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A key application of microchannel process technology (MPT) is its implementation in heat exchanger devices, since a larger surface contact area can be realized than in conventional approaches, thus achieving high heat transfer efficiency. To justify high volume production of configurations validated as prototypes, and to select from among the plethora of manufacturing techniques according to sustainable manufacturing requirements, an evaluation of the manufacturing economics and environmental impacts is needed. A spreadsheet-based economic and environmental impact assessment model is thus developed for microchannel device manufacturing. Bottom-up process-based cost calculation and the process-based cradle-to-gate life cycle assessment methods are integrated in this model to evaluate the manufacturing cost and environmental impacts for microchannel devices at a range of production volumes. A graphical user interface allows decision makers to manipulate the model by modifying various production and device geometry parameters. This model provides users a more comprehensive understanding of

the composition of manufacturing costs and environmental impacts, thus providing quantitative support for selecting MPT manufacturing strategies. A case study is given to demonstrate the analysis of cost and environmental impacts of several microchannel device manufacturing scenarios with this model.

An Economic and Environmental Assessment Model for Microchannel Device Manufacturing

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Qi Gao, Author

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CHAPTER I

INTRODUCTION

This chapter introduces the motivation and background of this research, as well as the objective and structure of this thesis.

1.1 Motivation

Due to the promising heat transfer efficiency brought by microchannels, a key application of microchannel devices is to utilize them as heat exchangers. Microchannels, with channel widths of 1-100 μm, facilitate heat transfer rate by enlarging the contact surface of the heat being transferred (Mehendale et al., 2000). Characterized as one of the most innovative and promising techniques, alternatives for microchannel device manufacturing have been explored by researchers to improve quality and performance. Facing the plethora of manufacturing techniques, a solution is needed to evaluate the manufacturing process and comparing between potential alternatives.

Standards of evaluating manufacturing processes and products are developing along with the evolution of manufacturing systems. Development of a manufacturing system can be divided into three phases: mass production, lean manufacturing, and sustainable manufacturing (Zhang et al., 2013). After pursuing productivity in mass production, realizing optimized quality and time management with lean principles, current manufacturing development is driven by a higher level standard: sustainability, which seeks an economic, environmental and socially friendly manufacturing system (Umeda et al., 2012; Haapala et al., 2013). Detailed elements of evaluating sustainability of manufacturing processes includes environmental impacts, manufacturing cost, energy consumption, waste management, operational safety, and personal health (Jawahir and Dillon, 2007).

This research is motivated by the fact that a solution is needed for industry to evaluate the many manufacturing processes available for microchannel devices in the view of sustainable manufacturing requirements. Manufacturing cost, energy consumption, and waste management are deterministic elements, while environmental impact, personnel health, and operator safety are non-deterministic (Lu et al., 2010). The life cycle assessment (LCA) method is considered as the most common method to estimate the environmental impacts through a products' lifetime (ISO, 2006) where energy consumption and waste management can also be considered in the life cycle inventory. Although there is no standard method to measure the societal aspect of sustainability, a method for estimating the economic and environmental impacts for microchannel device manufacturing will benefit the industry by providing a more thorough understanding of the manufacturing alternatives and evidence for potential improvements of the processes approaching sustainable manufacturing.

1.2 Background

Previous research considering economic or environmental impacts of microchannel device manufacturing focused on proposing new manufacturing techniques or improving current techniques according to economic and environmental impact requirements (Allen and Jefferies, 2006; Allen, 2004; Roy et al., 2004). Recent work started to economically evaluate the microchannel device manufacturing techniques by comparing the cost of different alternatives (Lajevardi et al., 2011; Leith et al., 2010). Total cost and cost associated with cost categories of microchannel device manufacturing were estimated and analyzed. Results were associated with production by demonstrating cost at various production volumes (Leith et al., 2010). Sensitivity analysis on process parameters was also conducted by the follow on research (Lajevardi et al., 2011). However, sufficient details were not provided for recreating the model. Environmental impacts of some microchannel device manufacturing process have been explored by prior work (Brown et al., 2011; Haapala et al., 2009), where life cycle assessment comparing several microchannel device manufacturing techniques and scenarios was conducted. However, the evaluation is tailored to specific techniques and designs. Also, environmental impact assessment is not integrated with production, thus the impacts of tool and facility use is not considered. The result of the analysis was focused on the analysis of the type of environmental impacts (e.g. damage to climate change) and environmental impacts associated with each step, while no evidence addressing the environmental impacts drivers was given. It can be seen that reported work integrating economic and environmental impact assessment of microchannel device manufacturing is deficient.

1.3 Problem Statement

To provide industry a more thorough understanding of the economic and environmental perspectives of microchannel device manufacturing, and to give evidence for choosing between different manufacturing alternatives and achieving potential improvements, a manufacturing-oriented model integrating economic and environmental assessment of microchannel device manufacturing is needed.

1.4 Research Tasks

This research was intended to propose a manufacturing-oriented economic and environmental impact assessment model for microchannel device manufacturing. First, the developed model was able to quantitatively estimate the total cost of different microchannel device manufacturing scenarios. Cost estimates were presented associated with various production volumes. Total cost was broken down by cost categories and process types so that the cost categories and processes that drive manufacturing cost can be observed. Evidence was also given pointing out the category within a process that drives the cost.

Second, the model was able to quantitatively estimate the environmental impacts of different manufacturing scenarios. Environmental impact estimates were calculated associated with various production volumes. Similar to cost analysis, the environmental impacts were broken down by impact categories and process types. Evidence was given pointing out the processes and the categories with high environmental impacts. The result was also able to indicate the drivers of environmental impacts within one process.

Lastly, a graphical user interface (GUI) was designed for users to manipulate the model. Device geometry and process parameters can be changed according to different designs and processes to facilitate evaluation of manufacturing costs and environmental impacts.

Aiming at establishing a framework of economic and environmental assessment of microchannel device manufacturing, this research laid a foundation that enabled microchannel device manufacturing to achieving internal and external sustainability goals and requirements.

1.5 Thesis Outline

This research is reported in manuscript format, and composed of five chapters. The current chapter (Chapter 1) introduces the background and provides the motivation for the research. A description of the research problem, research tasks and chapter flow is also mentioned in this chapter. A literature review is provided in Chapter 2 for existing manufacturing methods of microchannel device manufacturing and economic and environmental assessment of the techniques. Chapter 3 expresses the modeling methodology and describes underlying calculations. Chapter 4 focuses on the application of the model to a microchannel device, a heat recovery unit (HRU), where six manufacturing scenarios for the HRU are utilized to demonstrate the use of the model.

Chapter 5 summarizes the research discussed in previous chapters, points out limitations, and offers recommendations for future work.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Microchannel process technology (MPT) has emerged as a technological innovative solution for rapid heat and mass transfer. With the advantages offered by microchannel devices, they can be used in automotive, chemical, food, environmental technology, and aviation and space industries (Schubert et al., 2001). Although requiring fewer materials, microchannel device manufacturing cannot be characterized as have lower production cost and environmental impacts compared to traditional manufacturing. A working environment of preventing pollution and guaranteeing optimal thermal conditions is often required for microchannel device manufacturing, which result in higher energy consumption and higher costs, e.g., for air conditioning filtering system for clean rooms (Modica et al., 2011). Energy and emissions associated with the manufacturing process are also significant (Liow, 2009). Materials required for microchannel device manufacturing, like gold, platinum and titanium, are rare and of significant economic value, consumables are another important consideration (Modica et al., 2011). The need for higher purity levels in micro-manufacturing processes requires improved purification processes for chemicals, which contribute to higher environmental impact and costs. With all the concerns mentioned above, a standard method assessing cost and environmental impacts of microchannel device manufacturing is needed.

The objective of this literature review is to explain the emergence and development of microchannel device manufacturing, and the existing research work implementing economic and environmental consideration. This review will also lead to a new model integrating economic and environmental assessment of microchannel device manufacturing.

2.2 Development of Microchannel Heat Exchanger Manufacturing

Emergence and development of microchannel heat exchanger and the techniques for fabricating microchannel devices will be introduced in this section.

2.2.1 Emergence of microchannel heat exchanger manufacturing

Small channels involved in heat transfer and other applications can be classified as micro-, meso-, compact, or ultra-compact according to the channel size. When applied in micro heat exchangers, microchannels with a channel width of 1-100 µm facilitate heat transfer by enlarging the area of the contacting surface between the substances for which heat is being transferred (Mehendale et al., 2000). This phenomenon can be explained by the equation 2.1, where q is the thermal energy in Joules, h is the heat transfer coefficient, A is the surface area of heat being transferred, T_s is temperature of the object's surface and interior, T_{ent} is the temperature of the environment.

$$q = h * A * (T_s - T_{ent}) \qquad (2.1)$$

The microchannel heat exchanger was originated by Tuckerman and Pease as a compact heat sink aiming to remove heat from very-large-scale integrated circuits (Tuckerman and Pease, 1981). A series of experiments were conducted using a microchannel heat exchanger and it was proven that, with this design, a low thermal resistance could be achieved. Also, with smaller channels, a larger heat transfer coefficient scale was achieved. Subsequential work has extended Tuckerman and Pease's work. Flow characteristics and channel size have been explored to achieve more efficient heat exchange performance. Laminar flow was compared to turbulent flow by Goodling (1993) showing that laminar solution won't always guarantee the lowest thermal resistance for a given pressure loss through the system or for fixed pumping power. An relationship was proposed by Knight et al. (1992) to determine the optimized dimension of microchannels such that the thermal resistance can be minimized. Phase of cooling flow material has been explored by Phillips et al. (1990) and Tuckerman and Pease (1981) to realize a higher heat transfer rate.

Later works extended the applications into microprocessor cooling, cooling of high power electronic equipment, compact heat exchangers, and even compact and micro fuel cells (Steinke and Kandlikar, 2004). Two-phase flow systems have been explored and widely utilized as microprocessors. As the increasing concerns on environment and energy, microchannel heat exchangers have been utilized to solve energy conversion and utilization problems in recent works (Khan and Fartaj, 2011). Other applications of microchannel devices include micromixers and microstructured reactors. With all the advantages of microchannel devices, they can be used in automotive, chemical, food, environmental technology, and aviation and space industries (Schubert et al., 2001).

