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Life Cycle Environmental and Economic Comparison of Water Droplet Machining and Traditional Abrasive Waterjet Cutting

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Abstract: Abrasive waterjet (AWJ) cutting is a manufacturing technique, which uses a high-speed waterjet as the transport medium for abrasive particles to erode and cut through metal workpieces. The use of abrasives has significant environmental impacts and leads to the high operating costs of AWJ cutting. Therefore, it is important to investigate whether other metal cutting approaches can perform the same tasks with reduced environmental and economic impacts. One such manufacturing innovation is water droplet machining (WDM). In this process, the waterjet, which is immersed in a sub-atmospheric pressure environment, is discretized into a train of high velocity water droplets, which are able to erode and cut through the metal workpiece without abrasives. However, the cutting velocity of WDM is two orders of magnitude slower than AWJ. In this paper, a comparative life cycle and life cycle cost assessments were performed to determine which waterjet cutting technology is more beneficial to the environment and cost-efficient, considering their impacts from cradle to grave. The results show lower environmental and economic impacts for AWJ compared to WDM due to the AWJ's ability to cut more metal over the service life than the WDM. Further sensitivity analyses give insight into how the change in abrasive rate is the most sensitive input for the AWJ, whereas the machine lifetime and electricity usage are the most sensitive inputs for the WDM. These results provide a valuable comparison between these alternative waterjet cutting technologies.

Keywords: life cycle assessment; life cycle cost assessment; metal cutting; water droplet machining; abrasive waterjet cutting; sensitivity analysis

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1. Introduction

Metal machining is a controlled process that cuts metal pieces into the desired shape and size. The global metal cutting machine market size was valued at $6.17 billion USD in 2019 [1]. The market size was predicted to grow at a rate of 5.9% per year in the next six years, given the rising demand from the automotive, aerospace and defense, electronics, and marine industries [1,2]. In the US, the waterjet cutting machine market was valued at $102.4 million in 2016, which was expected to increase to $170.4 million by 2025 [3]. Metal machining of 2D profiles can be achieved through mechanical, waterjet, laser, flame, and plasma cutting machines. With respect to waterjet processes, the two primary types are abrasive waterjet (AWJ), which uses a high-speed stream of water along with abrasive materials to cut metal, and pure waterjet (PWJ), which uses high-speed water alone but is limited to soft materials. Waterjet cutting is a non-thermal process, and the water cools the metal as it cuts, which reduces the alteration of the metal's chemical and mechanical properties and increases the service life of the machined part [4,5]. However, traditional waterjet or AWJ cutting is generally considered water and energy intensive. The use of abrasive grit generates waste streams that can sometimes be toxic and non-biodegradable, and their disposal cost may be up to 17% of the total machining cost [6].

Water droplet machining (WDM) is a recent innovation in PWJ machining [7], which uses a high-velocity train of water droplets to repeatedly strike, erode, and cut through a metal workpiece. The absence of abrasive particles enables cutting in remote areas, i.e., in-space manufacturing, or in circumstances where the risk of abrasive particle embedment is intolerable, such as in medical applications. Furthermore, the elimination of abrasives promotes a cleaner working environment compared to AWJ cutting. Specifically, a sub-atmospheric pressure environment is used to isolate the waterjet and reduce aerodynamic drag and atomization. This preserves the waterjet momentum into a coherent stream. Droplet formation is enabled with a sufficient distance of travel, resulting in high-velocity impingement of pure-water droplets. The high-velocity impact facilitates supersonic flow within the collapsing droplet, which generates shock-waves and pressures beyond the water-hammer effect, e.g., 2.5 GPa [8]. Although the erosion mechanisms of WDM have yet to be identified, the higher peak forces experienced by a droplet train (when compared to a continuous waterjet of equal momenta) suggest that the droplet train exhibits a higher erosive potential and is therefore more effective at machining than a continuous waterjet [9]. In contrast with AWJ, WDM uses significantly less water (e.g., 0.5 L/min for WDM and 5 L/min for AWJ) and eliminates the need for the abrasive grit [10]. However, WDM might be more energy intensive to operate due to slower cutting velocities and other factors. Since WDM is a new innovation and few experimental setups have been examined, our understanding about its environmental and economic performances as compared to the AWJ is still limited.

Life cycle assessment (LCA) and life cycle cost assessment (LCCA) are well-suited tools for gaining a detailed understanding on the environmental and economic implications of AWJ and WDM, determining the WDM's environmental hotspots, and highlighting opportunities for WDM system improvement. LCA quantifies a wide spectrum of environmental impact indicators of a product or system throughout raw material extraction, equipment manufacturing, use, and disposal [11]. It has been previously applied to quantify the environmental impacts associated with various AWJ designs and processes. For instance, Abbatelli (2014) analyzed the life cycle environmental impacts of AWJ cutting using the environmental product declarations (EPD) method [12]. Four types of abrasives were compared, including alluvial garnet, crushed rock, recycled glass, and high-performance synthetic abrasive. This study, however, neglected the production phase of the AWJ equipment and the consumables (nozzles, filters, oil, and spare parts) [12]. Johnson (2009) applied an economic input–output LCA method to quantify the greenhouse gas emissions and energy consumption of three AWJ designs [13]. This study, however, did not consider the raw material extraction, production, and disposal phases of the AWJ machines, as well as the transport of the required consumables during the use phase. Jayakrishna et al. (2019) quantified the embodied energy and the wastewater-associated environmental impacts, including chemical oxygen demand, biochemical oxygen demand, total suspended solids, and total dissolved solids, when using an AWJ to cut a standard gear made of mild steel. Embodied product energies were classified by summing the direct and indirect energies of the AWJ machining process of the gear. This study also ignored the AWJ production and disposal [14].

LCCA, on the other hand, quantifies the total economic cost of a system over its service life, including capital, operation and maintenance, and end-of-life disposal costs. A few previous studies have examined the economic aspect of AWJ metal cutting. For instance, Henning et al. (2012) investigated the means to improve AWJ's cost efficiency during the use phase based on factors such as hydraulic power and abrasive usage [15]. They found that the abrasive rate does not need to be maximized in order for the best technical and economic efficiency. Radovanovic (2020) applied a multi-objective genetic algorithm (MOGA) to optimize the operating cost of an AWJ machine by considering factors such as traverse speed, water use rate, abrasive use rate, and jet standoff [16]. While both studies provide insight into cost efficiency in relation to productivity, they did not consider costs associated with the manufacturing and end-of-life phases, nor did they consider environmental impacts. To the authors' knowledge, no particular LCAs or LCCAs have been conducted for PWJ or WDM. There is still a limited understanding of the environmental and economic tradeoffs between AWJ and WDM processes.

