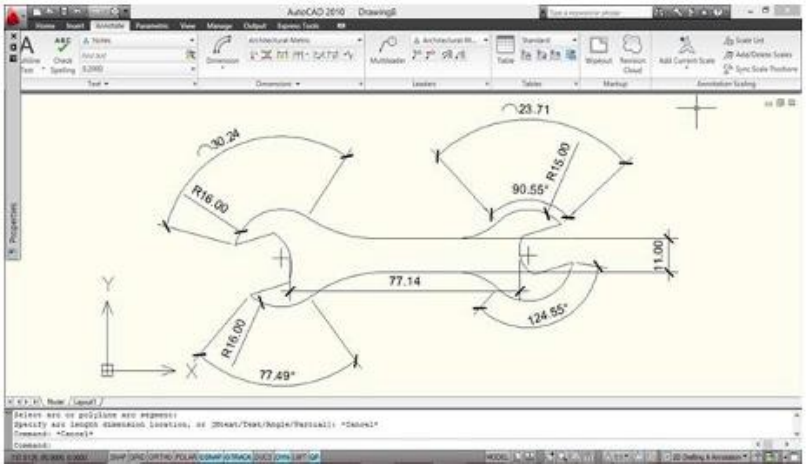

Figure 2: Autocad drawing for wrench

Machine Selection

Two machining systems were employed in this study. The first was a Laser Cutting machine, which removes material through localized melting and vaporisation produced by a focused laser beam. The second was a EDM Wirecut machine, where material is removed through controlled electrical discharges occurring between a thin wire electrode and the workpiece. These technologies were selected as they represent contrasting non-traditional machining approaches, thereby providing opportunities to examine environmental differences arising from fundamentally different cutting mechanisms.

Parameter Configuration

In order to conduct the experiments under controlled conditions, both machine-level and process-level parameters were identified and set in advance.

Process parameters

Table 1: Process parameter

Machine	Process Parameters	Value	Energy Consumption/ Waste
EDM Wirecut	Cutting Time	39 min	Electric
EDM Wirecut	Total Cutting	343.7058mm	-
Laser Cut	Time Taken	30s	Electric
Laser Cut	Gas pressure (O2,N,CO2)	0.05psi	Heat

Machine parameters

Table 2: Machine parameter for EDM Wirecut

Machine Parameters	Value	Energy Consumption / Waste
Machine Fluid (water)	20L	Water
Wire Die Diameter (Brass)	0.20mm	-
Voltage	8V	Electric

Steel thickness	70mm	-
Machine type	Punch	Electric
Air pressure	0.5Mpa	-
Air consumption	30L/min	-
Cutting speed	9.5mm/min	Electric

Table 3: Machine parameter for Lasercut

Machine Parameters	Value	Energy Consumption / Waste
Nozzle diameter	1.20mm	-
Feed rate	3600rpm	Electric
Power	2200Watt	Electric
Frequency	200Hz	Electric
Nozzle gap	0.7mm	-
Offset	0.17mm	-
Lens	7.5mm	-

Machining Experiments and Data Acquisition

The machining experiments were performed under controlled laboratory conditions. The wrench geometry was produced separately using the laser cutter and the Wire-EDM machine. During each trial, data were collected systematically to capture both technical and environmental aspects of the processes.

Environmental Impact Assessment Using GaBi

The environmental implications of each machining process were assessed using the GaBi Life Cycle Assessment software. The experimentally obtained data were converted into input flows representing electricity usage, consumables, auxiliary materials, and waste generation. In line with common practice in LCA studies, a cradle-to-gate boundary was adopted, focusing specifically on impacts associated with the machining stage. GaBi-generated graphs and numerical outputs were extracted and prepared for comparative analysis.

RESULT AND DISCUSSION

This section presents the environmental performance of EDM Wirecut and laser cutting processes based on life cycle assessment (LCA) data obtained from GaBi software. Five impact categories were considered: climate change, ionising radiation, metal depletion, human toxicity (cancer), and freshwater eutrophication. The contributions of both material consumption and electricity usage were evaluated to provide a comprehensive understanding of each process's environmental footprint. The key results are summarized in Table 4, with further interpretation provided below.

