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An economic and environmental assessment model for microchannel device manufacturing: part 2 – Application

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ABSTRACT

Microchannel heat exchangers provide large surface area to volume ratios and accelerated heat transfer, leading to compact form factors for application in portable and distributed thermal management and waste heat recovery. The application of microchannel heat exchangers in industry has been slowed by high manufacturing costs. Therefore, efforts are being made to find new ways to manufacture these components. This research investigates the application of a process-based cost and environmental impact assessment model to the evaluation of manufacturing alternatives to produce microchannel heat exchangers. A bottom-up process-based cost modeling method is used to estimate the cost of manufacturing a microchannel heat recovery unit (HRU). Cradle-to-gate life cycle assessment is simultaneously applied to evaluate environmental impact. Both sets of calculations extend from a single common set of data consisting of production and device geometry parameters. An analysis is demonstrated for different manufacturing alternatives for producing the HRU. Among the six manufacturing plans evaluated, the combination of laser cutting and diffusion brazing was found to have the lowest cost but the highest environmental impact, while the combination of photochemical machining and laser welding was found to have the lowest environmental impact with a comparatively high cost. Among the cost categories defined, consumables, capital tooling, and utilities were found to be the primary drivers for cost and environmental impact suggesting these as areas to concentrate in future process capability assessments and technology development.

1. Introduction

Mehendale et al. (2000) discussed different size regimes for small channels used in compact and ultra-compact heat exchangers; microchannels are defined as channels with heights below one millimeter, often on the order of several hundred micrometers. Microchannel heat exchangers provide compact form factors for portable and distributed applications. Compared to conventional heat exchangers, microchannel heat exchangers provide large surface areas per unit volume, and accelerate heat transfer due to shorter diffusional distances within the channels (Paul, 2006). The costs associated with producing microchannel heat exchangers have limited their use in industrial applications.

The primary processes in microchannel device manufacturing include patterning and bonding (Paul, 2006). Microchannels are first patterned on metal sheets, and the patterned sheets are then stacked and bonded into a monolithic device. Several patterning and bonding techniques have been explored to facilitate microchannel device manufacturing. Patterning techniques include micro-endmilling (Jeon and Pfefferkorn, 2008), micro-etching (Allen, 2004; Kandlikar and Grande, 2003; Rao and Kunzru, 2007), electrical discharging machining (EDM) (Ho and Newman, 2003), and laser machining (Alavi et al., 1991). Diffusion bonding (Tiwari and Paul, 2010), diffusion brazing (Tiwari and Paul, 2010), and nickel nanoparticle-assisted diffusion brazing (Eluri and Paul, 2013) have been used as bonding processes. Jasperson et al. (2010) evaluated manufacturability and the performance of several manufacturing techniques. They concluded that approaches like micro-casting, micro-extrusion, micro-slotting, and micro-sintering can be utilized for patterning microchannels and are

List of Abbreviations: CNC, Computer Numerical Control; EDM, Electrical Discharge Machining; GUI, Graphical User Interface; HRU, Heat Recovery Unit; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; NiNP, Nickel Nanoparticle; NiP, Nickel Phosphorus; PCM, Photochemical Machining; VBA, Visual Basic for Applications.

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appropriate for mass production. The researchers found that these techniques are not capable of achieving the precision necessary to produce microchannel laminae. EDM and micro-etching were characterized as techniques that can achieve high precision, however, EDM is not recommended for mass production due to its high cost and slow processing rate (Jasperson et al., 2010).

Some researchers have incorporated economic considerations when evaluating the effectiveness of microchannel manufacturing processes and have investigated approaches to drive manufacturing costs lower. Roy et al. (2004) analyzed the cost of photochemical machining (PCM) by building a bottom-up cost model to identify the cost drivers at each stage of its manufacturing process. Leith et al. (2010) estimated and analyzed the cost of microchannel device manufacturing by constructing a bottom-up, process-based cost model. Costs were analyzed for each manufacturing process step and for several cost categories (e.g., facility, tools, labor, and utilities). Based on this work, Lajevardi et al. (2011) further analyzed microchannel device manufacturing and performed a sensitivity analysis and Monte Carlo simulation of model parameters. Although comprehensive cost analysis was performed by prior work (Lajevardi et al., 2011; Leith et al., 2010), little detail was provided regarding cost calculations.

In addition to economic considerations, researchers have studied microchannel device manufacturing from an environmental perspective and tried to develop environmental friendly manufacturing solutions. Liow (2009) compared the energy consumption of conventional Computer Numerical Control (CNC) milling and micro-milling for producing microchannels. Liow concluded that the micro-milling machine analyzed used several hundred times less energy per unit material removed than the CNC milling machine. The design of the microdevice explored is not complex; it is possible that manufacturing energy would increase as design complexity increases. An environmental analysis of a micro-heat exchanger compared the environmental impacts of nickel phosphorus (NiP) electroplated diffusion brazing and nickel nanoparticle (NiNP) assisted diffusion brazing (Haapala et al., 2009). Results suggested that NiNP-assisted diffusion brazing may be a more environmental friendly bonding process. Follow-on work conducted by Brown et al. (2011) assessed the environmental impact of manufacturing a microchannel air preheater, where different patterning and bonding process combinations were analyzed. The results showed that as a patterning process, PCM has higher environmental impacts than laser cutting, although the processes do not provide equivalent shape forming capabilities. For bonding, diffusion brazing was found to have a higher environmental impact than diffusion bonding. The combination of laser cutting and diffusion bonding was found to provide the lowest environmental impacts than the other manufacturing scenarios explored. The framework established for environmental assessment of microchannel device manufacturing (Brown et al., 2011), only considered consumables and raw materials as mass inputs, while tool replacement and facility use were neglected. The analysis focused on quantifying various environmental impacts and the environmental impacts associated with each process step, whereas the sources of the drivers of environmental impacts were not reported.