To fill in this knowledge gap, this study analyzed and compared the life-cycle environmental, human health, and economic performances of AWJ and WDM using both LCA and LCCA from cradle to grave, which is one of the prominent gaps in this field. A sensitivity analysis was conducted to explore how important parameters such as electricity consumption, water usage, and abrasive consumption influence the environmental and economic performance associated with one unit of metal cut length for both waterjet systems, which, to the authors' knowledge, is novel in this field of literature.

2. Materials and Methods

2.1. Description of Waterjet Systems

The AWJ and WDM waterjet systems studied in this paper were implemented at the John Olson Advanced Manufacturing Center (Olson Center, thereafter) at the University of New Hampshire (UNH). Figure 1 below depicts a process flow diagram of the AWJ and WDM manufacturing processes that were analyzed in this study.

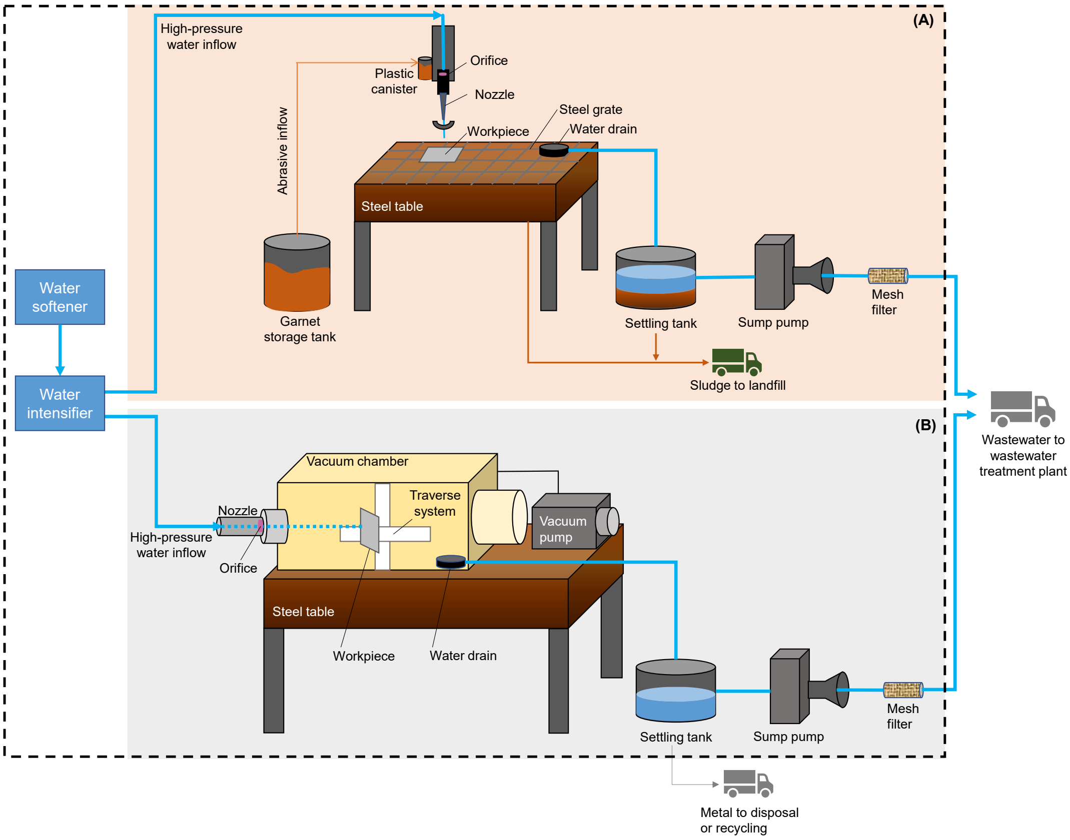

Figure 1. Conceptual process flow diagram for: (**A**) abrasive waterjet (AWJ) from generation of high-pressure water inflow to metal cutting to disposal of sludge and wastewater; (**B**) water droplet machining (WDM) from generation of high-pressure water inflow to metal cutting to disposal of sludge and wastewater. For the WDM system, recycling of used metals was not considered in calculation. The dashed box indicates the system components being considered in this study.

Water entering both systems first passes through a GE Water Softener system (model GXSF30V), where dissolved minerals were removed from standard tap water to protect the following devices. The softened water was then pressurized to 414 MPa (60 ksi) using a Hypertherm HyPrecision 60S waterjet pump powered by a Toshiba 45 kW (60 hp) motor. The high-pressure water flow is then used for metal cutting. The main cutting equipment of the AWJ system is a commercially available model purchased from WARDJet (model

E-1515). It primarily contains a cutting head that is comprised of an orifice and a nozzle, a steel table, a steel grate used to clamp the metal to be cut (workpiece, thereafter), and an abrasive storage and injection system (Figure 1A). After the workpiece is clamped, the cutting head can move in three axes to machine the workpiece. Three THK Ball Screws are responsible for moving the jet. When the jet is on, the high-pressure water inflow is passed through an orifice, which accelerates the water into a high-velocity stream before entering a mixing chamber. Meanwhile, abrasive is pumped from the storage tank into a plastic canister as a temporary storage spot. The abrasive particles carried in the air are then mixed with the high-pressure and high-velocity stream in the mixing chamber and exit the cutting head through a nozzle. The nozzle directs the multi-phase mixture of air, abrasive, and water onto the workpiece, allowing the abrasives to erode and cut through the metal. During the cutting, water, larger abrasive sediment, and metal particles from the workpiece settle to the bottom of the steel table. The waste stream will then exit the waterjet system through a drain and go into a settling tank. Heavier particles settle before the wastewater is pumped through a mesh filter. The settled abrasive and metal particles are manually collected and transported to a landfill. Abrasive recycling was not considered in this study because it is costly compared to purchasing a new supply [17], and landfill remains the most common choice of disposal in the AWJ industry. In addition, recycled abrasive particles lose their sharp edge, resulting in reduced cutting effectiveness. In this study, the type of abrasive used is 80 mesh alluvial garnet.