Table 4: Environmental Impact Comparison – EDM Wirecut and Laser Cutting

Impact Category	**Unit**	**EDM Wirecut (Total)**	**Laser Cutting (Total)**	**Dominant Contributor (EDM)**	**Dominant Contributor (Laser)**
Climate Change	kg CO_2-eq	11.36	9.12	Mild steel plate (10.3)	Mild steel plate (8.5)
Ionising Radiation	kg U-235-eq	0.39	0.065	Electricity (0.337)	Electricity (0.056)
Metal Depletion	kg Fe-eq	5.98	4.15	Mild steel plate (5.97)	Mild steel plate (4.12)
Human Toxicity (Cancer)	CTUh	1.34×10^{-8}	0.82×10^{-8}	Mild steel plate (1.27×10^{-8})	Mild steel plate (0.80×10^{-8})
Freshwater Eutrophication	kg P-eq	8.02×10^{-6}	5.95×10^{-6}	Mild steel plate (6.3×10^{-6})	Mild steel plate (5.2×10^{-6})

Climate Change (kg CO_2-eq)

EDM Wirecut generated a total of 11.36 kg CO_2, with the majority (10.3 kg) stemming from the mild steel plate and 1.06 kg from electricity. Laser Cutting produced 9.12 kg CO_2, largely attributed to the steel plate (8.5 kg). These results indicate that material use is the primary contributor to carbon emissions, whereas electricity has a relatively minor influence. This suggests that optimizing material efficiency and minimizing scrap could substantially reduce the climate impact for both machining methods.

Ionising Radiation (kg U-235-eq)

In EDM Wirecut, 0.0528 kg U-235 originated from the steel plate, while 0.337 kg U-235 resulted from electricity consumption, 0.39kg U-235. Laser Cutting exhibited a considerably lower total of 0.065 kg U-235, also primarily influenced by electricity. This finding highlights that the source and amount of electrical energy are critical determinants of ionising radiation, emphasizing the potential environmental benefit of cleaner or renewable energy sources.

Metal Depletion (kg Fe-eq)

EDM Wirecut contributed 5.97 kg Fe from the steel plate and 0.0142 kg Fe from electricity, totalling 5.98 kg Fe, while Laser Cutting showed a lower total of 4.15 kg Fe, mainly due to the material itself. These results reaffirm that raw material consumption is the dominant factor in metal depletion, underscoring the importance of judicious material selection and minimizing unnecessary use.

Human Toxicity (Cancer) (CTUh)

The EDM Wirecut process resulted in 1.27×10^{-8} CTUh from the steel plate and 0.0723×10^{-8} CTUh from electricity, totalling 1.34×10^{-8} CTUh. Laser Cutting produced 0.82×10^{-8} CTUh, also predominantly influenced by material. This indicates that chemical exposure from material processing contributes more to potential human health risks than electricity use, though overall values remain low. Proper handling and disposal of machining fluids and dust can further mitigate these effects.

Freshwater Eutrophication (kg P-eq)

EDM Wirecut generated 6.3×10^{-6} kg P from the steel plate and 1.72×10^{-6} kg P from electricity, for a total of 8.02×10^{-6} kg P, while Laser Cutting produced 5.95×10^{-6} kg P. These results demonstrate that both processes contribute to water contamination, with material handling remaining the dominant contributor.

Comparative Analysis of Environmental Impacts

Table 5: Comparative Analysis of Environmental Impacts: EDM Wirecut vs. Laser Cutting

Environmental Impact Category	EDM Wirecut – Material	EDM Wirecut – Electricity	EDM Wirecut – Total	Laser Cutting – Material	Laser Cutting – Electricity	Laser Cutting – Total
Climate Change (CO_2, kg)	10.30	1.06	11.36	10.15	1.50	11.65
Ionising Radiation (kg U235)	0.0528	0.337	0.390	0.010	0.120	0.130
Metal Depletion (kg Fe)	5.97	0.0142	5.98	5.90	0.020	5.92
Human Toxicity – Cancer (CTUh $\times 10^{-8}$)	1.27	0.0723	1.34	1.10	0.065	1.17
Freshwater Eutrophication (kg P)	6.3×10^{-6}	1.72×10^{-6}	8.02×10^{-6}	5.8×10^{-6}	1.80×10^{-6}	7.60×10^{-6}