In recent years, as broader sustainability considerations have gained public interest, consideration has been given to both economic and environmental perspectives of various manufacturing methods. However, little work has focused on microchannel device manufacturing. In prior work, researchers have demonstrated economically viable and environmentally friendly techniques for microchannel device manufacturing (Allen and Jefferies, 2006). No prior work has been performed to simultaneously compare different manufacturing candidates for economic and environmental impact. The work herein summarizes a combined process-based economic and environmental assessment model (Gao et al., 2016). The model is then applied to evaluate different production methods for microchannel device manufacturing, providing quantitative rationale for future process capability studies.

2. Research method

A process-based economic and environmental impact assessment model is developed to evaluate alternate process flows to produce microchannel devices for a range of production volumes. Production parameters, device geometry parameters, tool information, and manufacturing process parameters are required for the model calculations. The calculation method and model description are presented below, followed by a demonstrative application.

2.1. Cost model

A previously reported (Lajevardi et al., 2011; Leith et al., 2010) bottom-up process-based cost calculating method is utilized in this work. The cost of microchannel device manufacturing is divided into seven categories: tool cost, facility cost, labor cost, maintenance cost, raw materials cost, consumables cost, and utilities cost. The cost of each category is determined for each manufacturing process and associated process steps. By summing the cost of each category associated with each process step, total manufacturing cost can be estimated. In this model, several relevant factors, e.g. sales, interest, taxes, administrative activities, and profit, are not considered. Raw materials costs and consumables costs are assumed to be independent of production volume. A diagram of the bottom-up cost flow for microchannel device manufacturing is exhibited in Fig. 1, and described in detail by Gao et al. (2016).

2.2. Environmental impact model

By analyzing the material and energy inputs and outputs within a defined scope, life cycle assessment (LCA) quantitatively estimates the environmental impacts of products, processes, and systems (Goedkoop et al., 2009). To conduct an LCA study, four steps are included: defining the study goal and scope, conducting an inventory analysis, conducting an environmental impact assessment, and interpreting results (ISO, 2006). The scope of environmental assessment in this model is cradle-to-gate. The functional unit analyzed is one microchannel device under different production volumes, which assumes devices will be functionally equivalent. Knowing the device geometry and manufacturing processes, mass and energy inputs are recorded to form the life cycle inventory (LCI) and to conduct the environmental impact assessment. Environmental impacts are then evaluated for five of the cost model categories: tool, facility, utilities, consumables, and raw materials. Impacts of labor and maintenance are not evaluated. The impact of each category is allocated to each manufacturing process and the associated process steps.

Environmental impacts are calculated based on the ReCiPe 2008 method, which characterizes, normalizes, and reports the environmental impacts as environmental impact points (Goedkoop et al., 2009). One thousand points is equivalent to the environmental impact generated by one European citizen over the course of a year (Goedkoop et al., 2009). The unit environmental impact used herein, representing the environmental impact score of one unit of a product, material, energy or waste, is acquired via a commercially available LCA software, SimaPro 7. Environmental impact assessment exhibits two types of uncertainties: data uncertainties, due to challenges in data quality and availability, and modeling uncertainties, due to challenges in representing actual processes using mathematical relationships. Three weighting