The main cutting equipment of the WDM system is a custom-built waterjet system developed by mechanical engineering researchers at UNH. It mainly consists of a vacuum chamber, a vacuum pump, a custom-designed traverse system, and a cutting head (Figure 1B). The droplet formation process, known as a Plateau–Rayleigh instability, is a naturally occurring process enabled by surface tension, which minimizes the waterjet surface area by discretizing the jet stream into a series of droplets [9,18,19]. Droplet formation happens after the water leaves the waterjet nozzle and before it comes into contact with the workpiece and can occur at any orientation the stream travels. However, a sufficient distance (e.g., in this study, 68.58 cm between the cutting head and the workpiece) is required to ensure water droplet formation; otherwise, a continuous jet impacts the workpiece, which is significantly less effective at material removal. Unlike the AWJ system, the WDM system has a stationary cutting head feeding the high-pressure waterjet stream into the vacuum chamber (model EQ-VGB-1). There, the gas pressure is reduced to about 8 Torr using a vacuum pump (Edwards model GXS 750) to enable coherent droplet formation. Within the chamber, the workpiece is held and traversed two-dimensionally by a custom-built traverse system. After completing several cuts, wastewater that collects at the bottom of the vacuum chamber is drained to a settling tank and then pumped out as a waste stream. The metal particles from the workpiece are disposed. Given the relatively small amount of metal particles generated as compared to the AWJ waste stream, the metal particle disposal or recycling was not included in our analysis.

2.2. Life Cycle Assessment

2.2.1. Goal and Scope Definition

The system boundary of the two waterjet systems included material extraction, manufacturing, transportation, operation and maintenance (O&M), and end-of-life phases (Figure 2). The functional unit (FU) was defined as cutting 100 m of 6.35-mm thick mild steel plate, considering the ubiquitous use of steel throughout several industries such as the energy, transportation, construction, medical, and automotive industries [20]. The lifetimes of both AWJ and WDM systems were assumed to be 20 years. To meet the desired cutting quality, the optimal cutting speeds of the AWJ and WDM systems are 28.07 and 0.36 m/h, respectively. It was assumed that the waterjet systems are used for eight hours a day, 365 days per year during their lifetimes.

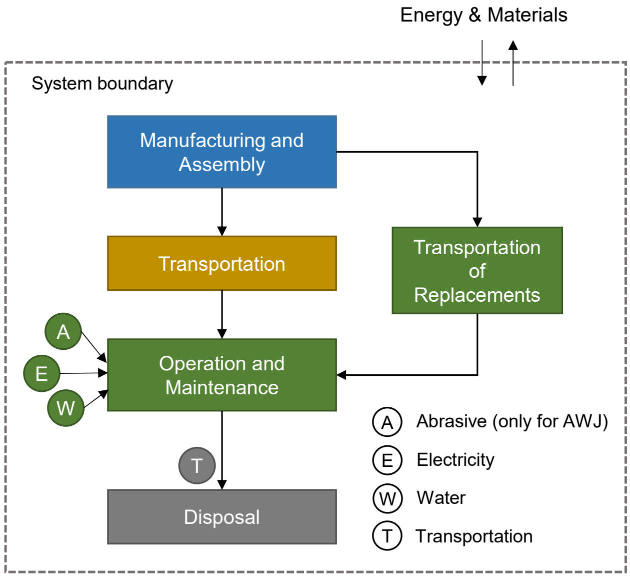

Figure 2. System boundary diagram of the two waterjet systems. The colors represent the various life cycle phases.

2.2.2. Life Cycle Inventory (LCI) Analysis

Material and energy use inventories of the two waterjet systems are provided in Tables 1 and 2. Manufacturing material and energy consumptions were collected directly from vendors or manufacturers. It has to be noted that unlike the AWJ, which has been commercialized, the WDM used in this study was assembled only for research purposes. It is a developing technology that has not been commercialized. Material and energy use during the O&M phase were metered at the Olson Center. The water flow rates of the two systems were measured with Blue-White Industries micro-flow meters (model numbers: FV1-501-7V and FV1-201-7V). The electricity consumptions of the intensifier pump, WARDJet table, sump pump, and vacuum pump were metered with YHDC® current transformers to record active power consumption. The largest energy consumer for the AWJ system is the 414 MPa (60 ksi) intensifier pump at 95 kW. While the WDM system was connected to the same intensifier pump as the AWJ system, a smaller pump is sufficient to supply the relatively low flow rate for the system. As a result, an 11.2 kW Echion 15 pump that is better aligned with the WDM's water supply needs was utilized in our assessment. Energy and water consumption data for this pump were obtained from the manufacturer. The largest energy consumer for the WDM system is the vacuum pump, which requires about 16 kW.

Table 1. Life cycle inventory of the abrasive waterjet (AWJ) system. Numbers show the consumptions over the 20-year life span of the AWJ system.

Life Cycle Phases	Components	Amount	Unit	SimaPro Entry Used	Notes
Manufacturing and Assembly	Pretreatment filter	36.74	kg	Polystyrene, high impact {GLO} | market for | POS, U	GE water softener appliance; 1 softener per waterjet.
	Pretreatment filter packaging	4.536	kg	Corrugated board box {RoW} | market for corrugated board box | APOS, U	Assuming corrugated board box represents a cardboard box.
	Intensifier and motor	1394.79	kg	Steel, low-alloyed {GLO} | market for | APOS, U	Assuming carbon steel is the same as low-alloy steel.

Table 1. *Cont.*

Life Cycle Phases	Components	Amount	Unit	SimaPro Entry Used	Notes
	Sump pump	27.22	kg	Cast iron {GLO} ∣ market for ∣ APOS, U	Assuming a 27.22 kg sump pump made of iron; 1 pump per waterjet.
	Steel table	680.39	kg	Steel, low-alloyed {GLO} ∣ market for ∣ APOS, U	Assuming carbon steel is the same as low-alloy steel.
	Steel grate	28.35	kg	Steel, low-alloyed {GLO} ∣ market for ∣ APOS, U	
	Garnet storage pot	227.00	kg	Steel, low-alloyed {GLO} ∣ market for ∣ APOS, U	
	THK ball screws	27.21	kg	Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	Assuming chromium steel and stainless steel are the same. There are 3 ball screws each with an assumed mass of 9.07 kg.
	Plastic tubing and canister	1.67	kg	Polyvinylchloride, suspension polymerized {GLO} ∣ market for ∣ APOS, U	Estimated based upon 7.01 m of plastic tubing.
Transportation	Transportation of the pretreatment filter and packaging	98.22	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ∣ market for transport, freight, lorry 16–32 metric ton, EURO4 ∣ APOS, U	Assuming it traveled 2379.4 km directly from its facility (Jackson, MS) to Durham, NH.
	Transportation of the intensifier and the sump pump	3334.12	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ∣ market for transport, freight, lorry 16–32 metric ton, EURO4 ∣ APOS, U	Assuming it traveled 2344.7 km directly from its facility (New Brighton, MN) to Durham, NH.
	Transportation of all other AWJ components	4689.24	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ∣ market for transport, freight, lorry 16–32 metric ton, EURO4 ∣ APOS, U	All components besides pretreatment filter, intensifier, and abrasive. Assuming it is directly transported from their facility (Tallmadge, Ohio) to Durham, NH.
Operation and Maintenance	Electricity	5,548,000	kWh	Electricity, at eGrid, NEWE, 2010/kWh/RNA	Assuming it operates 8 h/day and 365 days/year over its service life.
	Water	17,520	cubic meter	Tap water {GLO} ∣ market group for ∣ APOS, U	Rate of water use is 5 L/min.