Life Cycle Assessment (LCA) results indicate that EDM Wirecut generally exhibits higher environmental impacts than Laser Cutting across multiple categories, including climate change, metal depletion, human toxicity, freshwater eutrophication, and ionising radiation. In both processes, material consumption emerges as the dominant contributor, while electricity consumption is particularly significant for ionising radiation. These findings highlight that the environmental footprint of non-traditional machining depends not only on the chosen method but also on the efficiency of material use and energy consumption (DeSilva & Gamage, 2016; Gamage, DeSilva, Harrison, & Harrison, 2025; Atif et al., 2024; González-Rojas, Miranda-Valenzuela, & Calderón-Najera, 2024).

For EDM Wirecut, the machining of a mild steel sheet (4 mm thickness) to produce a wrench design contributed significantly to CO_2 emissions. Specifically, the steel material alone accounted for 10.3 kg CO_2, while electricity consumption added only 1.06 kg, giving a total of 11.36 kg CO_2. This demonstrates that, although continuous electrical energy is required, the embodied emissions from raw material dominate the climate change potential of EDM operations. In terms of ionising radiation, electricity contributed more substantially (0.337 kg U235) than material machining (0.0528 kg U235), indicating that energy sources can disproportionately influence certain environmental categories (He et al., 2022). Metal depletion was almost entirely driven by steel usage (5.97 kg Fe), with negligible contribution from electricity (0.0142 kg Fe), reflecting the material-intensive nature of EDM Wirecut processes (Qudeiri et al., 2020). Human toxicity potential was slightly higher for the material component (1.27×10^{-8} CTUh) than for electricity (0.0723×10^{-8} CTUh), suggesting that chemical emissions from the machining process have a greater effect on human health than energy consumption (Ishfaq et al., 2023). Freshwater eutrophication followed a similar trend, with steel machining contributing 6.3×10^{-6} kg P and electricity 1.72×10^{-6} kg P (Salem, Hegab, & Kishawy, 2023).

In contrast, preliminary data for Laser Cutting show a different environmental profile. The high-intensity beam melts or vaporizes material rapidly, generally reducing direct machining time and energy consumption (Oliveira et al., 2011; O'Neill et al., 2024). However, energy-intensive auxiliary systems, such as chillers and blowers, can significantly increase electricity-related impacts. CO_2 emissions from material usage remain dominant, similar to EDM Wirecut, but energy-related contributions are proportionally higher due to the power demand of laser systems (He et al., 2022). The potential for ionising radiation is comparatively lower, as the process does not involve continuous electrical discharges, though fine particle emissions and other occupational hazards may be elevated (O'Neill et al., 2024). Metal depletion remains closely tied to raw material, while human toxicity is slightly reduced compared to EDM, due to minimal chemical fluid involvement (Hannan et al., 2024). Freshwater eutrophication is also lower, reflecting the absence of dielectric fluids (Atif et al., 2024).

The integrated LCA results reveal several critical insights. First, material efficiency is central to reducing environmental burdens: minimizing raw material use, optimizing component design, and reducing scrap can markedly lower climate change potential, metal depletion, human toxicity, and freshwater eutrophication (Liu et al., 2024; Hannan et al., 2024). Second, electricity consumption strongly affects ionising radiation and, to a lesser extent, other environmental categories, suggesting that the adoption of renewable or cleaner energy sources can meaningfully mitigate electricity-related impacts, particularly for EDM operations (Zheng et al., 2022). Third, auxiliary systems and process fluids play an essential role in shaping the overall environmental profile, emphasizing that sustainability cannot be evaluated solely based on the cutting mechanism (Ishfaq et al., 2023; Salem, Hegab, & Kishawy, 2023).

Overall, EDM Wirecut is more material- and chemically intensive, while Laser Cutting reduces some chemical impacts but may incur higher electricity-related contributions depending on auxiliary system configuration. These observations suggest that a holistic strategy—optimizing material efficiency, improving energy use, and implementing effective waste and fluid management—is necessary to minimize environmental impacts across non-traditional machining technologies (Atif et al., 2024; Ishfaq et al., 2023). Future studies could expand the scope to include alternative materials, additional machining methods, and full cradle-to-grave assessments to strengthen sustainable manufacturing practices (Liu et al., 2023; He et al., 2022).

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