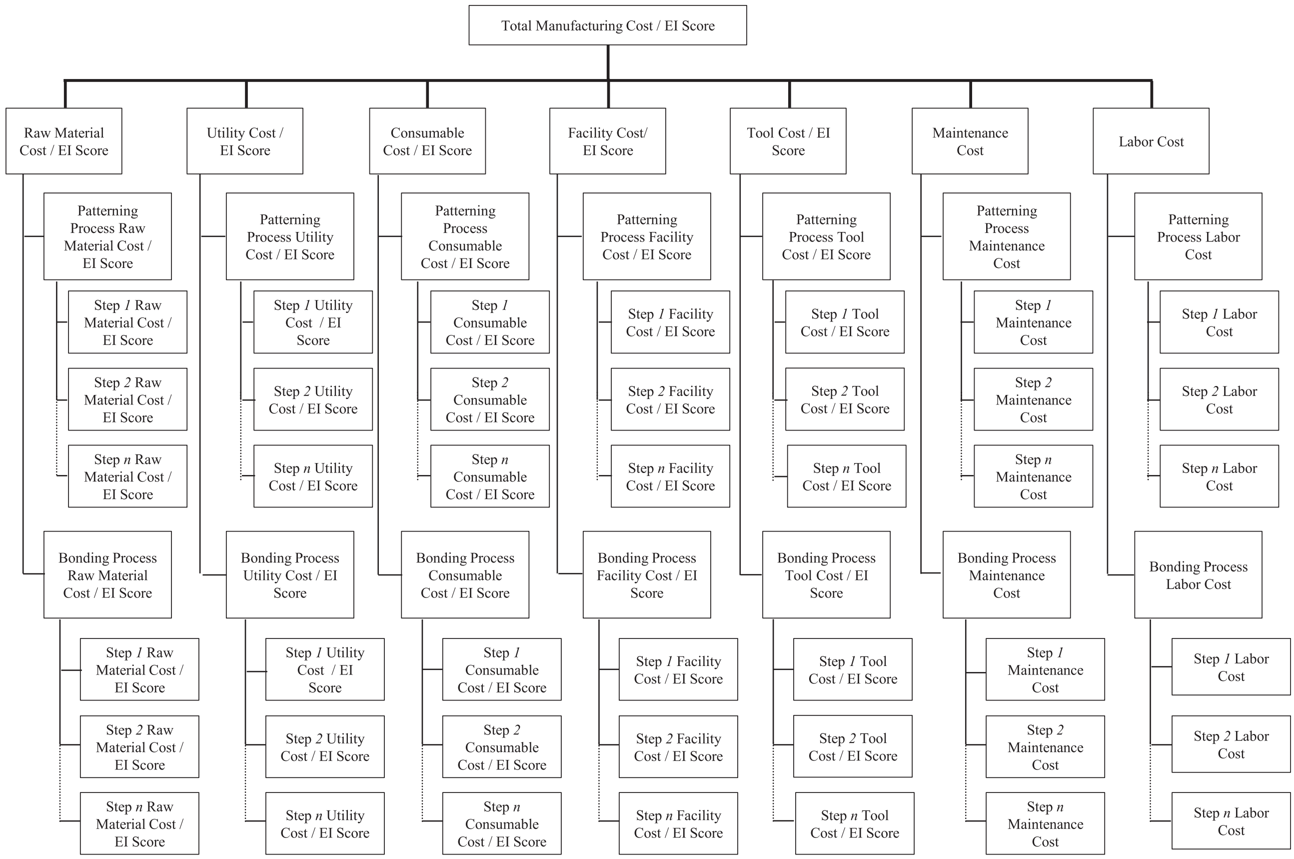

Fig. 1. Process-based bottom-up cost flow and environmental impact score breakdown for microchannel device manufacturing.

archetypes have been developed to account for uncertainties in environmental impact assessment (Goedkoop and Spriensma, 2001): Egalitarian, where a long time perspective is represented and little scientific proof is needed, Individualist, where a short time perspective is represented and only proven effects are considered, and Hierachist, where a balanced time perspective is represented and consensus-based scientifically determined effects are needed. In this work, the Hierachist archetype is chosen to weight environmental impacts. The total manufacturing environmental impact score can be obtained by summing the environmental impact score for each process category. Environmental impact score flow is exhibited in Fig. 1, and described in detail by Gao et al. (2016).

2.3. Modeling interface

The cost and environmental impact models are implemented within MS Excel in the form of three types of worksheets: model inputs, calculations, and results. Input worksheets include a Production and Design Inputs sheet, where production parameters and device geometry are recorded; a Process Flow Inputs sheet, where manufacturing process parameters are recorded; and an EI (environmental impact) Inputs sheet, where environmental impact parameters are stored. Calculation worksheets include the Process Calculation sheet, where the cost calculations are performed; and an EI Calculation sheet where the environmental impact calculations are performed.

The results worksheets include the Process Results sheet and the EI Results sheet, where the cost and environmental results are reported, respectively, in tabular and graphical form. A graphical user interface (GUI) was created using MS Visual Basic for Applications (VBA) to help the user manipulate the model. The GUI is composed of a user form where the user can input expected minimum and maximum annual production volumes, input information about the shim (microchannel laminae) designs, and input device design parameters. Cost and environmental impact results are then calculated and can be viewed in the results worksheets or in a PDF file. The user can also calculate the results for default settings or recall the previous analysis. By inputting the range of annual production rates, the model will analyze nine intermediate data points as potential annual production volumes, and calculate the cost and environmental impact scores for each of these scenarios. To assist product design analysis, cost results for the nine scenarios are shown for each of the seven cost categories, and environmental impact results are shown for five of the seven cost categories, as mentioned above. To assist process analysis, costs and environmental impacts of each process are reported for each category.

3. Application of the method

The manufacturing of a microchannel heat recovery unit (HRU) is chosen to demonstrate the application of the integrated cost and environmental impact assessment method. The HRU is designed to capture the heat energy from diesel engine exhaust, which can reduce the operating cost and heat signature of military vehicles (Wang and Peterson, 2011). By using microchannels in a cross-flow configuration, a higher heat transfer rate can be realized in a much smaller and lighter package than conventional heat exchange devices. Stainless steel laminae, or shims, are produced, layered alternately, and then bonded to form the monolithic HRU device.

This process is termed microlamination (Paul and Peterson, 1999). The HRU consists of two shim configurations – one guides the exhaust air flow and the other the oil flow. The design of the device was reported by Gao et al. (2016) and shown in Fig. 2.

There are two fundamental ways to fabricate the two shim designs. First, as shown in Design A of Fig. 3, is to implement blind cut on a single laminae to make blind channels. The other, as illustrated in Design B of Fig. 3, is to implement a through cut on a shim to make a channel shim and then bond the channel shim to a base shim without any channels. In the Design B case, four kinds of shim are needed to make one HRU device.

PCM is modeled as patterning process for production of Design A, where blind channels are directly etched on the shims. Due to the challenges of making blind cuts using a laser, Design B is applied for laser cutting to simulate an equivalent laminate design. Three alternative bonding techniques are chosen for the bonding process: diffusion bonding, diffusion brazing, and laser welding. Therefore, as shown in Table 1, there are six manufacturing scenarios to be evaluated in terms of cost and environmental impacts to determine the most attractive strategy. The scenarios can be explored to identify key cost and environmental impact drivers and opportunities for potential cost and environmental impact improvements.

3.1. Patterning processes

As summarized by Gao et al. (2016), steps used in modeling the PCM process include cleaning the surface of the metal panel, heating the panels to lamination temperature, laminating the dry film, laminating the photomask and exposing it to ultraviolet light to harden the selected area, spraying chemicals to develop the pattern and to clean the unexposed area, chemically etching the pattern in the panel, stripping the photoresist, inspecting for visual defects, metal etchant waste treatment and reclamation. The model assumes that the whole surface of the stainless steel panel needs to be cleaned. Based on prior work, alkaline and acid chemical use is assumed to be 0.11 L/m^2, and panel etch rate is assumed to be 0.1 mm/min.

A CO_2 laser tool is assumed to be used for the laser cutting process. The laser beam travels through fiber optics and is focused by a lens to ablate the through-cut geometries, including the channels and holes in the metal panels. The cycle time for laser cutting is based on a linear cutting rate of 350 cm/min. For the channel shim, the cutting length is assumed to be the length of all the channels plus the perimeters of the holes and other through-cuts. For the base shims, the cutting length is calculated as the perimeters of the holes and other through cuts. Detailed material and energy input information is shown in Table 2. Material assumptions are made based on commercially available data.