Microchannel heat exchanger can be fabricated with various materials including stainless steel, hastelloy, copper, aluminum, titanium, brass, silver, palladium, cermet, and cubic boron nitride (Schubert et al., 2001). For different materials, fabrication techniques various, materials that can be processed by each technique are described in section 2.2.2.

2.2.2 Introduction to microchannel device manufacturing techniques

Typical microchannel device fabrication includes a patterning process and a bonding process (Leith et al., 2010). Patterning approaches, e.g., micromachining, micro-etching, micro-molding, micro-electrical discharge machining (micro-EDM), laser machining, are utilized to fabricate the microchannels on materials. Bonding approaches, e.g., diffusion bonding, diffusion brazing, nano-assisted diffusion brazing, laser welding, are then used to bond the patterned sheets to form a monolithic device.

Micromachining techniques, where conventional machining techniques are applied to microscale part manufacturing, can be applied to any material making geometry of the minimum size of 10 μm and tolerance of 1 μm (Liow, 2009). Micromachining techniques include micro-sawing and micro-milling. Micro saws which are able to make saw cuts of 25 μm width are commercially available. Micro-milling, like micro-slot-milling and micro-end-milling can also be utilized to make micro geometries. A slot saw of 150 μm is commercially available. However, a limitation of micro slot milling is only straight channels can be made (Jasperson et al., 2010). Micro-milling applies conventional end milling to a micro scale with the cutting tools size between 5 and 1000 µm in diameter (Jeon and Pfefferkorn, 2008). Thus, a higher spindle speed is required comparing to conventional milling. Most micro-end-milling operations are done with a spindle speed between 50,000 and 100,000 RPM (Jasperson et al., 2010). Micro-end-milling can be utilized in creating complex geometry, however, due to the small size of the tools, they are easily fractured in inappropriate cutting conditions, and the tool wear and fracture cannot be detected easily (Kang et al., 2007). Thus, shop machining processes are suitable for prototyping but not for mass production.

Micro-extrusion is also a feasible method of fabricating microchannels. However, due to the nature of this approach, only straight channels can be made by micro-extrusion, and high precision can hardly be achieved (Jasperson et al., 2010).

Micro-molding can be applied on polymer materials, ceramics, and metallic powders to fabricate precise micro geometries (Weber et al., 1996). Due to the microscale dimension, micro-molding requires a number of equipment modifications. Features made by micro-molding can be as small as 200 µm (Jasperson et al., 2010). Micro-casting and micro-sintering are feasible alternatives of fabricating microchannels. Both are good for mass production and are able to make complex channel structures. Since metal is considered as a better material for heat transfer, a metal mold is needed for a micro-casting. For micro-sintering, the part may shrink upon cooling, result in distortion and stresses in the part.

Micro-etching is characterized as a “modern” technology by Kandlikar and Grande, (2003). Alternatives of micro-etching include wet chemical etching (WCE) and dry format etching, where wet chemical etchant or dry etchants are applied to remove the unwanted material and form the channels (Rao and Kunzru, 2007). Micro-etching can be applied on metal (Rao and Kunzru, 2007), silicon (Abbott et al., 1994), ceramics (Li and Gianchandani, 2006), and glass (Diepold and Obermeier, 1996; Rodriguez et al., 2003). Photochemical etching, which is also known as photochemical machining (PCM), is an advanced micro-etching method with a combination of photoresist imaging and chemical etching (Roy et al., 2004). Characterized as having low cost, fast processing, no burring, precise control of channel dimensions, capability of processing thin materials, and short lead time between prototyping and production (Kandlikar and Grande, 2003), PCM is current widely used in industry. The PCM manufacturing process has the following steps: metal cleaning, light-sensitive resist coating, ultraviolet (UV) light exposure, photoresist hardening, resist removal, etch solution spraying, and unwanted metal removing. Typically, PCM can be applied on metals, glasses or ceramics (Allen, 2004). Micro features fabricated by PCM can be as small as 0.01 μm. Micro-etching is suitable both for bulk production and prototyping.

Electrical discharge machining (EDM) is extensively used to machine complex designed parts or hard materials (Ho and Newman, 2003). EDM removes material when a spark discharges between an electrode and a workpiece (Tsai et al., 2003). By transfering electrical energy into thermal energy, a channel of plasma can be generated between cathode and anode, and thus melt the surface of each pole. Due to the nature of EDM, it can only be applied on conductive materials. By using EDM, channels can be created as small as 5-10 μm, and precise and complex microstructure can be created on hard materials (Anastaselos et al., 2011). Due to the relatively low material removal rate, the cost of EDM is primarily a function time. Although it is proficient in making precise geometries, it is not a suitable technique for mass production (Jasperson et al., 2010).

Laser machining has been mentioned in the literatures as a feasible way to make microchannels. Laser machining is used to make microstructures on silicon instead of conventional etch techniques. The geometry can be as small as 50 μm Alavi et al., (1992).

To laminate the microchannel metal sheet, a series of methods can be used join the patterned metal sheets (with microchannels). Diffusion bonding is a joining process applied on metals and alloys where high temperature, high pressure, and long processing time are required (Burlet et al., 2001). Due to the surface finish of the laminae material, diffusion bonding products may have asperities on the surface (Tiwari and Paul, 2010).

Diffusion brazing is a precise metal and alloy joint process (He et al., 1999). Compared to diffusion bonding, diffusion brazing requires lower temperature and pressure as well as shorter processing time. An interlayer is needed, which would melt while heated to a certain temperature, and then solidify and homogenize in the bond region (Tiwari and Paul, 2010). Diffusion brazed products exhibit better bonding quality compared to diffusion bonded products.

Nanotechnology has been brought into the bonding techniques. Tiwari and Paul, (2010) conducted an experiment comparing nickel nanoparticle (NINP)-assisted diffusion brazing, conventional diffusion brazing, and diffusion bonding. By analyzing the scanning electron microscope (SEM) images of bonding lines, the shear stress, void fraction, and fractography of the bonding samples, they found that NINP diffusion bonding reduced the bonding temperature, increase the shear strength, and increased the bonding quality.

2.3 Economic and Environmental Concerns of MPT

Although fewer materials are utilized to manufacturing microchannel devices than conventional products, microchannel device manufacturing cannot necessarily be characterized as having lower production cost and environmental impacts compared to the traditional manufacturing. On the contrary, the large amount energy, rear raw materials and purified consumables required for the manufacturing process can result in significant costs and environmental impacts (Modica et al., 2011; Liow, 2009). A few studies have implemented economic and environmental considerations on microchannel device manufacturing, trying to achieve a cost-effective and environmental friendly manufacturing.

2.3.1 Economic assessment of MPT

Aiming to achieve lower manufacturing cost, researchers have incorporated economic considerations to the microchannel device manufacturing approaches. As concluded by

Jasperson et al. (2010), most micromachining techniques are suitable for prototyping but not for mass production, not only because of their limited capability of creating complex or desired geometries, but also since they are time and cost consuming. Jasperson et al. (2010) compared the manufacturing cost of two designs for microchannel heat exchanger, micro-pin-fin and straight microchannels, by calculating the cost (C_{total}) based on cost of tools (C_T), cost of materials (C_M), the manufacturing time (t) and cost rate (R).

$$C_{total} = C_T + C_M + t * R \tag{2.2}$$

As they defined it, the cost of tools (C_T) is the sum of capital cost for *N* tools, where *N* is determined by tool life and time required to manufacture one part. The cost of materials is determined by amount of material required and the unit cost of material. Cost rate refers to the capital machinery, any overhead and utilities required for operation, and additional training or labor costs. Total manufacturing time includes machining time, tool change time, set up time, and cleaning time. According to the results of case study, where end-milling was chosen to produce the micro features, the cost of machining the micro-pin-fin surface was estimated to be three times the cost of making equivalent straight channel design (Jasperson et al., 2010). That is because the tool path of micro-pin-fin design is approximately three times the straight channel design. This work proposed a framework to estimate manufacturing cost of microchannel device manufacturing where cost is categorized as tool cost, material cost, and manufacturing cost in the calculations, however the determination of cost rate is still ambiguous. Also, only patterning process microchannel device manufacturing was considered in this work.

Micro-EDM was also evaluated by Jasperson et al., (2010), they concluded that its cost is primarily decided by the cycle time and part geometry. Micro-EDM has a low material removal rate, and the electrodes will wear out after repeated use. Hence, a part with complex design or requiring long tool path would be costly.

Roy et al. (2004) identified the cost drivers of PCM and proposed a method to build a bottom-up cost model to evaluate the cost. The authors analyzed the each process of PCM, listed materials, labor, equipment, and environment along with each process, and identified all the direct and indirect cost associated with them. To build up a cost model, the authors listed all associated information and summed up the total cost. They found the cost is basically driven by chemical usage and tool usage.

Leith et al. (2010) built up a process-based cost model for microchannel device manufacturing, where several manufacturing processes are analyzed. The cost categories were defined as capital equipment, labor, direct materials, indirect materials, energy/utilities, facilities and maintenance. Cost of each process step associated with each cost category were calculated and summed up to the total cost. The manufacturing cost of an MPT device utilized in an ammonia absorption cycle heat pump system is evaluated with this cost model, and the result illustrated that at a production rate of 100 devices/year, manufacturing cost exceeds \$9,000/device. As the production volume increased to 10,000 devices per year, manufacturing cost dropped to around \$3,500/device. The cost of PCM was analyzed as a patterning process in this work. According to their calculations, at a production rate of 3,375 m^2/year, the cost for PCM is approximately $275/m^2 while at a higher production rate of 23,625 m^2/year, the cost drops below $100/m^2, and stays constant as the production rate increases from that level. Leith et al. (2010) also drew a comparison between the absorber's various patterning processes including PCM, electrochemical machining (ECM), stamping/piercing, laser cutting, and abrasive water jet cutting. They claimed all of the above technologies are able to make larger and through channel geometries, however for blind channels as small as 5000 mm^3/m^2, only PCM, ECM and stamping are capable. For through channels, they found that at a lower production rate (3,450 m^2/year), PCM is the most expensive process with a cost of around $300/m^2, followed by water jet with its cost of around $200/m^2. The three other processes cost around $135/m^2 at this rate. At a production rate of 24,000 m^2/year or higher, the cost of all processes would stay constant with an increase in production. Water jet cutting has the highest cost at around $150/m^2, PCM drops to approximately $90/m^2, and stamping is at around $75/m^2, while laser cutting and ECM rank with the lowest costs, which are approximately $50/m^2. For blind cut technologies, at the lower production rate of 3,450 m^2/year, the cost of PCM, stamping, and ECM are approximately $300/m^2, $200/m^2, and $135/m^2, respectively, and at a production rate of 24,000 m^2/year or higher, the cost drops to $90/m^2, $105/m^2, and $50/m^2, respectively. Leith et al. (2010) also conducted a comparison between the absorber's bonding processes including diffusion bonding and laser welding at different parameters. Due to the fact that the cost of laser welding is dependent upon the length of welding path, different welding length is considered. At a lower production rate of 240 devices per year, when four devices are bonding in one cycle, the cost of diffusion bonding is $2700 per device, while it is $2400 per device for sixteen devices per bond cycle. For laser welding, however, the cost at this production rate is lower, ranging from $1000 to $1200 for different process designs with tool path of 6,000cm, 60,000cm, and 120,000cm per device. At a production rate of 3,840 devices per year or higher, the cost of diffusion bonding drops to around $800 per device and $200 per device for 4 devices and 16 devices per bonding cycle. For laser welding the cost drops to a range of $50 to $350 per device.