Table 1. *Cont.*

Life Cycle Phases	Components	Amount	Unit	SimaPro Entry Used	Notes
	Transportation of abrasive and its packaging	51,246,991.60	tkm	Transport, freight, sea, transoceanic ship {GLO} ∣ market for ∣ APOS, U	Assuming abrasive directly traveled from Australia to Durham, NH.
	Abrasive	2,543,020.26	kg	Sand {GLO} ∣ market for ∣ APOS, U	Abrasive is used at a rate of 0.73 kg/min.
	Abrasive packaging	5087	kg	Kraft paper, bleached {GLO} ∣ market for ∣ APOS, U	Assuming 2 kg of packaging per ton of abrasive. Assuming it is bleached.
	Orifice replacement materials	182.5	kg	Steel, low-alloyed {GLO} ∣ market for ∣ APOS, U	Approximate service life is 40 h.
	Orifice replacement transportation	203.36	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ∣ market for transport, freight, lorry 16–32 metric ton, EURO4 ∣ APOS, U	
	Orifice disposal	3.41	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} ∣ market for ∣ APOS, U	
	Steel grate replacement materials	3316.95	kg	Steel, low-alloyed {GLO} ∣ market for ∣ APOS, U	Approximate service life of 500 h.
	Steel grate replacement transportation	3696.11	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ∣ market for transport, freight, lorry 16–32 metric ton, EURO4 ∣ APOS, U	
	Steel grate disposal	61.93	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} ∣ market for ∣ APOS, U	
	Nozzle replacement materials	167.90	kg	Steel, low-alloyed {GLO} ∣ market for ∣ APOS, U	Approximate service life of 80 h.
	Nozzle replacement transportation	187.10	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ∣ market for transport, freight, lorry 16–32 metric ton, EURO4 ∣ APOS, U	
	Nozzle disposal	3.13	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} ∣ market for ∣ APOS, U	
	Plastic tubing and canister replacement materials	6.68	kg	Polyvinylchloride, suspension polymerized {GLO} ∣ market for ∣ APOS, U	Approximate service life of 1460 h.

Table 1. *Cont.*

Life Cycle Phases	Components	Amount	Unit	SimaPro Entry Used	Notes
	Plastic tubing and canister replacement transportation	7.44	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} ǀ market for transport, freight, lorry 16–32 metric ton, EURO4 ǀ APOS, U	
	Plastic tubing and canister disposal	0.12	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} ǀ market for ǀ APOS, U	
End-of-Life	Disposal transport of non-consumables	107.74	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} ǀ market for ǀ APOS, U	Assuming all components are disposed at the Turnkey Landfill in Rochester, NH, which is 18.67 km from Durham, NH.
	Landfill of the sump pump	27.22	kg	Municipal solid waste {RoW} ǀ treatment of sanitary landfill ǀ APOS, U	
	Landfill of the pretreatment filter	36.74	kg	Waste polystyrene {RoW} ǀ treatment of waste polystyrene, sanitary landfill ǀ APOS, U	
	Landfill of the pretreatment filter packaging	4.536	kg	Waste paperboard {RoW} ǀ treatment of sanitary landfill ǀ APOS, U	Assume Paperboard represents cardboard.
	Landfill of the intensifier and other steel components for AWJ	6126.95	kg	Scrap steel {RoW} ǀ treatment of inert material landfill ǀ APOS, U	Includes the disposal for the intensifier cover and motor, the steel table, the steel grate, the garnet storage pot, the ball screws, the orifice, and the nozzle.
	Landfill of plastic tubing	2.79	kg	Waste polyvinylchloride {RoW} ǀ treatment of waste polyvinylchloride, sanitary landfill ǀ APOS, U	Includes the disposal for all replacements.
	Landfill of abrasive	2,543,020.26	kg	Inert waste {RoW} ǀ treatment of sanitary landfill ǀ APOS, U	

Table 2. Life cycle inventory of the water droplet machining (WDM) system.

Life Cycle Phases	Components	Amount	Unit	Simapro Entry Used	Notes
Manufacturing and Assembly	Pretreatment filter	36.74	kg	Polystyrene, high impact {GLO} | market for | APOS, U	GE water softener appliance; 1 softener per waterjet.
	Plastic filter housing	4.13	kg	Polystyrene, high impact {GLO} | market for | APOS, U	
	Pretreatment filter packaging	4.536	kg	Corrugated board box {RoW} | market for corrugated board box | APOS, U	Assuming corrugated board box represents a cardboard box.
	Vacuum chamber	145.15	kg	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	
	Piping components from the intensifier to the chamber	26.94	kg	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	
	12″ hose with fitting	1.22	kg	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	
	Solenoid valve	1	kg	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	
	Couplings	1	kg	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	
	4″ hose and pneumatic valve	28.12	kg	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	
	Traverse system	25	kg	Aluminium, cast alloy {GLO} | market for | APOS, U	
	ISO100 to Conflat Flange	6.61	kg	Aluminium, cast alloy {GLO} | market for | APOS, U	
	Fittings (6)	1	kg	Brass {RoW} | market for brass | APOS, U	Including all other fittings used (6).
	Mounting bracket filter housing	1	kg	Steel, low-alloyed {GLO} | market for | APOS, U	Assuming mild steel is the same as low-alloy steel.
	Edwards GXS750 dry pump	679	kg	Steel, low-alloyed {GLO} | market for | APOS, U	
	Accustream nozzle	0.23	kg	Steel, low-alloyed {GLO} | market for | APOS, U	
	Echion 15 Pump	775.00	kg	Steel, low-alloyed {GLO} | market for | APOS, U	
	Sump pump	27.22	kg	Cast iron {GLO} | market for | APOS, U	Assuming a 27.22 sump pump made of iron; 1 pump per waterjet.
	Garden hoses (2)	4.39	kg	Steel, low-alloyed {GLO} | market for | APOS, U	