3.2. Bonding processes

Diffusion bonding can be utilized to bond the etched panels and end plates into a monolithic panel stack. Cleaning of the shims is needed at the beginning of the process for degreasing and

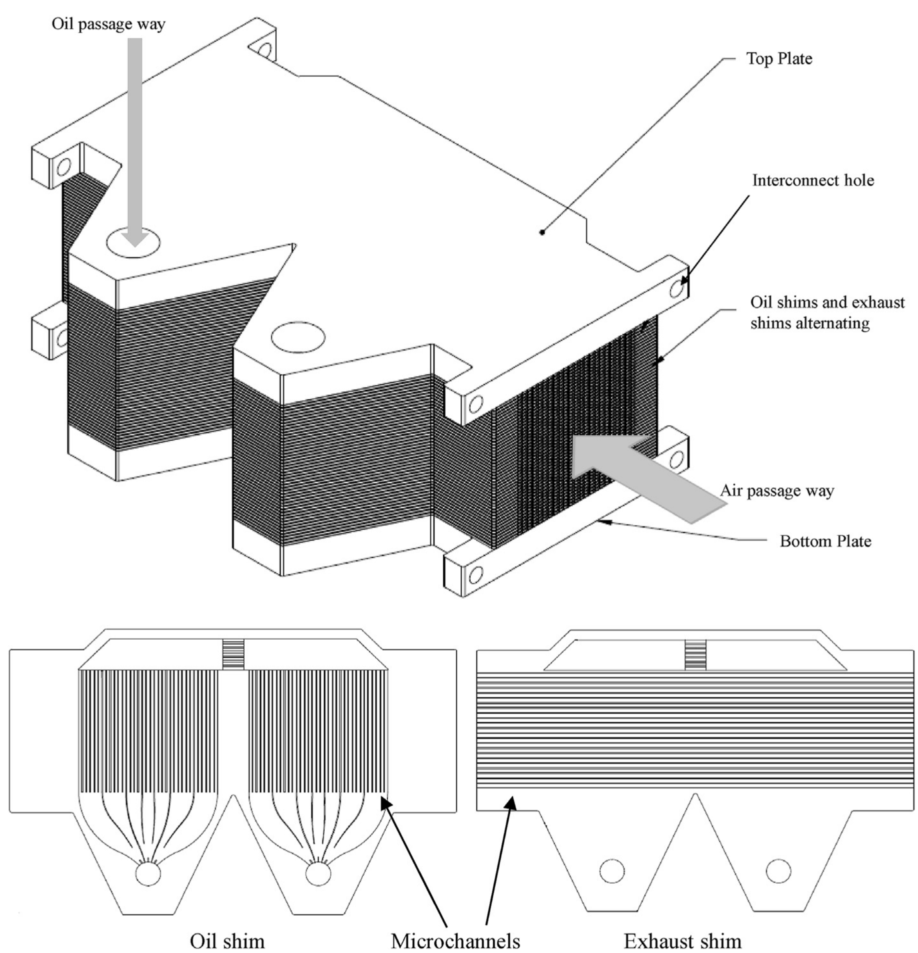

Fig. 2. Microchannel HRU design.

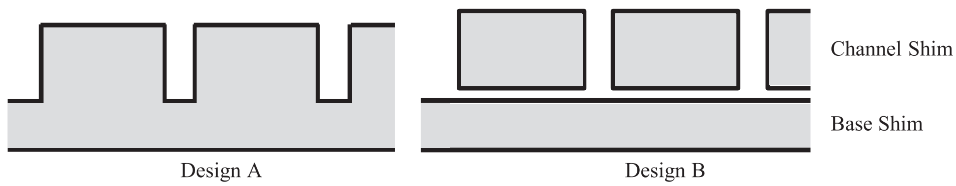

Fig. 3. Two designs to make the channel geometry for the exhaust air shim.

Table 1
Selected scenarios for HRU device manufacturing.

Scenario	Patterning process	Bonding process
1	PCM	Diffusion Bonding
2	PCM	Diffusion Brazing
3	PCM	Laser Welding
4	Laser Cutting	Diffusion Bonding
5	Laser Cutting	Diffusion Brazing
6	Laser Cutting	Laser Welding

particulate removal. The cleaned panels are stacked and aligned in a fixture and bonded. During the diffusion bonding process, panel stacks are heated to a bonding temperature of 980 °C. The total bonding time is 42.7 h, with a heating rate of 5 °C/min., a cooling rate of 0.23 °C/min., a holding time of 120 min., and a furnace load time of 30 min. Diffusion bonding is assumed to have a process yield of 75%.

Diffusion brazing offers a lower bonding temperature and shorter processing time by electroplating a thin interlayer containing a melting point depressant (Tiwari and Paul, 2010). Diffusion brazing includes electroless deposition of NiP, visual defect inspection, alignment of the panel stack in the fixture, loading the panel stack into the oven, and furnace processing. A cleaning and preparation process is needed prior to the NiP deposition. For modeling in this study, total bonding time is calculated based on a heating rate of 5 °C/min., a cooling rate of 0.5 °C/min., a bonding holding time of 60 min., and a furnace loading time of 30 min., with a bonding temperature of 880 °C. Diffusion brazing is assumed to have a process yield of 75%.

Laser welding can be utilized as a bonding process only when the gap between channels is larger than the width of the welding path. It is assumed that the welding path includes the path around all channels and holes where sealing is needed, thus the length of welding path varies for different shim designs. Cycle time is determined based upon a linear weld rate of 350 cm/min. The laser welding process flow includes cleaning and welding of the shim stack. For the bonding processes considered, detailed material and energy input information is reported in Table 3.