Follow-on work investigated the manufacturing cost of a microchannel device from a product perspective, where cost along the whole microchannel device manufacturing process was calculated at different production rates (Lajevardi et al., 2011). The yield between processes is also calculated. The process combination analyzed were PCM and diffusion bonding. At a low production rate of 200 devices per year, the cost is around $5,250 per device, while at a production rate of 20,000 devices per year, the cost drops below $500 per device. Supported by the result obtained by Leith et al. (2010), processes such as PCM and diffusion bonding with high tool capital cost are suitable for mass production but not prototyping. A sensitivity analysis was also conducted by Lajevardi et al. (2011) on model parameters where values of parameters were changed by ±50%. The results showed that cost estimates are most sensitive to the parameters of diffusion bonding yield, shims per panels, shims per device and PCM yield, where shims are the patterned plates that the device is formed with.

2.3.2 Environmental assessment of MPT

In addition to cost, environmental considerations have been implemented into microchannel device manufacturing. Munoz and Sheng proposed a general model of determining the environmental impact of machining processes (Munoz and Sheng, 1995). The environmental impact can be calculated by analyzing mass loss and energy loss. Four general aspects of the machining process were studied in order to calculate the environmental impact: material removal mechanics, tool life, scrap production, and cutting fluid flow. Not only would waste material be generated during the machining process, the tool would be disposed after its useful life. Scrap parts and cutting fluid also contribute the mass flow. Energy flow is mainly due to electrical energy use. This is basically determined by the machine characteristics and the cycle time.

The main consideration for PCM is the need to dispose spent etchant, which may result in environmental impacts since the etchants are commonly based on aqueous solutions of ferric chloride (Allen and Jefferies, 2006). Allen and Jefferies proposed an economic and environmentally friendly oxygen hydrochloric acid regeneration system for ferric chloride etchants for PCM (Allen and Jefferies, 2006). With this design, it was reported that the system ran for 18 months without any scale deposits or blocked nozzles. The drawback is the slow regeneration process.

Life cycle assessment (LCA) is the most common method applied in recent work evaluating environmental impacts of microchannel device manufacturing. As defined by

ISO 14040, LCA addresses the environmental impacts throughout a product's life cycle including phases of raw material acquision, production, use, and end-of-life. General LCA is conducted with four steps: defining the study goal and scope, conducting an inventory analysis, conducting an environmental impacts assessment, and interpreting the results (ISO, 2006, p. 200). Eco-indicator 99 and ReCiPe 2008 are common methods used for characterizing and normalizing the environmental impacts for analysis (Goedkoop and Spriensma, 2001; Goedkoop et al., 2009).

Eco-indicator 99 is a method that evaluates the environmental impacts of a product or process in terms of points, where one point represents the impact equivalent to one thousandth of the annual load of a person living in Europe. Three damage types are defined for environmental impacts: human health, where effects of climate change, ozone layer depletion, carcinogenic effects, respiratory effects and ionizing radiation are included; ecosystem quality, where effects of ecotoxicity, acidification, eutrophication and land-use are considered; and resources, where surplus energy needed in the future to extract lower quality mineral and fossil resources are addressed (Goedkoop and Spriensma, 2001).

ReCiPe 2008 is a recently developed and widely applied life cycle impact assessment (LCIA) method reported by Goedkoop et al. (2009). Developed based on the Handbook on LCA (Guinée et al., 2002) and Eco-indicator 99 (Goedkoop and Spriensma, 2001), this method quantifies life cycle environmental impacts for impact categories at the midpoint and endpoint level. At the midpoint level, environmental impacts are calculated in the following eighteen impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionising radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource depletion (MRD), and fossil fuel depletion (FD). At the endpoint level, the midpoint impact categories are further converted and aggregated into three damage types: damage to human health (HH), which is indicated by disability-adjusted loss of life years (DALY); damage to ecosystems diversity (ED), which is indicated by loss of species during a year; and damage to resource availability (RA), which is indicated by increased cost. As with Eco-indicator 99, environmental impacts are represented using a score where one point is defined as the environmental impact equivalent to one thousandth of the annual load of a person living in Europe.

Haapala et al., (2009) conducted a cradle-to-gate environmental analysis of nanoparticle assisted diffusion brazing. Different than cradle-to-grave life cycle assessment, where the whole life cycle of a product of manufacturing process will be analyzed, a cradle-to-gate life cycle assessment only considers the material acquisition and production phases. Life cycle inventory (LCI) analysis of nickel nanoparticle (NINP)-assisted diffusion brazing and nickel phosphorous (NiP) electroplating diffusion brazing were conducted. Environmental impacts of the two bonding processes were assessed with the Eco-indicator 99 method and the results are compared. The results demonstrated that NiNP diffusion brazing has less environmental impacts than NiP diffusion brazing due to the less energy and nickel usage.

A later work by Brown et al. (2011) compared environmental impacts of different microchannel device manufacturing processes and process combinations, which are also called scenarios. By analyzing material and energy inputs of each process and assessing the environmental impact with ReCiPe 2008, they formed a comparison of four manufacturing processes: PCM, laser cutting, NiP diffusion brazing, and diffusion bonding. The result showed PCM, with a ReCiPe points of 167,000, has the highest environmental impact among the four techniques. Laser cutting, with a total score of 158,000 ranks the second. Diffusion brazing and diffusion bonding had comparatively low scores, 58,000 and 4,800, respectively. Correspondingly, the manufacturing scenario with laser cutting as the patterning process and diffusion bonding as the joining process was the most environmental friendly, while PCM with diffusion brazing exhibited the most environmental impacts.

2.4 Need for Combined Economic and Environmental Assessment

Characterized as being innovative and promising, microchannel process technology has been applied to a wide array of academic, government lab and industry research. The products and related manufacturing processes, however, are in doubt in terms of their sustainability performance. Microchannel device manufacturing has been shown to be more expensive and have more significant environmental impacts compared to products using conventional manufacturing methods. Furthermore, among the existing techniques, the most economically beneficial is not necessarily the most environmentally friendly. Thus, a method which can combine economical and environmental assessment would be useful for decision makers who struggle between low cost and less environmental impact.

Some researchers have brought economic and environmental considerations together for microchannel device manufacturing techniques. Most of them either characterize one technique to be economic and environmental friendly or proposed improved methods aimed at reducing the environmental impacts and cost compared to conventional methods, however few of them provided a method integrating the economic and environmental considerations and gave quantitative evidence for comparison between microchannel device manufacturing alternatives. Also, prior environmental assessment of microchannel device manufacturing focused on the analysis of the types of environmental impacts, while evidence of potential improvements is not given. Thus, a manufacturing oriented economic and environmental assessment model for microchannel device manufacturing is needed.

A manufacturing oriented economic and environmental assessment model for microchannel device manufacturing is proposed in this research. The modeling methodology and underlying calculations will be described in the next chapter.

CHAPTER III

AN ECONOMIC AND ENVIRONMENTAL ASSESSMENT MODEL FOR MICROCHANNEL DEVICE MANUFACTURING: PART 1 – METHODOLOGY

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3.1 Abstract

A key application of microchannel process technology (MPT) is its implementation in heat exchanger devices, since a larger surface contact area can be realized than in conventional approaches. Therefore, microchannel devices tremendously increase the efficiency of heat transfer. To justify high volume production of configurations validated as prototypes, however an evaluation of the manufacturing economics and environmental impacts is needed. A spreadsheet-based cost and environmental impact assessment model is thus developed for microchannel devices. The bottom-up process-based cost calculation method is used to estimate device manufacturing costs for a range of production volumes, while process-based cradle-to-gate life cycle assessment is utilized to evaluate environmental impacts. A graphical user interface allows users to manipulate the model by modifying various production and device geometry parameters. This approach provides users a more comprehensive understanding of the composition of manufacturing costs and environmental impacts, thus providing quantitative support for selecting MPT manufacturing strategies and leading to profitable business decisions.

3.2 Introduction

As more innovative ideas and techniques emerge to generate technological solutions to problems in society today, manufacturing industry must similarly develop innovative solutions in order to realize the plethora of resulting design configurations. This has led to many recent advancements in enabling materials, processes, and equipment.

Microchannel process technology (MPT) is one of these innovative advancements that portends transformative solutions in many industries, but requires manufacturing innovation to achieve competitive commercial viability. The advantages of MPT technology are due to the small working distances within microscale channels, which facilitate rapid heat and mass transfer (Mehendale et al., 2000).

Mehendale et al. (2000) reported that small channels utilized in heat transfer and other applications include micro-, meso-, and compact and ultra-compact channels. Microchannels are defined as channels with widths of 1-100 μm. Microchannel heat exchangers were originated by Tuckerman and Pease, (1981) aiming to remove heat from very-large-scale integrated circuits. Since that time, various studies relevant to MPT have been undertaken. Knight et al., (1992) proposed a model to determine the optimal dimension of microchannels so that the minimized thermal resistance can be realized and the highest heat transfer efficiency can be achieved.