Table 2. *Cont.*

Life Cycle Phases	Components	Amount	Unit	Simapro Entry Used	Notes
Transportation	Transportation of all WDM components (non-consumables)	2835.361	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} | market for transport, freight, lorry 16–32 metric ton, EURO4 | APOS, U	Assuming it traveled directly from the corresponding facilities to Durham, NH.
Operation	Electricity	1,588,480	kWh	Electricity, at eGrid, NEWE, 2010/kWh/RNA	Assuming it operates 8 h/day and 365 days/year over its service life.
	Water	3854.40	cubic meter	Tap water {GLO} | market group for | APOS, U	Rate of water use is 0.511 L/min.
	Orifice replacement materials	182.5	kg	Steel, low-alloyed {GLO} | market for | APOS, U	Approximate service life of 40 h.
	Orifice replacement transportation	163.89	tkm	Transport, freight, lorry 16–32 metric ton, euro4 {RoW} | market for transport, freight, lorry 16–32 metric ton, EURO4 | APOS, U	
End-of-Life	Orifice disposal	3.41	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} | market for | APOS, U	Assuming all components are disposed at the Turnkey Landfill in Rochester, NH, which is 18.67 km from Durham, NH.
	Disposal transport (non-consumables)	31.93	tkm	Municipal waste collection service by 21 metric ton lorry {GLO} | market for | APOS, U	Assuming all components are disposed at the Turnkey Landfill in Rochester, NH, which is 18.67 km from Durham, NH.
	Landfill of all polystyrene components	40.87	kg	Waste polystyrene {RoW} | treatment of waste polystyrene, sanitary landfill | APOS, U	
	Landfill of pretreatment filter packaging	4.536	kg	Waste paperboard {RoW} | treatment of sanitary landfill | APOS, U	
	Landfill of all stainless-steel components	203.43	kg	Scrap steel {RoW} | treatment of inert material landfill | APOS, U	
	Landfill of all Aluminium components	31.61	kg	Waste Aluminium {RoW} | treatment of sanitary landfill | APOS, U	
	Landfill of fittings (6)	1	kg	Municipal solid waste {RoW} | treatment of sanitary landfill | APOS, U	No available waste treatment option specifically for brass.

Table 2. *Cont.*

Life Cycle Phases	Components	Amount	Unit	Simapro Entry Used	Notes
	Landfill of all mild steel components	1455.236	kg	Scrap steel {RoW} ǀ treatment of inert material landfill ǀ APOS, U	
	Landfill of sump pump	27.22	kg	Municipal solid waste {RoW} ǀ treatment of sanitary landfill ǀ APOS, U	
	Landfill of garden hoses (2)	4.39	kg	Waste polyvinylchloride {RoW} ǀ treatment of waste polyvinylchloride, sanitary landfill ǀ APOS, U	

2.2.3. Life Cycle Impact Assessment (LCIA)

Using the TRACI 2.1 methodology (version 1.05), a LCIA was conducted for ten impact categories, including global warming potential (GWP), ozone depletion (OD), smog (SM), acidification (AC), eutrophication (EU), ecotoxicity (ET), fossil fuel depletion (FFD), carcinogenic human health (CHH), non-carcinogenic human health impact (NCHH), and respiratory effects (RE). These categories represent key environmental and human health impacts for changes in energy use, metal manufacturing, and water use that are caused by the two waterjet systems. TRACI is a mid-point LCIA method created by the US Environmental Protection Agency (EPA). It was chosen because this study was conducted in the United States, and it provides a wide range of environmental and human health impacts to consider. All LCIA modeling and characterization were performed using the SimaPro 9.0 software with the Ecoinvent 3.4 dataset. For both the AWJ and WDM systems, the characterized results of a certain environmental or human health impact category associated with one FU were calculated using Equation (1). Detailed calculations can be found in the Supplementary Materials.

$$E_i = \frac{A_i + (O_i + M_i) \times n + D_i}{N_{FU}} \quad (1)$$

where:

E_i = Life cycle environmental or human health impact, i, normalized to one FU for a waterjet system;

A_i = Environmental impact, i, created during raw material extraction, manufacturing, and the assembly phase;

O_i = Annual environmental impact, i, created during the operation phase;

M_i = Annual environmental impact, i, created during the maintenance phase;

D_i = Environmental impact, i, created during the end-of-life phase;

n = Service life of the waterjet system under consideration, 20 years for both systems; and,

N_{FU} = Total meters cut by each waterjet system during its service life counted by the number of *FU*s. N_{FU} equals 16,392.85 FUs for the AWJ system and 210.22 FUs for the WDM system.

2.3. Life Cycle Cost Assessment

The LCCA was conducted to estimate the sum of all costs incurred (one-time or recurring) over the projected lifetime of the two waterjet systems. All the past and future costs, including capital, annual operation and maintenance, and end-of-life investments, were summed up in the net present value with a discount rate of 5% taking 2019 as the base year [21]. The life cycle cost for each waterjet system was calculated and normalized to one FU using Equation (2). Detailed calculations can be found in the Supplementary Materials.

$$P = \frac{C_C + C_{O\&M} \times \left[\frac{(1+i)^n - 1}{i \times (1+i)^n}\right] + \frac{C_D}{(1+i)^n}}{N_{FU}} \tag{2}$$

where:

P = Total life cycle cost of a certain waterjet system per FU, 2019 $/FU;
C_C = Capital cost, 2019$;
$C_{O\&M}$ = Annual operation and maintenance cost, 2019$;
C_D = End-of-life disposal cost, 2019$;
i = Discount rate, 5%.

The detailed cost data used to calculate C_C, $C_{O\&M}$, and C_D for the AWJ and WDM systems are provided in Tables 3 and 4. Costs of the AWJ system were based on WARDJet's estimations of the E-1515 model [22]. Costs of the WDM system were estimated based upon data collected through the Olson Center.

Table 3. Life cycle costs inventory of the AWJ system. Numbers represent component costs over the 20-year lifespan.