3.3. Other processes

Due to the differentiation in the raw material stock size and the actual designed device, a singulation process is needed to cut the bonded panel stacks and endplates to the final HRU dimensions. For the six scenarios, water jet cutting is modeled as the singulation process, and CNC milling is chosen for drilling the interconnect holes. In order to achieve a smooth interconnect surface, EDM is applied to finish the interconnect surface. The cycle time of water jet cutting and EDM are calculated based on a linear cutting rate of 50 cm/min and 30 cm/min, respectively. The cycle time of CNC machining is determined based on a feed rate of 10,000 mm/min, cutting tool diameter of 1 mm, and depth of cut of 33% of the tool diameter. Detailed material and energy input information is presented in Table 4.

Labor, water, electricity, wastewater and sewer costs are assumed based on the rates from Portland, Oregon in 2013, in addition to the process parameters (e.g. tool and facility depreciation years, tool capital costs), as reported by (Gao et al., 2016). Due to the uncertainties regarding expendable components of some of the tools, such as the filter for the EDM tool, the nozzle and pump internals of the water jet cutter, these parts are neglected in environmental impact modeling.

Table 2
Inventory of material and energy inputs for patterning processes.

Process name	Category name	Material/energy type	Process name (SimaPro)
	Raw material	316 Stainless steel	X5CrNiMo18 (316)I
PCM	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Sodium hydroxide (3%, 4%, 25% solutions)	Sodium hydroxide (concentrated) E
		Hydrochloric acid (10%, 15%, 30% solutions)	Hydrochloric acid, 30% in H_2O
		Polymethyl methacrylate	Polymethyl methacrylate, sheet
		PET film	PET film (production only) E
		Sodium carbonate	Sodium carbonate from ammonium chloride production
		Ferric chloride (40%)	Iron (III) chloride, 40% in H_2O
		Sodium chlorate (45%)	Sodium chlorate, powder
Laser cutting	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Silicon	Silican I
		Copper	Cu-E I
		Zinc selenide	Zinc Selenide
		Nitrogen	Nitrogen, liquid

Table 3
Inventory of material and energy inputs for bonding processes.

Process name	Category name	Material/energy type	Process name (SimaPro)
Diffusion bonding	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	25% Sodium hydroxide	Sodium hydroxide (concentrated) E
		15% Hydrochloric acid	Hydrochloric acid, 30% in H_2O
Diffusion brazing	Tool	Iron and Steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	25% Sodium hydroxide	Sodium hydroxide (concentrated) E
		15%, 30% Hydrochloric acid	Hydrochloric acid, 30% in H_2O
		Nickel metal	Nickel
		Sodium phosphate	Sodium phosphate
Laser welding	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Silicon	Silicon I
		Zinc selenide	Zinc selenide
		Nitrogen	Nitrogen, liquid

4. Results

Cost and environmental impact estimates of the six manufacturing scenarios are reported below, followed by an analysis of the results. Drivers to overall costs and environmental impacts will be identified, processes with significant contribution to cost and environmental impacts will be studied, and comparison between processes and scenarios will be drawn.

4.1. Cost modeling results

Per device cost estimates are reported for a range of production volumes in Table 5 for each manufacturing scenario. Projected trends for these results are shown in Fig. 4. It can be seen that total manufacturing cost per unit decreases with increasing production volume, and more significant reductions occur at lower production volumes.

As the production rate increases from 20,000 to 500,000 units, the manufacturing cost for each scenario is comparatively constant.*Scenario 5*, involving laser cutting and diffusion brazing, exhibits the lowest cost for each production volume. At production volumes of 2000 and below, *Scenario 6*, a combination of laser cutting and laser welding, is estimated to have the highest cost. At higher production rates (5000 and higher), however, *Scenario 3* has the highest cost, followed by *Scenario 1*. This indicates that *Scenario 6* becomes a more cost competitive manufacturing method at higher production rates. A detailed cost analysis of each scenario is illustrated in the following sections.

4.1.1. Scenario 1 cost results

Cost estimates for *Scenario 1* are illustrated in Fig. 5. The manufacturing cost per HRU device decreases from $1521.65 to $700.37 as the production volume increases from 1000 to 500,000 HRUs per year. As shown in Fig. 5a, the capital tooling cost accounts for 32.7% of the total cost and is the largest cost driver at a production volume of 1000 units, which would be a volume on the order of a military market. Labor and raw materials are also significant contributors at this production volume, and account for 16.2% and 14.8% of the total cost, respectively. However, as the production volume increases, per unit tool cost, facility cost, utilities cost, maintenance cost, and labor cost decrease significantly due to improvements in equipment and labor utilization. Improved

Table 4
Inventory of material and energy inputs for water jet cutting, EDM, and CNC milling.

Process name	Category name	Material/energy type	SimaPro process name
Water jet cutting	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Garnet abrasive	Abrasive products
		Nozzle	N/A
		Pump internals	N/A
EDM	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Filter	N/A
		Brass wire	Brass
CNC milling	Tool	Iron and Steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionized
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Carbide cutting tool	Ferrochromium, high-carbon, 68% Cr

Table 5
Unit manufacturing cost comparison for different production volumes (in U.S. dollars).