Several manufacturing approaches have been explored to facilitate MPT device production, including micro-endmilling (Jeon and Pfefferkorn, 2008), micro-etching (Allen, 2004; Kandlikar and Grande, 2003; Rao and Kunzru, 2007; Roy et al., 2004), electrical discharge machining (EDM) (Ho and Newman, 2003), laser machining (Alavi et al., 1991), diffusion bonding (Tiwari and Paul, 2010), diffusion brazing (Tiwari and Paul, 2010), and nickel nanoparticle assisted diffusion brazing (Tiwari and Paul, 2010). Jasperson et al. (2010) studied some of these techniques, considering their performance and manufacturability for microchannel device production. Some researchers have incorporated economic considerations into manufacturing process development in order to reduce manufacturing cost (Allen and Jefferies, 2006; Lajevardi et al., 2011; Leith et al., 2010; Roy et al., 2004). In recent years, as broader sustainability considerations have gained public interest and entered into manufacturing decisions, the importance of environment impact assessment has come to the fore. Several researchers have investigated the environmental aspects of various manufacturing methods of microchannel devices (Allen and Jefferies, 2006; Anastaselos et al., 2011; Bradley et al., 2006; Brown et al., 2011; Haapala et al., 2009; Liow, 2009; Modica et al., 2011; Munoz and Sheng, 1995).

The cost of microchannel device manufacturing has been modeled and analyzed in prior work (Lajevardi et al., 2011; Leith et al., 2010), however, little detail of the calculations was given. Brown et al. (2011) evaluated the environmental impacts of microchannel devices under four manufacturing scenarios, however only effects of consumables, raw material, water, and electricity were considered, while environmental impacts due to tool depreciation is not considered. Prior work assessing environmental impacts for microchannel device manufacturing has only focused on the impacts analysis. No evidence has been provided to identify the contributors to environmental impacts. Also, the estimates of their environmental impacts are not associated with production volume. Currently, little work has been done providing solutions of estimating both economic and environmental assessment simultaneously. To address these limitations, a combined process-based economic and environmental assessment model is introduced which can provide users a more thorough understanding of the manufacturing costs and environmental impacts of microchannel devices. Detailed calculations estimating the cost and environmental impacts and a description of the graphic user interface are expressed in the next section. In the third section, a case of microchannel devices manufacturing is given to demonstrate the application of the model, followed by conclusions in Section 3.4.

3.3 Assessment Modeling Methodology

The economic and environmental impact assessment model developed in this research is intended to estimate the overall manufacturing costs and environmental impacts of alternative process flows to product MPT 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 algorithms for calculating the costs and environmental impacts are presented below.

3.3.1 Cost model

The process-based cost calculation method is utilized to build the cost model. Process-based cost modeling is a bottom-up cost calculation method, which has been applied in prior work (Lajevardi et al., 2011; Leith et al., 2010). Total cost is broken down into different cost categories, and the cost associated with each category is calculated based on the associated process steps. As illustrated in Figure 3.1, cost categories include tool, facility, labor, maintenance, raw materials, consumables, and utilities costs, which are discussed in greater detail below.

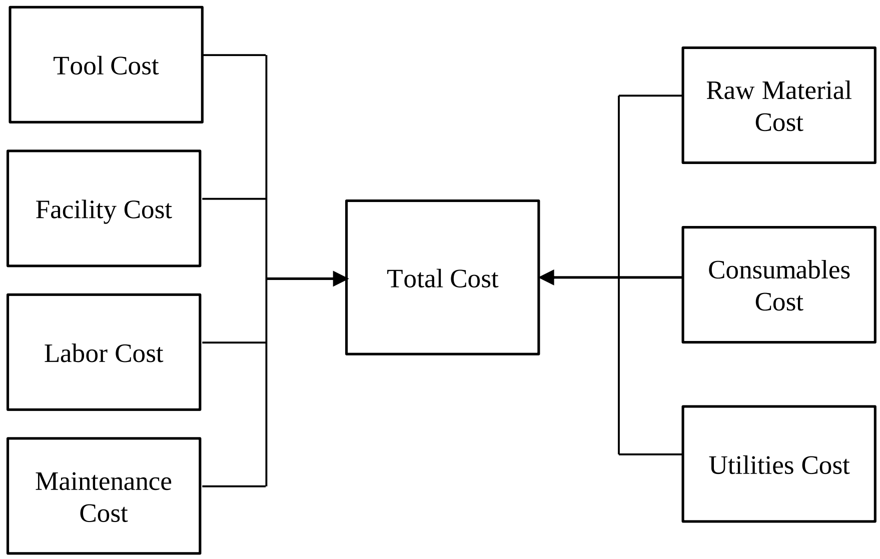

Figure 3.1. Contributors to product manufacturing costs

3.3.1.1 Tool cost

Tool cost includes the capital costs and installation costs of the equipment required to perform the manufacturing operations. Since the total capital tool cost is depreciated over the lifetime of the tool, the cost of one tool (one unit of equipment) is allocated to each of the parts processed by that tool during its operational lifetime. Thus, to calculate cost, assume an annual production volume, P, requires n tools of type j working simultaneously. Let t_j represent the lifetime of tool j in years, then n times the sum of unit tool capital cost, C_{tool}, and unit tool installation cost, $C_{installation}$, gives the tool cost over the n-year period. To allocate the cost to each part processed by the tools over n years, the total cost is divided by the total number of parts processed over n years. This calculation is illustrated in Eq. 3.1, where C_T refers to the tool cost per part.

$$C_T = \frac{(C_{tool} + C_{installation}) * n}{t_j * P} \tag{3.1}$$

To determine the number of tools, n, required for a given production volume, information about the production capacity and tool capacity is needed. To meet the annual production volume, P, with every tool working k hours per year, hourly production capacity of the system is P/k. Tool capacity, the number of parts processed per tool per hour, can then be determined by knowing the cycle time, t_c (number of hours for one part to be processed), step yield, y (fraction of acceptable parts produced), and the tool utilization, u (Eq. 3.2). Since the number of tools is an integer value, the result of the calculation is rounded up to the nearest integer.

$$n = \left\lceil \frac{P / k}{y * (1 / t_c) * u} \right\rceil \tag{3.2}$$

If a process has several steps and each step requires multiple tools, the cost equation can be changed to

$$C_T = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \frac{(C_{tool_{ij}} + C_{installation_{ij}}) * n_{ij}}{t_{ij} * P} \tag{3.3}$$

where i is the number of steps in the process (i = 1, 2, 3, ..., a) and j is the number of tools used in each step (j = 1, 2, 3, …, b_i), where the value of b_i depends on the nature of each step). Note that n_{ij} is calculated based on cumulative yield, Y_{ij}, the probability of success for a series of steps is based on the success of each step and the success of each tool within each step. Let y_{ij} be the yield of current step, and Y_{ij} be the cumulative yield, then,

$$Y_{ij} = \prod_{i=1}^{a} \prod_{j=1}^{b_i} y_{ij} \tag{3.4}$$

3.3.1.2 Facility cost

Facility cost refers to facility construction cost and is allocated to the parts processed during the lifetime of the facility (t_{fac}). The cost of manufacturing space is C_{mfg} per unit area ($/m^2) and the space required for each tool is S_{tool} (m^2). To allocate the facility cost to each part processed over the facility lifetime, the total cost is divided by the number of parts processed over that time period (Eq. 3.5).

$$C_F = \frac{C_{mfg} * S_{tool} * n}{t_{fac} * P} \tag{3.5}$$

The floor space required includes the actual footprint of each tool (S_{tool_act}), as well as space needed for workers to operate around it (S_{tool_work}). Therefore, S_{tool} can be calculated as Eq. 3.6.

$$S_{tool} = S_{tool\_act} + S_{tool\_work} \tag{3.6}$$

If a process has several steps and each step requires multiple tools, Eq. 3.7 can be used,

$$C_F = \sum_{i=i}^{a} \sum_{j=1}^{b_i} \frac{C_{mfg} * S_{tool_{ij}} * n_{ij}}{t_{fac} * P} \tag{3.7}$$

where *i* is the number of steps of a process and *j* is the number of tools used in step *i*.

3.3.1.3 Labor cost

Labor cost (C_L) is calculated for each process based on the annual salary of manufacturing technician(s) working on this tool, C_S, loaded labor rate, R, the number of technicians needed to staff the production tool, n_s, the annual production volume, P, and the number of tools needed to meet the production volume, n. Loaded labor rate accounts for employee hourly rate plus employee fringe benefits. As shown in Eq. 3.8, total labor cost is allocated to each part processed.

$$C_L = \frac{C_S * R * n_s * n}{P} \tag{3.8}$$

If a process has *i* steps and each step requires *j* tools (j = 1, 2, 3,…, b_i) Eq. 3.8 can be modified as follows:

$$C_L = \sum_{i=1}^{a} \sum_{j=1}^{bi} \frac{C_{S_{ij}} * R_{ij} * n_{s_{ij}} * n_{ij}}{P} \tag{3.9}$$

3.3.1.4 Tool maintenance cost

In order to maintain the equipment in operating condition, periodic service is needed. Service includes inspection, problem detection, and failure correction (DOD, 2010). In this model, the maintenance cost is assumed to be a fraction, r_m, of tool capital cost. Per part tool maintenance cost can be calculated as (Eq. 3.10):

$$C_M = \frac{C_{tool} * n * r_m}{P} \tag{3.10}$$

If a process has *i* steps and each step requires *j* tools, Eq. 3.11 would then apply.

$$C_M = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \frac{C_{tool_{ij}} * n_{ij} * r_{m_{ij}}}{P} \tag{3.11}$$

3.3.1.5 Utilities cost

Utilities cost, C_U, includes the cost of water, electricity, and wastewater (Eq. 3.12). Water use cost is determined by the hourly water use per tool, n_W, water unit cost, C_W, and cycle time (hr.), t_c. Similarly, electricity use cost is determined from the hourly electricity use per tool, n_E, electricity unit cost, C_E, and cycle time, t_c. Wastewater charges are determined from the amount of wastewater generated, n_{ww}, cycle time, and wastewater charges per unit, C_{WW}. If there are other utilities used in the process, e.g., natural gas, they can be added to the model accordingly.

$$C_U = (C_W * n_W + C_E * n_E + C_{WW} * n_{WW}) * t_c \tag{3.12}$$

If a process has *i* steps and each step requires *j* tools, Eq. 3.13 can be applied.