Life Cycle Phases	Components	Amount	Notes
Manufacturing and Assembly	Capital cost of the AWJ Capital cost of the intensifier	$68,780.00 $88,198.00	Cost from WARDJet [22]
Operation and Maintenance	Abrasive for AWJ operation and disposal over lifetime	$1,407,477.17	Cost from WARDJet [23]
	Cost of water use and disposal	$60,874.65	Cost from Durham's sewage disposal rate [24]
	Cost of electricity over lifetime	$587,692.92	Cost from EIA [25]
	Orifice replacement	$14,557.33	Lifetime of 40 h
	Nozzle lifetime operation	$38,573.03	Lifetime of 80 h
	Steel grate lifetime operation	$72,806.25	Lifetime of 500 h
	Intensifier operation	$1091.69	
	Plastic tubing and canister lifetime operation	$247.53	Assume lifetime is 1460 h
End-of-Life	Disposal of non-consumable components	$7.10	Includes steel table, garnet storage pot, and ball screws. Disposal costs of solid waste estimated from waste management's disposal rate of $24.30/m^3 [26]
	Intensifier disposal	$8.66	

Table 4. Life cycle costs inventory of the WDM system. Numbers represent component costs over the 20-year lifespan.

Life Cycle Phases	Components	Amount	Notes
Manufacturing and Assembly	Capital cost of all WDM components	$176,368.31	Cost information from MTI Corporation [27] and Hypertherm Products [28]
Operation and Maintenance	Lifetime cost of water use and disposal Lifetime cost of electricity Lifetime cost of orifice Total operational cost of intensifier	$6221.39 $163,935.39 $14,557.40 $1091.69	
End-of-Life	Disposal of all non-consumable WDM components	$13.23	Disposal costs of solid waste estimated from waste management's disposal rate of $24.30/m^3 [26]

Sensitivity Analysis

A sensitivity analysis was performed to evaluate the robustness of the results and elucidate how model parameters and key assumptions influenced the environmental, human health, and economic performances of the two waterjet systems. Three model parameters were included in both waterjet systems: the machines' service lives, electricity consumption rates, and water usage rates were investigated by adjusting their values by +/− 50% one-at-a-time considering their important impacts on the results. For the AWJ system, an additional sensitivity analysis was conducted by changing the abrasive usage rate given considerable abrasive consumptions and resultant impacts. For both the AWJ and WDM systems, the characterized result of a certain environmental or human health impact category associated with one FU was calculated using Equation (3) [29].

$$S_i = \frac{E_{i,A} - E_{i,O}}{E_{i,o}} * 100\% \quad (3)$$

where:

S_i = Percent change in environmental/economic impact, i, between $E_{i,A}$ and $E_{i,O}$;
$E_{i,A}$ = Adjusted environmental/economic impact, i, normalized to one FU;
$E_{i,O}$ = Original environmental/economic impact, i, normalized to one FU.

When S_i is larger than 1%, the input variable is considered sensitive. When S_i is larger than 25%, the input variable is considered highly sensitive.

3. Results

3.1. LCA Results

When looking at the LCA results for the waterjet systems, the impacts of WDM are greater across all environmental impacts assessed except for OD (Figure 3). A major factor that has contributed to the WDM's higher impacts in these categories is the WDM's much slower cutting speed as compared to the AWJ. The amount of cutting function that can be provided by the AWJ per time unit is about 78 times the cutting function that can be provided by the WDM. If the WDM's traverse speed is increased by 1150% to 2.95 m/h, WDM will have comparable or lower environmental impacts in all categories as compared to the studied AWJ. In practice, the traverse speed might be improved through a reduction in ambient gas pressure or increased water pressure and thus higher droplet stream velocity. The biggest differences between the two systems comes from the GWP, the FFD, and the CHH, where the WDMs' impacts are around 12.4, 12.2, and 11.2 times that of the AWJs' impacts, respectively (Table 5). Electricity use is the highest contributing factor to the WDM's GWP, SM, AC, NCHH, RE, ET, and FFD impacts. Its CHH impact is primarily contributed by material extraction and manufacturing, with stainless steel and mild steel bearing the greatest burden, as well as electricity. The OD impact is primarily dominated by the machine's material extraction and manufacturing—specifically for the stainless steel, mild steel, and aluminum components—and transportation to the facility. For its EU impact, both material extraction/manufacturing and electricity are key contributors, representing about 53% and 41% of the total impacts, respectively. To summarize, environmental impacts of WDM are primarily dominated by electricity consumption during the operation phase, which is representative in all impacts except for OD, EU, and CHH. Therefore, improved energy efficiency as well as the greening of the electricity grid may help improve the WDM's overall environmental performance.

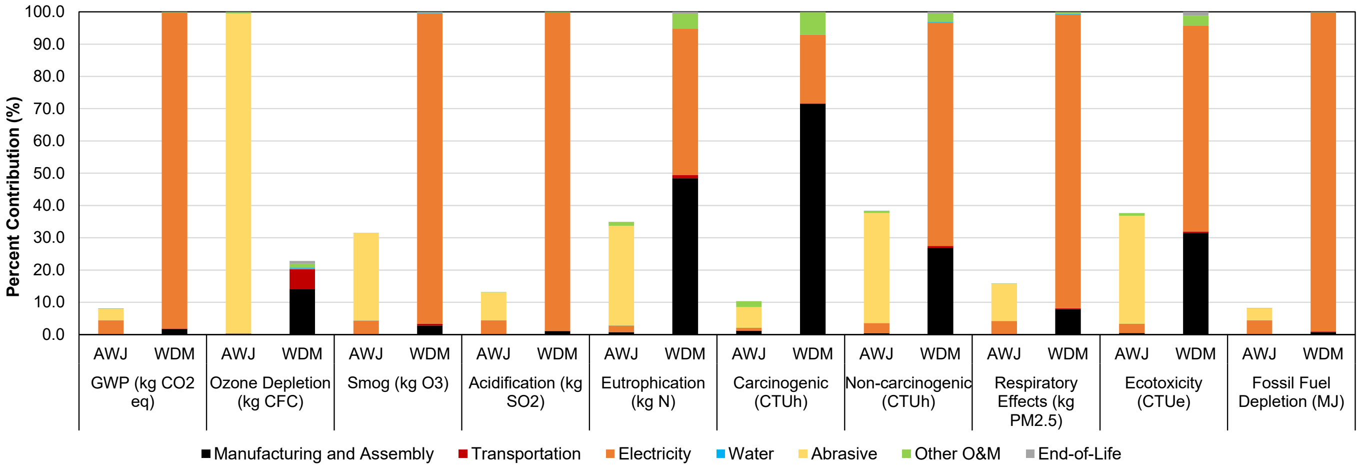

Figure 3. Results of the LCA comparison characterized to the functional unit. Each impact category has two bars. The system with the higher impact in a category is shown as 100% and the system with the lower impact is depicted as a percent relative to 100%. The abrasive category includes the manufacturing, packaging, transportation, and disposal of abrasive during the use phase.