Scenario	Production volume (devices/year)								
	1000	2000	5000	10,000	20,000	50,000	100,000	200,000	500,000
1	1521.65	1075.48	840.04	768.99	728.42	712.83	704.76	701.36	700.37
2	1307.54	907.88	666.62	588.62	554.70	543.92	536.54	533.14	531.66
3	1555.64	1117.65	854.47	769.31	735.51	720.74	712.89	709.34	707.91
4	1367.28	950.09	735.59	670.14	632.31	618.94	611.15	608.08	607.11
5	1147.93	778.73	568.76	496.54	464.67	454.86	447.63	444.47	443.59
6	1666.35	1126.57	806.52	712.36	661.41	643.87	636.23	631.52	630.31

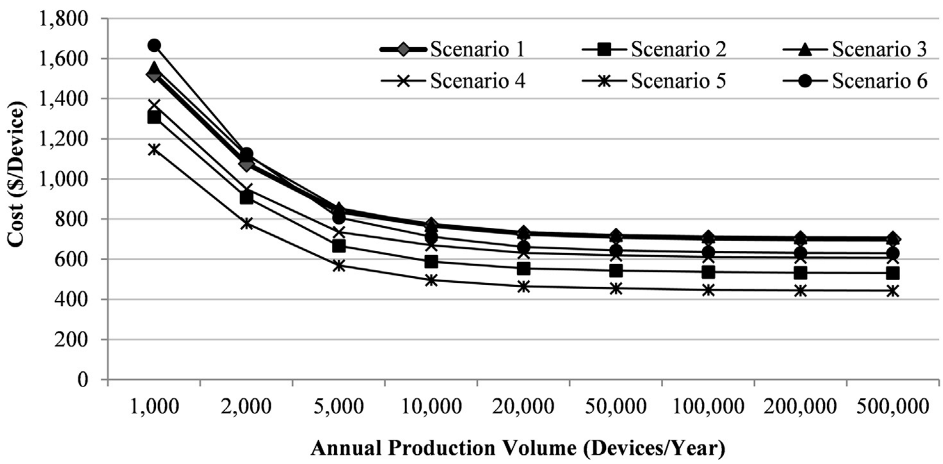

Fig. 4. Cost per unit for each scenario at different production volumes.

equipment utilization affects facility size, maintenance costs, and the amount of utilities.

Raw materials and consumables are considered commodities, and do not change as a function of production volume. Thus, at a high production volume of 500,000 HRUs per year, raw materials and consumables costs become the top two cost contributors. Although decreasing, the cost of tool still accounts for 23.7% of the total device cost. The cost breakdown by process type and raw materials is exhibited in Fig. 5b.

At low production rates, bonding, interconnect, and pattering processes are the top three drivers, accounting for 31.8%, 24.4%, and 17.1%, respectively. As production rates increase, the cost of interconnect and singulation processes drop significantly, from $370.87 and $182.96 at 1000 devices per year to $12.65 and $18.04 at 500,000 devices per year, respectively.

Again, these improvements are due to improved equipment and labor utilization. Comparatively, patterning cost and bonding cost are not affected as much, dropping from $259.49 and $483.33 to $138.28 and $306.39 at 1000 devices and 500,000 devices per year, respectively. The reason for this variation can be explained by examining Fig. 6.

Since the total cost stabilized at a production volume of 20,000 HRUs per year and higher, the figure displays the cost breakdown of each process by cost category at this production volume. PCM

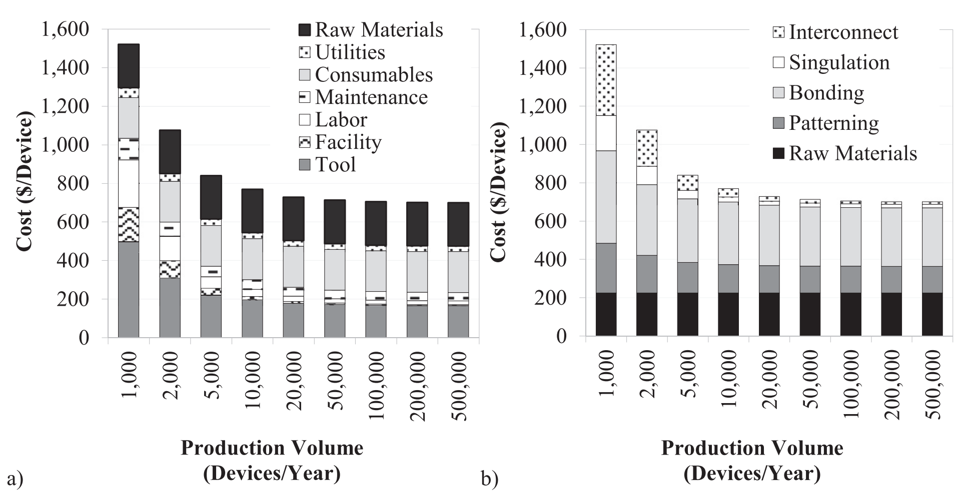

Fig. 5. Cost breakdown for *Scenario 1* by a) Cost category and b) Process type and raw material.

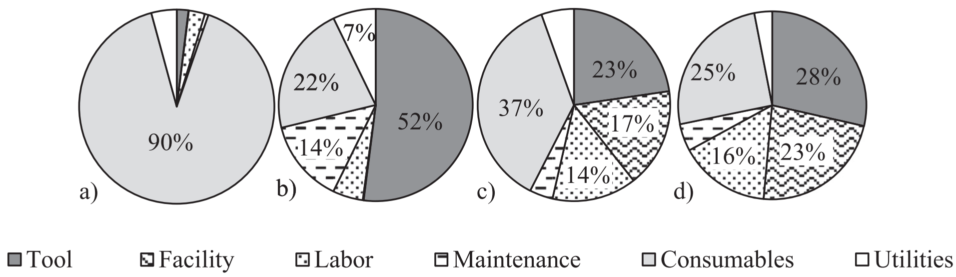

Fig. 6. Cost breakdown for a) PCM, b) Diffusion bonding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining processes for *Scenario 1* (20,000 devices/year).

Table 6
Cradle-to-gate environmental impact per device (Pts/HRU) at different production volumes.