$$C_U = \sum_{i=1}^{a} \sum_{j=1}^{b_i} (C_W * n_{W_{ij}} + C_E * n_{E_{ij}} + C_{WW_{ij}} * n_{WW_{ij}}) * t_{c_{ij}} \tag{3.13}$$

3.3.1.6 Consumables cost

The cost of consumables, C_C, is calculated according to the consumables, c, used, their unit price, C_c, and the amount of each consumable used, n_c. This can vary among the different processes and even among steps in one process. Cost of a consumable can be expressed by Eq. 3.14.

$$C_C = C_c * n_c \tag{3.14}$$

If a process has i steps and each step requires j tools with c consumables applied (c = 1, 2, 3,…, d_{ij}), Eq. 3.14 can be modified as follows:

$$C_C = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \sum_{c=1}^{d_{ij}} C_{cij} * n_{cij} \tag{3.15}$$

3.3.1.7 Raw material cost

In this model, raw material cost, C_R, is calculated based on unit price, P_R, and amount used n_R. It is assumed that the unit price is not affected by the amount of raw material use. If i types of raw materials are used (i = 1, 2, 3, ..., a), total raw material cost can be expressed by Eq. 3.16.

$$C_R = \sum_{i=1}^{a} P_{Ri} * n_{Ri} \tag{3.16}$$

3.3.2 Environmental impact model

Life cycle assessment (LCA) is a method to quantitatively analyze the environmental impacts of products and systems (Goedkoop et al., 2009). Generally, there are four steps in LCA, which include defining the study goal and scope, conducting an inventory analysis, conducting an environmental impacts assessment, and interpreting the results (ISO, 2006, p. 200). The purpose of the environmental impact model is to assist users in estimating cradle-to-gate environmental impacts of microchannel devices, where the material acquisition and production phases can be analyzed. The functional unit for comparison is one microchannel device, as also considered in cost modeling. Device geometry and production rate is defined by the user. From the process-based manufacturing information used in the cost analysis, a list of mass and energy input can be obtained, thus forming the life cycle inventory (LCI) for the LCA.

To generate environmental impact assessment values from the LCI data, a commercially available software tool (e.g., SimaPro 7) can be used. The ReCiPe 2008 method can be used to characterize and normalize environmental impacts. ReCiPe is a recently developed life cycle impact assessment (LCIA) method reported by Goedkoop et al. (2009). This method quantifies life cycle environmental impacts and displays the results as environmental impact scores, where one point represents the impact equivalent to one thousandth of the annual load of a person living in Europe. As addressed by Goedkoop et al. (2009), there are three perspectives available when choosing to weight impact assessment results: the hierarchist perspective, the egalitarian perspective, and the individualist perspective. The characteristics and timeframes for each perspective are shown in Table 3.1. In the hierachist perspective, 100 years is chosen as timeframe for consensus consideration. In the egalitarian perspective, the timeframe is assumed to be 500 years for long term consideration. The individualist perspective takes a short term consideration with assumption of a 20 years timeframe.

Table 3.1. Three perspectives for weighting of environmental impacts (Goedkoop et al., 2009)

Perspective	Characteristics	Timeframes
Individualist (I)	Short term	20 years
Hierarchist (H)	Consensus	100 years
Egalitarian (E)	Long term	500 years or more

The environmental impacts of microchannel device manufacturing are quantitatively calculated herein using the ReCiPe 2008 method. It is assumed in this model that the timeframe of a microchannel device is 100 years, therefore, environmental impacts are weighted and aggregated using the hierarchist perspective to generate a single environmental impact score for one unit of material. It is assumed that the unit environmental impact score is not affected by the amount of substance used. Unlike traditional environmental impact analysis, where impacts are shown in environmental impact categories (e.g., damage to human health or resources), this model calculates the overall environmental impact scores with manufacturing related categories considered in cost analysis: tool, facility, utilities, consumables, and raw material, so that environmental impact assessment and cost analysis can be conducted and interpreted simultaneously.

3.3.2.1 Tool environmental impacts

Environmental impacts of one tool (one unit of equipment) are allocated to each of the parts processed by that tool during its operational lifetime. To meet an annual production volume, P, requires n tools of type j working simultaneously. The value of n can be calculated using Eq. 3.2. Assume tool j is made of h types of material (h = 1, 2, 3..., e_j) with a mass of m_{jh} and a unit impact score of I_{jh} (Pts/kg), and let t_j represent the lifetime of the tool j in years. The environmental impact score of tool j allocated to one device at a given production volume can be calculated as shown in Eq. 3.17.

$$I_{T_j} = \frac{\sum_{h=1}^{e_j} m_{jh} * I_{jh} * n}{t_j * P} \tag{3.17}$$

If a process has i steps and each step requires j tools, Eq. 3.17 can be changed to

$$I_T = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \frac{\sum_{h=1}^{e_{ij}} m_{ijh} * I_{ijh} * n_{ij}}{t_{ij} * P} \tag{3.18}$$

3.3.2.2 Facility environmental impacts

Facility environmental impacts refer to environmental impacts caused by facility construction and are allocated to the parts processed during the lifetime of the facility (t_{fac}). The environmental impact score of manufacturing space is I_{mfg} per unit area (Pts/m^2) and the space required for each tool is S_{tool} (m^2). The value of S_{tool} can be calculated using Eq. 3.6. To allocate the facility environmental impacts to each part processed over the facility lifetime, the total impact score is divided by the number of parts processed over that time period (Eq. 3.19).

$$I_F = \frac{I_{mfg} * S_{tool} * n}{t_{fac} * P} \qquad (3.19)$$

If a process has *i* steps and each step requires *j* tools, Eq. 3.20 can be used,

$$I_F = \sum_{i=i}^{a} \sum_{j=1}^{b_j} \frac{I_{mfg} * S_{tool_{ij}} * n_{ij}}{t_{fac} * P} \qquad (3.20)$$

3.3.2.3 Utilities environmental impacts

Utilities environmental impacts, I_U, include the impacts of water, and electricity (Eq. 3.21). Water impact score is determined by the hourly water use per tool, n_W, water unit impact score, I_W, and cycle time, t_c. Similarly, electricity environmental impacts is determined from the hourly electricity use per tool, n_E, electricity unit impact score, I_E, and cycle time, t_c. If there are other utilities used in the process, e.g., natural gas, they can be added to the model accordingly.

$$I_U = (I_W * n_W + I_E * n_E + I_{WW} * n_{WW}) * t_c \tag{3.21}$$

If a process has *i* steps and each step requires *j* tools, Eq. 3.22 can be applied.

$$I_U = \sum_{i=1}^{a} \sum_{j=1}^{b_j} (I_W * n_{W_{ij}} + I_E * n_{E_{ij}} + I_{WW} * n_{WW_{ij}}) * t_{c_{ij}} \tag{3.22}$$

3.3.2.4 Consumables environmental impacts

The environmental impacts of consumables are calculated according to the consumables used, c, their unit impact score, I_c, and the amount of each consumable used, n_c. This can vary among the different processes and even among steps in one process. The environmental impacts for a consumable can be expressed by Eq. 3.23.

$$I_C = I_c * n_c \tag{3.23}$$

If a process has *i* steps and each step requires *j* tools with *c* consumables applied (c = 1, 2, 3,…, d_{ij}), Eq. 3.24 can be modified as follows:

$$I_C = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \sum_{c=1}^{d_{ij}} I_{cij} * n_{cij} \tag{3.24}$$

3.3.2.5 Raw material environmental impacts

In this model, the raw material environmental impact score, I_R, is calculated based on unit impact score, I_r, and amount used n_R. If *i* types of raw materials are used (i = 1, 2, 3, ..., a), total raw material environmental impacts can be expressed by Eq. 3.25.

$$I_R = \sum_{i=1}^{a} I_{ri} * n_{Ri} \tag{3.25}$$

3.3.3 Modeling interface

The spreadsheet-based model is realized using MS Excel, which contains three sets 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 Inputs sheet, where environmental impact parameters are stored. Calculation worksheets include the Process Calculation sheet, where all the cost calculations are contained; and an EI Calculation sheet where all environmental impact calculations are performed. Results worksheets include the Process Results sheet and the EI Results sheet, where the cost and environmental impact results are reported, respectively, in tabular and graphical form.

A graphical user interface (GUI) was designed and implemented using MS Visual Basic for Applications (VBA) to facilitate data entry to the model. The GUI is composed of a user form with three tabs: a Production Parameters tab, where the user can input expected minimum and maximum annual production volumes; a Shim Geometry tab, where the user can input information about the shim design; and the Device Geometry tab, where overall device design parameters can be input. Shim Geometry tab is shown in Figure 3.2, the other two tabs are shown in Appendix A. The user can calculate the results for default settings by clicking the Default button, and the previous analysis can be recalled by hitting on the Last Record button. Cost and environmental impact results are calculated automatically when the Calculate button is clicked, while a PDF report is generated if the Save Results as PDF checkbox is checked.

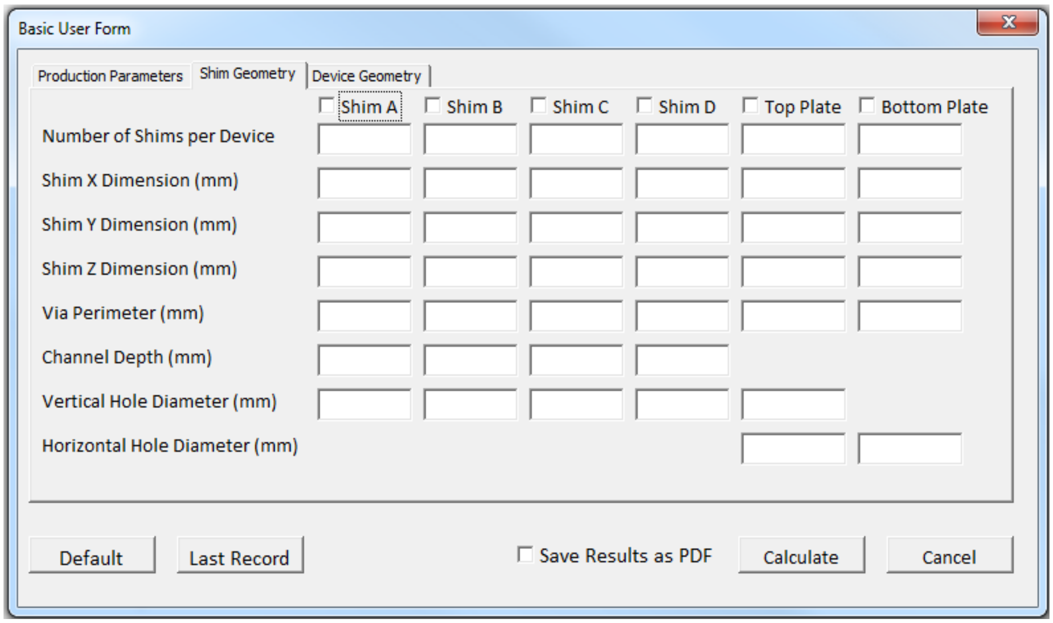

Figure 3.2. Spreadsheet model graphical user interface

By inputting the range of annual production rates for evaluation, the model will then 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 production volumes are shown for each of the seven cost categories, as well as according to the cost per process step. Environmental impact results are shown for the same impact categories as cost analysis. To assist a process analysis, cost and environmental impacts of each process are shown by the seven categories as well.