The AWJ only has a higher impact in terms of OD. Particularly, AWJ's OD impact is almost four times that of the WDM's. This is mainly because of the transport of the abrasive. In fact, impacts from abrasive are the dominant component in all of the AWJ's life cycle impacts besides GWP and FFD, where electricity use is a greater contribution than the abrasive. Specifically, the GWP's electricity and abrasive use represents about 54% and 45% of the total impacts, respectively, while the FFD's electricity and abrasive use represents about 54% and 46% of the total impacts, respectively (Figure 3). Specifically, the material extraction/manufacturing, the assembly transport, the disposal transport, and the disposal treatment represent the largest amounts of the abrasive life cycle impacts across all categories. Therefore, efficient use of the abrasive material will give the best improvement on the AWJ's lifetime environmental impacts.

Table 5. Total characterized environmental impacts per functional unit for AWJ and WDM.

Impact Category	Unit	AWJ	WDM	% Difference [1]
Global warming potential (GWP)	kg CO_2 eq	89.2	1107	1141%
Ozone depletion (OD)	kg CFC-11 eq	0.0000088	0.0000024	−72.7%
Smog (SM)	kg O_3 eq	13.3	42.5	220%
Acidification (AC)	kg SO_2 eq	1.10	8.44	667%
Eutrophication (EU)	kg N eq	0.084	0.27	221%
Respiratory effects (RE)	kg PM2.5 eq	0.078	0.50	541%
Fossil fuel depletion (FFD)	MJ	171	2080	1116%
Carcinogenic impact (CHH)	CTUh	0.0000026	0.000029	1015%
Non-carcinogenic impact (NCHH)	CTUh	0.000036	0.00010	178%
Ecotoxicity (ET)	CTUe	802	2280	184%

[1] % difference = 100% × (impact of WDM − impact of AWJ)/impact of AWJ.

3.2. LCCA Results

Figure 4 presents the life cycle cost results of the two waterjet systems. Based on the results, the WDM has a higher total life cycle cost per FU than the AWJ, as shown in Figure 4a. The largest contributor to the AWJ's life cycle cost is the use of abrasive during the O&M phase, which costs about $38.40 per hour to use at 0.73 kg/min [23]. This resulted in a cost of $85.86 per FU. Other significant contributors to the AWJ's life cycle cost include electricity use, which costs $35.85 per FU. The largest contributor to the WDM's life cycle cost is its electricity use during the O&M phase, which costs $800.42 per FU, followed by capital cost and operation and maintenance, which are $681.12 and $74.43 per FU, respectively. Similarly, with the LCA, the WDM's economic performance is also limited by its much lower cutting speed. When the WDM's cutting speed is increased to about

2.60 m/h, the WDM will have a comparable life cycle cost per functional unit to the AWJ. Figure 4b shows that the life cycle cost of the WDM is much less than that of AWJ over the 20-year service life of the equipment. However, the WDM does not cut nearly as much of the steel used in this analysis as the AWJ, i.e., 21,022 versus 1,639,285 m, respectively.

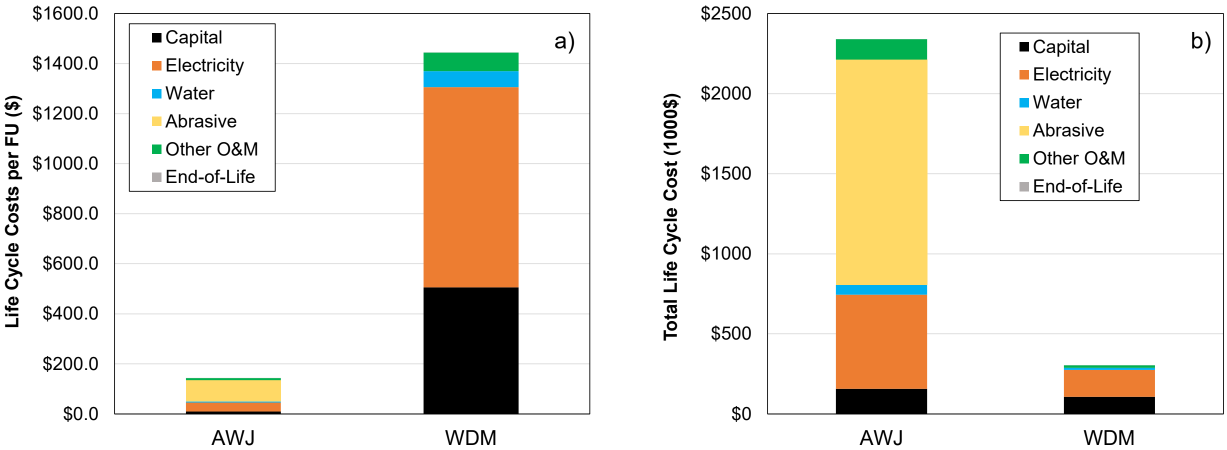

Figure 4. Life cycle costs of AWJ and WDM with respect to (**a**) the functional unit and (**b**) the total life cycle costs over the 20-year service life of the equipment.

3.3. Sensitivity Analysis

The sensitivity analysis results for the AWJ and the WDM are provided in Table 7. Detailed calculations are provided in the Supplementary Materials. Reduction of the abrasive use rate by half can decrease the environmental impacts of the AWJ by a range of 42.0–93.0%. The life cycle cost of the AWJ will also drop by 29.9%. Changes in the AWJ's electricity use rate can result in relatively significant changes in its GWP (±27.1%) and FFD (±26.9%), and less significantly, in AC (±16.9%), and RE (±12.9%) effects, and life cycle cost (±12.6%). Increasing the lifetime of AWJ will significantly decrease most of the environmental impacts by 44.1–49.9%, except for the GWP. It will also decrease its life cycle cost by 18.9%.

Table 6. Sensitivity analysis on the environmental and economic results of AWJ and WDM.