Scenario	Production volume (devices/year)								
	1000	2000	5000	10,000	20,000	50,000	100,000	200,000	500,000
1	303.34	299.07	296.51	295.80	295.45	295.30	295.22	295.18	295.16
2	1773.15	1768.84	1766.24	1765.51	1765.16	1765.00	1764.93	1764.90	1764.88
3	288.40	283.33	280.27	279.43	278.93	278.68	278.63	278.61	278.59
4	2286.02	2284.65	2283.94	2283.71	2283.61	2283.56	2283.54	2283.53	2283.52
5	5473.19	5471.70	5470.90	5470.65	5470.55	5470.49	5470.47	5470.46	5470.45
6	2280.35	2278.88	2278.08	2277.80	2277.66	2277.64	2277.61	2277.60	2277.59

requires a higher fraction of consumables, such as the photoresist and etchant, which are considered commodities, unaffected by higher usage. In the case of diffusion bonding, long bonding times leading to a small capacity for bonding devices per tool. Cost results for *Scenarios 2–6* are reported in the Supplementary Materials document.

4.2. Environmental impact results

Environmental impact assessment is performed for the same nine production volumes for each of the six manufacturing scenarios as done in the cost analysis. Environmental impact scores are shown in Table 6. It is clear that the environmental impact per device of each scenario decreases with increasing production volumes. For each scenario, however, the decrease is not significant.

Environmental impact scores per device for the six scenarios are compared in Fig. 7. As shown, *Scenario 3*, a combination of PCM and laser welding, has the lowest predicted impact. *Scenario 5*, with laser cutting as the patterning process and diffusion brazing as the bonding process, has the highest environmental impacts. A detailed environmental impact analysis is exhibited in following sections, where per device values were based on a production volume of 500,000 devices.

4.2.1. Scenario 1 environmental impact results

As indicated by Fig. 8a, where the environmental impact score is broken down by the categories considered, utilities dominate (87.8%). Raw materials and consumables, with the impact scores of 19.20 Pts and 16.58 Pts, rank the second and third, respectively. Due to the assumption that raw materials and consumables impacts are not dependent upon production volume, their environmental impact scores are constant for all production volumes. The only variable that affects the environmental impact score for utilities is cycle time, which is slightly sensitive to change in production volume. Therefore, environmental impact scores for utilities, raw materials, and consumables are constant at all production rates. Thus, changes in the total environmental impacts only reflect changes in the tool and facility categories, which account for less than 1% of the total score.

Fig. 8b exhibits the environmental impact score by process type. The bonding process, with an environmental impact score of 251.53 Pts/device, accounts for 85.2% of the total impacts. The patterning process and raw materials, with impact scores of 19.58 Pts and 19.20 Pts, account for 6.6% and 6.5%, respectively.

Detailed analysis of each process is illustrated in Fig. 9, where the environmental impact score for each process is broken down into the previously defined categories. It can be seen that consumables account for 67.6% of the environmental impacts for the patterning process, followed by utilities, which account for 32.2% of the environmental impacts. For the bonding process, utilities account for 99.4% of the total impacts, due to process heating. For singulation and interconnect processes, utilities are the major contributors to impact, while consumables are also significant drivers for both processes.

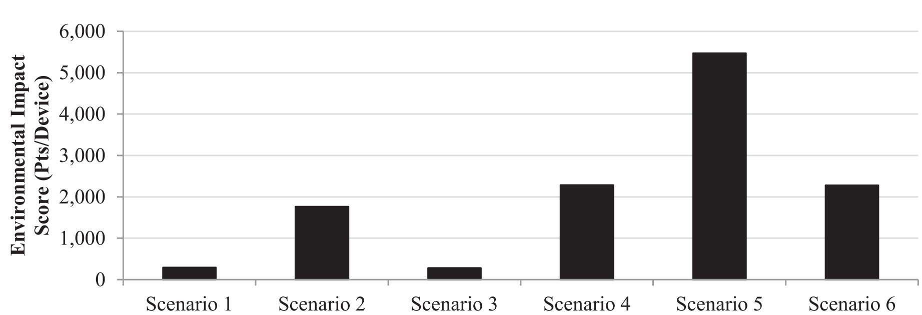

Fig. 7. Environmental impact assessment of the six scenarios (based on 500,000 HRUs per year).

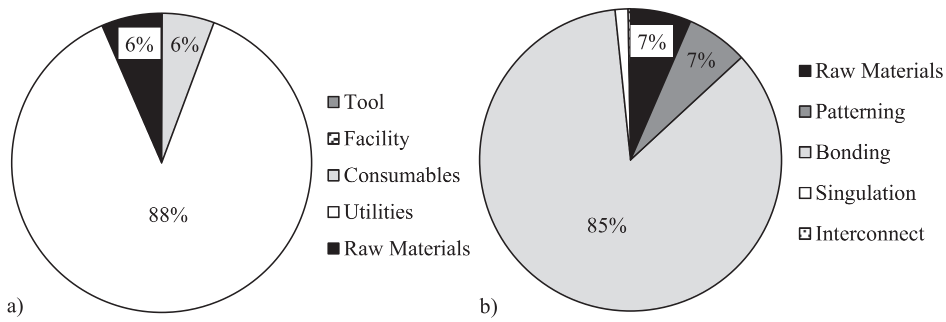

Fig. 8. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 1* (500,000 HRUs per year).