3.4 Application of the Modeling Methodology

The manufacturing of a microchannel device, a heat recovery unit (HRU), is chosen to illustrate the cost and environmental impact assessment modeling methodology (Figure 3.3). Diesel engines are used to provide energy to many activities in deployment situations, which generate a large amount of waste heat, resulting in a significant loss of energy. An HRU can be used to capture energy from the hot exhaust gases, which can then be used to provide energy to other applications. By using microchannels in a cross-flow configuration, the efficiency of heat transfer is increased in a much smaller package than conventional heat exchange devices. In the HRU, which captures the exhaust energy by heating oil, stainless steel laminae, or shims, are produced, layered alternately, and then bonded to form a monolithic device. This process is termed microlamination (Paul and Peterson, 1999). The device consists of two shim configurations – one guides the exhaust air flow and the other the oil flow. The HRU is a composed of 46 air shims (210mm x 140mm x 0.9906mm) and 45 oil shims (210mm x 140mm x 0.3048mm). The channel depths are 0.8mm and 0.15mm, respectively, for the air shims and oil shims. Two holes are designed on each shim with a diameter of 11.68mm. After being bonded into a monolithic device, the holes form a channel to guide the oil flow. Additional microchannels are designed on oil shims so that rapid heat exchange can be realized. The HRU design utilizes top and bottom end plates (210mm x 140mm x 12.7mm), which each contain four 6.35mm diameter holes for interconnecting the device with the vehicle exhaust system.

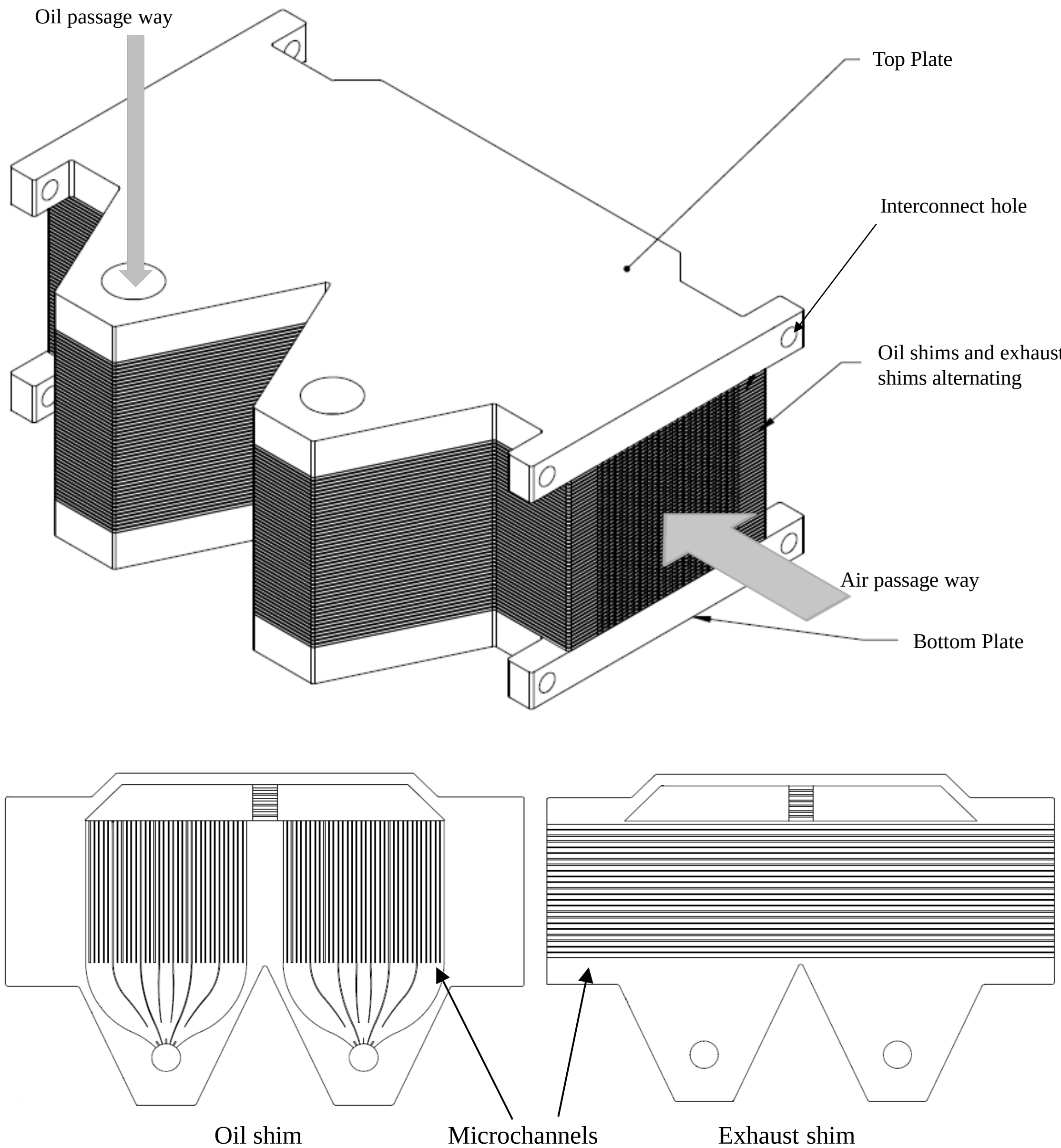

Figure 3.3. Design of heat recovery unit (HRU)

To produce the device, photochemical machining (PCM) can be used to etch the microchannels and holes into the shims. PCM starts with an alkaline and acid clean process in order to achieve a clean surface condition for etching. The panels will be heated to lamination process temperature. Photoresist dry films and photomasks will be laminated to the cleaned substrate and expose to ultraviolet light to harden selected area. Chemical will be sprayed to wash away the unexposed area and develop the pattern. Then, chemical solution will be sprayed to the sheet to etch pattern in metal panel. Next, the remaining photoresist will be stripped, followed by a visual defect inspection to check the quality of the product. Finally, the metal etchant waste treatment and reclaim will be done. The model assumed that the whole surface of the stainless steel panel needs to be cleaned. Alkaline and acid chemical usage is assumed to be 0.11 L/m^2. Panel etch rate is assumed to be 0.1 mm/min.

Diffusion bonding can be used to bond the shims and end plates together. An alkaline and acid clean is needed at the beginning of the process for degreasing and particulate removal. Afterwards, the cleaned panels are stacked and aligned in a fixture and bonded. During the bonding process, panel stacks will be heated to a bonding temperature of 980 ℃. The total bonding time is 42.7 hours, with a heating rate of 5 ℃/min, a cooling rate of 0.23 ℃/min, a holding time of 120 minutes, and a furnace load time of 30 minutes.

Due to the differentiation in size of raw material and actual designed device, a singulation process is needed to cut the bonded panel stacks and endplates to the final dimensions of the HRU. Water jet cutting can be used to singulate the device into its final geometry. The linear cutting rate of water jet cutting is assumed to be 50 cm/min per millimeter of laminate thickness. Computer numerical control (CNC) machining with a quarter inch cutting tool can be used to drill the interconnect holes into the endplates, and electrical discharging machining (EDM) can be used to finish the mating surfaces. The linear cutting rate for EDM is assumed to be 30 cm/min per millimeter laminate thickness. The general manufacturing process flow of the HRU is illustrated in Figure 3.4.

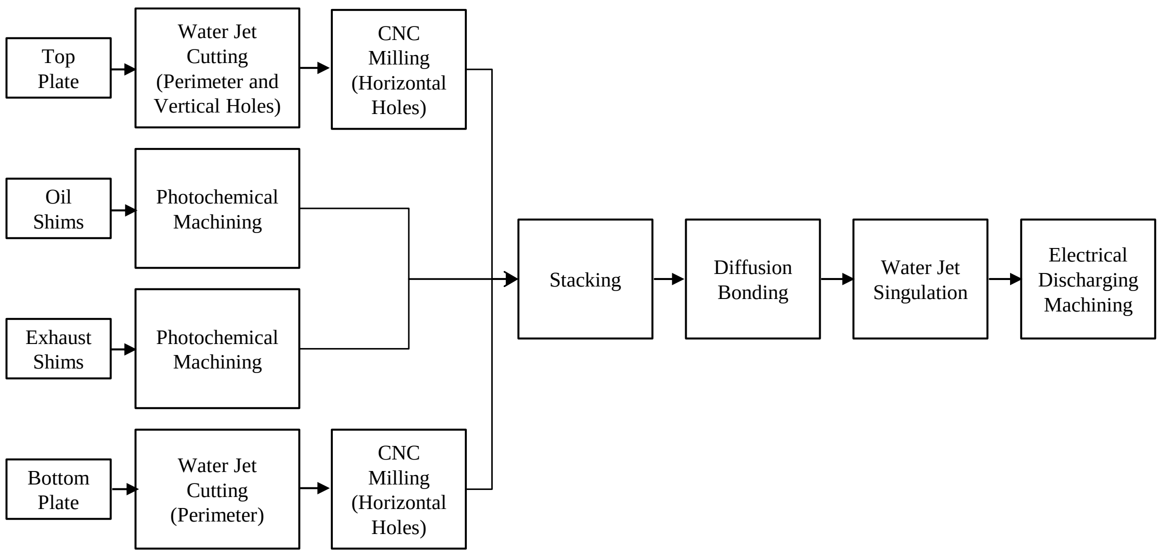

Figure 3.4. General heat recovery unit (HRU) manufacturing process flow

To perform modeling, a piece of equipment (tool) is selected for each process step. Tool installation cost is assumed as 4-5% of tool capital cost, yield for each process step is assumed to be 95-100%, tool utilization is assumed to be 90-95%, maintenance cost is assumed to be 3-5% of tool capital cost, and tools are assumed to be depreciated over seven years. For each tool, the facility space needed is assumed to be twice the actual footprint of the tool. Tools are assumed to operate 24 hours per day for 360 days per year. The facility depreciation period is assumed to be 25 years. Labor cost is assumed to be $40,000 per year, based on the average salary rate of a Manufacturing Technician II in Portland, OR for 2013 (Salary.com, 2013).