Impacts	Adjusted Abrasive Use (−50%)	Adjusted Electricity Use (−50%)	Adjusted Electricity Use (+50%)	Adjusted Water Use (−50%)	Adjusted Water Use (+50%)	Adjusted Lifetime (+50%)	Adjusted Traverse Speed (+50%)
Results for AWJ							
GWP	−42.0%	−27.1%	+27.1%	−0.012%	+0.012%	−0.012%	−33.3%
Ozone depletion	−93.0%	−0.0041%	+0.0041%	−0.0097%	+0.0097%	−49.8%	−33.3%
Smog	−80.5%	−6.85%	+6.85%	−0.0047%	+0.0047%	−49.9%	−33.3%
Acidification	−61.8%	−16.9%	+16.9%	−0.0045%	+0.0045%	−49.9%	−33.3%
Eutrophication	−83.0%	−2.91%	+2.91%	−0.0082%	+0.0082%	−48.9%	−33.3%
Carcinogenic	−57.7%	−4.59%	+4.59%	−0.029%	+0.029%	−44.1%	−33.3%
Non-carcinogenic	−83.3%	−4.04%	+4.04%	−0.0093%	+0.0093%	−49.4%	−33.3%
Respiratory effects	−68.0%	−12.9%	+12.9%	−0.019%	+0.019%	−49.7%	−33.3%
Ecotoxicity	−83.3%	−3.8%	+3.8%	−0.0015%	+0.0015%	−49.3%	−33.3%
Fossil fuel depletion	−43.0%	−26.9%	+26.9%	−0.0048%	+0.0048%	−49.9%	−33.3%
Life cycle cost	−29.9	−12.6%	+12.6%	−1.30%	+1.30%	−18.9%	−33.3%

Table 7. Sensitivity analysis on the environmental and economic results of AWJ and WDM.

Impacts	Adjusted Abrasive Use (−50%)	Adjusted Electricity Use (−50%)	Adjusted Electricity Use (+50%)	Adjusted Water Use (−50%)	Adjusted Water Use (+50%)	Adjusted Lifetime (+50%)	Adjusted Traverse Speed (+50%)
Results for WDM							
GWP		−49.0%	+49.0%	−0.0163%	+0.0163%	−0.814%	−33.3%
Ozone depletion		−0.403%	+0.403%	−0.730%	+0.730%	−36.1%	−33.3%
Smog		−48.1%	+48.1%	−0.0255%	+0.0255%	−1.45%	−33.3%
Acidification		−49.4%	+49.4%	−0.0101%	+0.0101%	−0.502%	−33.3%
Eutrophication		−22.6%	+22.6%	−0.0491%	+0.0491%	−23.0%	−33.3%
Carcinogenic		−10.6%	+10.6%	−0.0529%	+0.0529%	−33.6%	−33.3%
Non-carcinogenic		−34.6%	+34.6%	−0.0614%	+0.0614%	−13.1%	−33.3%
Respiratory effects		−45.6%	+45.6%	−0.0516%	+0.0516%	−3.56%	−33.3%
Ecotoxicity		−31.9%	+31.9%	−0.00977%	+0.00977%	−15.2%	−33.3%
Fossil fuel depletion		−49.5%	+49.5%	−0.00683%	+0.00683%	−0.374%	−33.3%
Life cycle cost		−27.9%	+27.9%	−2.2%	+2.2%	−17.1%	−33.3%

Highlighted cells indicate highly sensitive variables.

For the WDM, changes in electricity use rate can result in significant changes in the GWP (±49.0%), FFD (±49.5%), AC (±49.4%), RE (±44.9%), and SM (±48.1%) effects and life cycle cost (±27.9%). Increasing the WDM's life span by 50% also shows significant decreases in OD (36.1%) and CHH (33.6%) effects. It will also reduce the life cycle cost by 17.1%.

Both waterjets are sensitive to changes in the traverse speed, where a 50% increase in traverse speed resulted in a 33.3% reduction in both life cycle environmental and cost impacts. However, both AWJ and WDM are not sensitive to changes in the rate of water use.

4. Conclusions

The metal manufacturing industry is a large factor in markets around the world, and production is projected to increase over time. Many corporations and manufacturers around the world are ascertaining the best pathways to take to reduce their environmental footprint while maintaining or improving their economic efficiencies. Studies like this will therefore become increasingly important so that those in industry can understand where these tradeoffs are likely to occur and what can be done to optimize the system. One significant takeaway of this comparison was the use of a cradle-to-grave system boundary, which was, to the best of the authors' knowledge, the first study to do so with and AWJ and an emerging WDM system. The findings on the magnitude of the environmental an economic impact of both waterjet systems can give an enhanced idea of the impacts caused by waterjet machines at a larger scale. Mitigating environmental impacts of recent concern, such as global warming, can now be addressed in this industry with more confidence. One interesting implication is that the manufacturing and assembly impacts of the OD, EU, CHH, NCHH, and ET of the WDM had a more significant contribution than expected. Therefore, if a cradle-to-grave system boundary was not used, the comparison would have given a much more inaccurate conclusion, which could have led decision-makers to use these improperly. Due to issues with the uncertainty of LCA and LCCA, especially for an emerging technology such as the WDM, the sensitivity analysis can provide decision makers with insight into what could be expected if they are trying to improve the environmental and economic performance of these systems based on the parameters that were found to be of most importance. Our sensitivity analysis proved the significance of the traverse speed and lifespan had on the entire system, making those the first parameters that manufacturers should consider when attempting to optimize waterjet systems. Another finding to note was how both systems were not sensitive to the water use parameter, despite both machines using water throughout their life span. Further analyses on the industry's impact on water scarcity at a larger scale could be beneficial for future decisions on system improvements. While the elimination of abrasive in the WDM was expected to have environmental and cost benefits, implementing the current WDM process at a large scale would actually risk increasing the environmental burdens of a global industry and add excessive costs to the process. Increasing the WDM's cutting speed and/or energy efficiency might significantly improve the WDM's environmental and economic performances. However, no specific solutions have been currently identified for improving cutting speed. On the other hand, recent studies have shown reduced orifice diameters may reduce the water flow rate and thereby reduce the required size of the intensifier pump and electricity consumption. Based on the abundance of data from WARDJet about AWJ and the lack of information about WDM, additional studies should be conducted to inform the development of the WDM. If design optimization measures are focused on effectively cutting more metal, while keeping constant or improving the magnitude of key inputs, WDM and AWJ can likely become comparable in the market in terms of lifetime environmental impacts.

Supplementary Materials: The following are available online at http://www.mdpi.com/xxx/s1: LCA Data and Calculations.

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