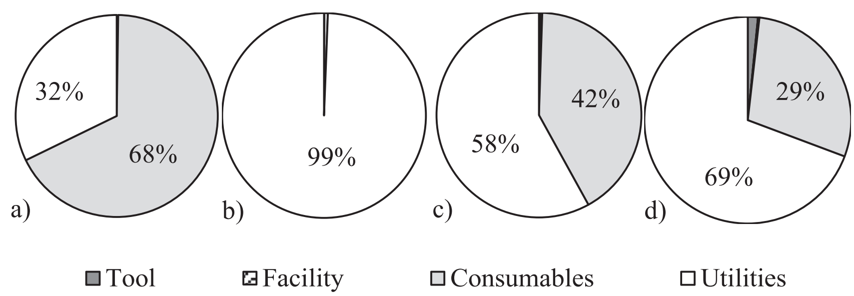

Fig. 9. Categories of environmental impact for a) PCM, b) Diffusion bonding, c) Water jet cutting and CNC milling, and d) Electrical discharge machining process for *Scenario 1.*

Analysis indicates that the major environmental driver of *Scenario 1* is utilities use for diffusion bonding. This result is due to the nature of diffusion bonding for which laminated metal plates are heated to a high temperature for a long time, which requires a large amount of water and electricity. Environmental impact results of the other five scenarios are reported in the Supplementary Materials document.

5. Discussion

Six scenarios for HRU manufacturing were analyzed and compared using the cost and environmental impact assessment method developed in this research (Gao et al., 2016). For each of the scenarios, it was found that per unit cost and environmental impacts decreased as the production volume increased. *Scenario 5* (laser cutting and diffusion brazing) was shown to have the lowest cost, but exhibited the highest environmental impacts. *Scenario 3* (PCM and laser welding) had the lowest environmental impact, but was the most costly manufacturing scenario for a production volume of 5000 HRUs per year or higher. From this brief analysis, it can be seen that it is a challenge to achieve a balance between manufacturing cost and environmental impacts for microchannel devices. Thus, methods for simultaneously quantifying and visualizing both would be beneficial for their sustainable production.

Table 7 summarizes the primary driver for cost and environmental impact of each process step. Consumables are the primary driver of cost and environmental impact for PCM, laser cutting, and diffusion brazing. Therefore, changes to the commodity nature of these consumables with increasing production volume should lead to improvements in cost analysis. Additionally, changes to the amount of consumables used per device would lead to changes in both cost and environmental impact. For PCM this could involve the use of less photoresist or shorter etchant reclamation cycles. For laser cutting, this involves increasing the longevity of optics and photon sources. For diffusion brazing, this involves using less nickel plating. While these are not simple improvements to implement, these results do suggest where process development resources could be concentrated to provide improvement in both the economics and environmental impact.

For diffusion bonding, changes to increase the capacity of the tools would lead to improvements in both cost (lower equipment capital per device) and environmental impact (less energy per device). Opportunities for improving capacities for both diffusion bonding and diffusion brazing could involve improved yields, the gang pressing of multiple panel stacks, or increasing furnace dimensions to handle larger panels or more device stacks. Research to date suggests further improvements in diffusion bonding and diffusion brazing yields may be difficult to achieve (Paul et al.,

Table 7
Primary cost and environmental impacts drivers for each process (20,000 devices per year).

Process	Primary cost driver	Primary environmental impact driver
PCM	Consumables	Consumables
Laser cutting	Consumables	Consumables
Diffusion bonding	Tool	Utilities
Diffusion brazing	Consumables	Consumables
Laser welding	Tool	Consumables
Singulation (Water jet and CNC milling)	Consumables	Utilities
Electrical discharge machining	Tool	Utilities

2006; Paul and Lingam, 2012; Wattanutchariya and Paul, 2004). Thus, novel engineering and technology solutions must emerge.

Laser cutting was found to be much lower cost than PCM. This is mainly due to the nature of the variety of consumables for PCM and the amount of consumables required. Therefore, cost reduction requires lower cost consumable alternatives, or photoresist or etchant reclamation. One limitation of this analysis, however, is that it is assumed that through-cut laser machining can be used to implement the design evaluated in this case study. That capability has not been demonstrated for the HRU and it is expected that it would be difficult to implement, with the need for ribs between each channel, further increasing the complexity of the design and the cost of production.

Laser welding was found to be a less environmentally–impactful bonding process compared to diffusion bonding and diffusion brazing but had higher cost. Shorter paths and improved yields would lead to improvements in both the cost and environmental impact of laser welding. In this way, increased tool capacities would reduce capital equipment costs, while also reducing the number of devices per laser consumable. Finally, both laser cutting and laser welding are both highly dependent on device design due to the impact on weld length. The device design used in this study was optimized for diffusion bonding and diffusion brazing. Therefore, it is expected that additional improvements in cost and environmental impact are possible through dedicated design for laser processing. These results suggest future research can lead to further reduction in the cost and environmental impact of microchannel devices manufacturing and lead to competitive, sustainable technology solutions.

6. Conclusions

An analysis of six manufacturing alternatives for producing a microchannel HRU was performed using a combined process-based economic and environmental assessment model reported in Part 1 of this work. The comparison showed that *Scenario 5* (laser cutting and diffusion brazing) had the lowest cost but the highest environmental impact while *Scenario 3* (PCM and laser welding) exhibited the lowest environmental impact but had the highest cost. A breakdown of the process steps by cost category showed opportunities for prioritizing future process developments aimed at simultaneous improvements in cost and environmental impact. Improvements in both economic and environmental impact of PCM, laser cutting, and diffusion brazing could be made using alternative consumables or by reducing the amount of consumables utilized. For diffusion bonding, changes to increase the capacity of the tools would lead to cost and environmental improvements. For both diffusion bonding and diffusion brazing, higher yields would lead to significant cost and environment improvements. Shorter tool paths would significantly reduce cost and environmental impacts for laser cutting and laser welding.

This work presents a unique combined cost and environmental impact assessment for evaluating microchannel device manufacturing process flows. Compared to prior work, more detailed calculations for cost and environmental impact assessment were illustrated. Unlike conventional environmental impact analysis, impacts were shown to scale with production volume (though future work can lead to further improvements in this regard). This manufacturing-oriented economic and environmental assessment model for microchannel device manufacturing can benefit decision makers by providing quantitative evidence for concentrating investments in process development aimed at improving the economic and environmental performance of microchannel device manufacturing.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.04.141.

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