Table 3.2. Material and energy inputs for each process

Process Name	Category Name	Material/Energy Type	SimaPro Process Name
	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
	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
		40% Ferric chloride	Iron (III) chloride, 40% in H_2O
		45% Sodium chlorate	Sodium chlorate, powder

Table 3.2. Material and energy inputs for each process (continued)

Process Name	**Category Name**	**Material/Energy Type**	**SimaPro Process Name**
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
	Consumables	25% Sodium Hydroxide	Sodium hydroxide (concentrated) E
		15% Hydrochloric acid	Hydrochloric acid, 30% in H_2O
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
	Consumables	Garnet abrasive	Abrasive products
		Nozzle	N/A
		Pump internals	N/A

Table 3.2. Inventory of mass and energy inputs (continued)

Process Name	**Category Name**	**Material/Energy Type**	**SimaPro Process Name**
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
	Consumables	Filter	N/A
		Brass wire	Brass
CNC	Tool	Iron and steel	Iron and steel, production mix
	Facility	Building	Building, Hall/CH/I
	Utilities	Water	Water, deionised
		Electricity	Electricity, medium voltage, production UCTE
	Consumables	Carbide cutting tool	Ferrochromium, high-carbon, 68% Cr

All process parameters, such as cycle time and tool capital costs are determined based on information from equipment vendors. Due to the lack of information about tool material composition, it is assumed that tools are made of iron and steel for the inventory analysis of environmental impacts modeling. For tools without available mass information, a density of 150 kg/m^2 of footprint is assumed. Although there are uncertainties regarding expendable tool components, such as the filter for the EDM tool, and the nozzle and pump internals of the water jet cutter, these parts are neglected in the environmental impact model. An inventory of material and energy inputs is given in Table 3.2. Utility assumptions, including water price of $0.004/gal ($0.001/L) (Portland Water Bureau, 2013), wastewater and sewer charge of $0.015/gal ($0.004/L) (Environmental Service, 2013), and electricity cost of $0.035/kWh (Portland General Electric, 2013) are obtained based on the average rates for industrial users in Portland, OR in 2013.

3.4.1 Cost modeling for the HRU

For this illustrative example, the minimum and maximum annual production volumes are chosen to be 1,000 and 500,000 HRUs, respectively, giving the nine production scenarios of 1,000, 2,000, 5,000, 10,000, 20,000, 50,000, 100,000, 200,000, and 500,000 units. The manufacturing cost per unit for each production volume is shown in Figure 3.5. For an annual production of 1,000 HRUs, the cost of each device is estimated as $1,521.88. As the production volume increases from 1,000 to 20,000 units, the cost of each device decreases tremendously (52.12%), from $1,521.88 to $728.65 (Fig. 3.5a). As the production volume increases from 20,000 to 500,000, manufacturing cost of each device continues to decrease, but is comparatively constant ($728.65 to $700.61). As the production volume increases, tool cost, facility cost, utilities costs, maintenance cost, and labor cost decrease significantly, while raw material cost and consumables costs remain constant per unit produced. The model assumes the raw materials and consumables unit costs are not dependent upon production volume. Figure 3.5b illustrates the cost breakdown by process type and raw materials. It can be seen that the cost for each process decreases with increasing production rate, while raw material costs are again constant. Costs for interconnect and singulation processes have the most significant impact, while costs for patterning have less variability. Figure 3.6 illustrates this more clearly, where the cost for each process is broken down into the selected cost categories for a production volume of 20,000 HRUs per year, at which point costs starts to become constant.

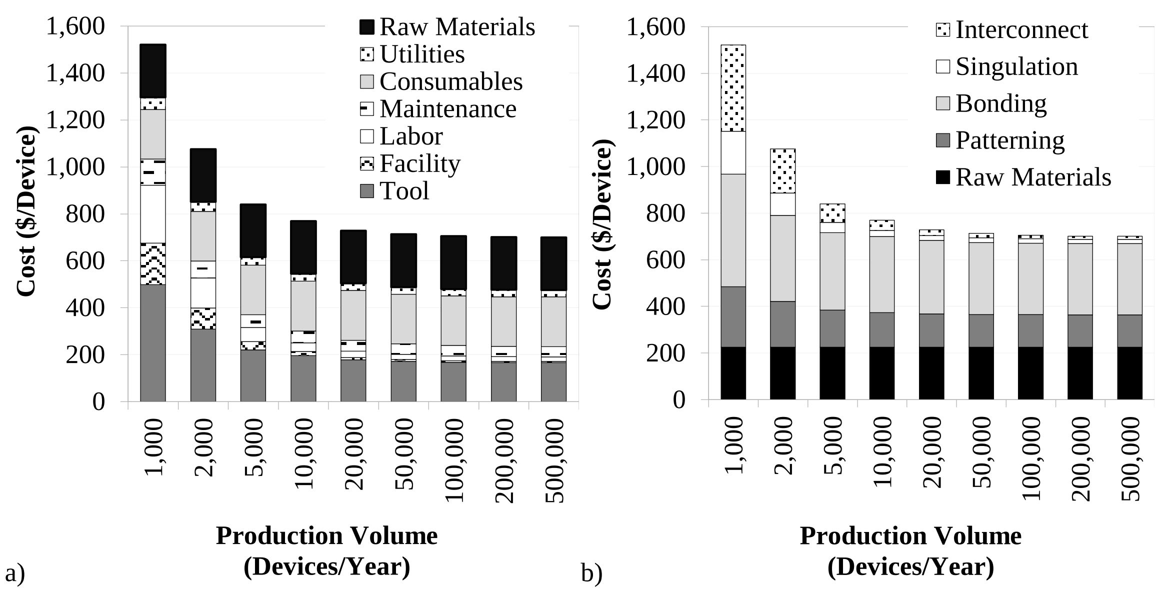

Figure 3.5. Cost breakdown by a) Cost category and b) Process type and raw material

As shown in the figure, the major contributor to patterning process costs is consumables, and the amount of consumables per device is not dependent on production volume.

Therefore, changes in the total cost of the patterning process only reflect changes in other cost categories, which are comparatively minor, resulting in the relative insensitivity of patterning cost. For the bonding process, which is done with diffusion bonding, majority of the cost is tool. This is not only because of the high capital cost of diffusion bonding tool, but also because of the large number of tools needed to meet the demand due to the long bonding time. For the singulation process, which is done using water jet cutting, the majority of cost is consumables, while for interconnect process, which is done with EDM, the majority of the cost is related to the tool. As production volume increases, the costs associated with each tool are allocated across a larger number of devices, the cost of each device decreases.

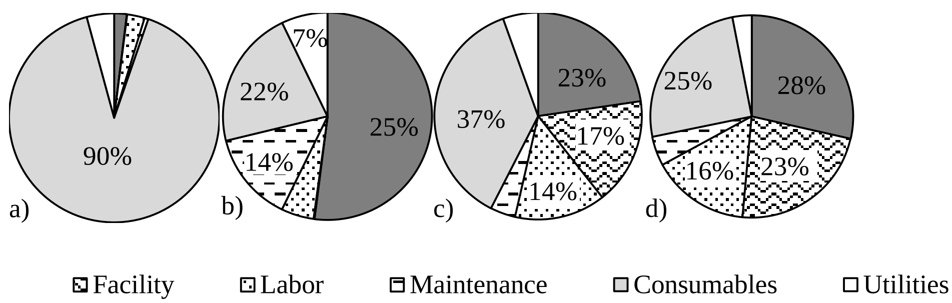

Figure 3.6. Cost categories for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes

3.4.2 Environmental impact modeling for HRU

The environmental impact assessment is next performed for the nine production volume scenarios. Similar to cost, environmental impacts per unit show a decreasing trend from low production volume to high production volume, from 297.10 Pts at 1,000 HRUs per year to 295.16 Pts at 500,000 HRUs per year. This reduction (0.85%) is relatively minor, however, due to the uncertainties in the analysis. Environmental impact results for a production rate of 500,000 HRUs per year are shown in Figure 3.7, which illustrates the environmental impact score breakdown by impact category of key importance, utilities contribute 87.82% of the impacts. Raw material and consumables, with impact scores of 19.20 Pts and 16.58 Pts, rank second and third, respectively. Cycle time is the variable that affect the environmental impacts of utilities, and is little sensitive to the change in production volume. The model also assumes the environmental impact scores of raw materials and consumables are not dependent upon production volume. Therefore, environmental impact scores of utilities, raw material and consumables are constant at all production rates. Thus, changes in the total environmental impacts only reflect changes in other impacts categories, namely tools and the facility. Since tools and the facility account for less than 1% of the total score, the environmental impacts per device are insensitivity to the changes in production volume. Figure 3.7b exhibits the environmental impact score breakdown by process type. It can be seen that bonding process, which is done with diffusion bonding, accounts for 85.22% of the total process impacts. This is because of the nature of diffusion bonding the laminated metal plates to be heated to a high temperature for a long bonding time which requires a huge amount of water and electricity. The patterning process and raw materials, with impact scores of 19.58 Pts and 19.20 Pts, account for 6.63% and 6.51% of impact, respectively. Figure 3.8 illustrates this more clearly, where the environmental impact score for each process is broken down according to the different category types.

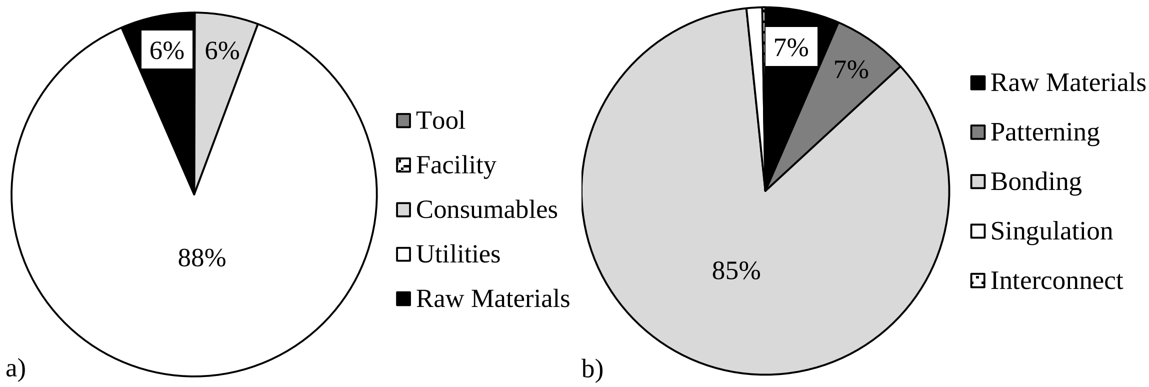

Figure 3.7. Environmental impact score breakdown by a) Impact category and by b) Process type and raw material at production rate of 500,000 HRUs per year

As shown in the figure, the major contributor to patterning process environmental impacts is consumables, while the impact of utilities is also significant. This is due to the large amount of consumables used in this process. For the bonding process, utilities account for 99.39% of the total impacts. For singulation and interconnect process, utilities are again the major contributor, while consumables is also a significant driver for both processes.

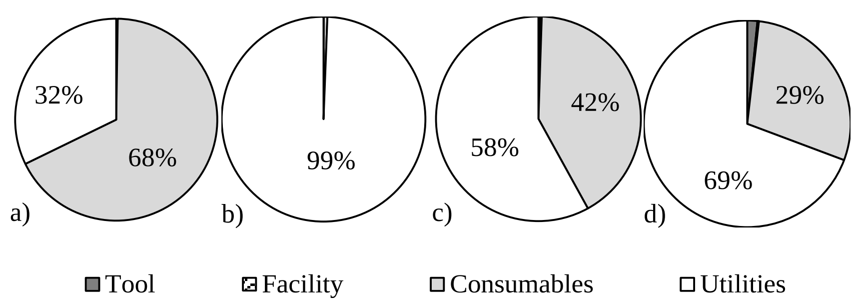

Figure 3.8. Environmental impact categories for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes

By considering the results of cost and environmental impact modeling, it can be seen that diffusion bonding is both the top cost driver and the top environmental impact driver. Among the cost and environmental impact categories, utilities contribute to half of the cost and most of environmental impacts, which indicate that to achieve a more economically and environmentally friendly bonding processes, shorter bonding time and less amount of energy consumption needs to be realized. At an annual production volume of 1,000 units, the interconnect process is the next most significant cost driver, and accounts for 24.38% of the total cost, however, its environmental impact is low. PCM ranks as the third cost driver and second environmental impact driver at this production volume, with 17.05% of cost and 6.96% of environmental score. Among the cost and environmental impact categories, consumables are the main contributor for both cost and environmental impacts, which indicate a more economically and environmentally friendly patterning process may require changes in consumables. The next most significant cost and environmental impact driver is raw material, which accounts for 14.78% of the cost and 6.46% of the environmental impacts. This indicates seeking for a less expensive and environmentally impactful raw material will also reduce the cost and environmental impacts. As the production rate increases, the cost of PCM and EDM per unit decreases. Thus, for production volumes of 2,000 or larger, raw materials become the second highest cost driver, while environmental impact is not as sensitive to production volume. The overall results show that to achieve lower cost and less environmentally impactful HRU production, changes are needed in bonding the device.

3.5 Conclusions

In order to provide users a more thorough understanding of the manufacturing costs and environmental impacts of microchannel devices, a combined process-based economic and environmental assessment model was developed in this research. By illustrating cost and environmental impacts of microchannel device manufacturing at different production volumes and analyzing the results by process type, cost and manufacturing impact category, evidence can be given for identifying potential improvements towards a lower cost and more environmental friendly manufacturing system using this approach. A graphical user interface (GUI) was designed and implemented in MS Visual Basic for Applications (VBA) to facilitate cause-effect analysis with the model. The methodology for modeling the cost and environmental impacts was described, followed by analysis of a microchannel heat recovery unit (HRU) as a case to illustrating how to use the model. It was shown that cost and environmental impacts decrease with an increase in production volume. Also, the diffusion bonding process used for microchannel device manufacturing as found to be the most costly and the most environmentally impactful manufacturing process. To improve the manufacturing process from the cost and environmental perspectives, a bonding process with shorter cycle time and less water and electricity consumption is needed.

This work presents a unique combined process-level cost and environmental impact assessment model for microchannel device manufacturing. Unlike conventional environmental impact analysis, impacts scale with production volume and are associated with manufacturing processes and impact categories related to manufacturing: tools, facility, utilities, consumables, and raw materials. Thus, this manufacturing-oriented economic and environmental assessment model for microchannel device manufacturing can benefit manufacturing decision makers by providing quantitative evidence for potential sustainable process and product design improvements. This will benefit the future development of sustainable microchannel device manufacturing industry.

The model proposed in this paper establishes a framework for assessment of economic and environmental impacts of microchannel device manufacturing, however, limitations of this work remain. Firstly, for economic assessment model, factors like interests, tax, profit and management are not considered. Also, cost of raw materials and consumables are assumed to be not dependent upon production volume. Although labor and maintenance are considered as cost categories, they are not completely addressed in environmental impact assessment model. Since there is not any standard method to estimate the environmental impacts of labor, labor is not considered for environmental impact assessment. Tool replacement parts are calculated in consumables due to their relatively shorter lifetime compared to the tool itself. Environmental impact of other maintenance, like service, is not considered. For case study, due to the lack of tool information, material of each tool is assumed as iron and steel. Thus, for tools with unknown weight, weights are calculated based on footprint and a density assumption of 150 kg/m^2. For future work, a cost model able to incorporate considerations like interests, tax, profit and management is needed, labor and maintenance needs to be addressed for environmental impact analysis, and more detailed tool information is needed to achieve more accurate results. Study of utilizing the model to assess different manufacturing scenarios of microchannel device is needed for validating the model's capability of choosing between manufacturing alternatives.

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CHAPTER IV

AN ECONOMIC AND ENVIRONMENTAL ASSESSMENT MODEL FOR MICROCHANNEL DEVICE MANUFACTURING: PART 2 – APPLICATION

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4.1 Abstract

A key application of microchannel devices is use as heat exchangers. By utilizing microchannel process technology (MPT), a larger surface contact area can be realized. Therefore, microchannel devices tremendously increase the efficiency of heat transfer rate. Before bringing prototypes into mass production, however, an evaluation of the manufacturing costs and environmental impacts are needed due to the associated high cost and environmental impacts. This paper describes a process-based cost and environmental impact assessment model for microchannel devices. The bottom-up process-based cost modeling method is then used to estimate the cost of manufacturing a microchannel device. Cradle-to-gate life cycle assessment is simultaneously applied to evaluate environmental impacts. A graphical user interface allows users to manipulate the model by inputting the production and device geometry parameters. This approach can provide manufacturing decision makers a comprehensive understanding of the composition of the manufacturing costs and environmental impacts, thus giving quantitative evidence while selecting product design parameters and manufacturing processes. The model is demonstrated for a microchannel heat recovery unit (HRU). It is found that cost and environmental impacts decreased as the annual production volume increased. Among the six selected manufacturing scenarios, *Scenario 5* (laser cutting and diffusion brazing) has the lowest cost but the highest environmental impacts. *Scenario 3* (Photochemical machining and laser welding) has the lowest environmental impact but is with comparatively significant cost. Among the defined cost categories, consumables and

tool, and utilities are primary drivers to cost and environmental impacts for the manufacturing processes.

4.2 Introduction

Microchannel devices have been utilized as heat exchangers in order to achieve high heat transfer rate. Compared to conventional heat exchangers, microchannels facilitate heat transfer by enlarging the area of the surface where heat is being transferred (Mehendale et al., 2000). Mehendale et al. (2000) concluded that small channels utilized in heat transfer and other applications include micro-, meso-, and compact and ultra-compact channels. Microchannels are defined as channels with widths of 1-100 μm.

The primary processes in microchannel device manufacturing include patterning and bonding (Leith et al., 2010). Microchannels are first patterned on metal sheets, and then the patterned sheets are stacked and bonded into a monolithic device. Several techniques have been explored to facilitate microchannel device manufacturing. These techniques include micro-end-milling (Jeon and Pfefferkorn, 2008), micro-etching (Allen, 2004; Kandlikar and Grande, 2003; Rao and Kunzru, 2007; Roy et al., 2004), electrical discharging machining (EDM) (Ho and Newman, 2003), and laser machining (Alavi et al., 1991) as patterning process, diffusion bonding (Tiwari and Paul, 2010), diffusion brazing (Tiwari and Paul, 2010), and nickel nanoparticle assisted diffusion brazing (Tiwari and Paul, 2010) as bonding processes. Jasperson et al. (2010) evaluated the performance and manufacturability of several patterning techniques. They concluded that approaches like micro-casting, micro-extrusion, micro-slot, and micro-sintering can be utilized for patterning microchannels and are appropriate for mass production, however, they are not capable for achieving high precision. 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 show processing rate (Jasperson et al., 2010).

Some researchers have incorporated economic considerations when evaluating the microchannel manufacturing processes and investigated approaches to drive manufacturing towards a lower cost. 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 process-based cost model. Cost was analyzed by manufacturing processes and by cost categories. Based on their work, Lajevardi et al., (2011) further analyzed microchannel device manufacturing and performed a sensitivity analysis and Monte Carlo simulation on the model parameters. Although comprehensive cost analysis has been done by (Lajevardi et al., 2011; Leith et al., 2010), insufficient detail was provided about the calculations of the cost estimation.

Some researchers have studied microchannel device manufacturing from the environmental perspective and tried to develop environmental friendly solutions for manufacturing. Liow took sustainability considerations into account for micromachining by comparing the energy consumption of conventional CNC milling and micro-milling facility (Liow, 2009). As a conclusion, micro-milling facility has a lower energy requirement. Due to the simplicity of the design of micro device explored, it is possible that the energy consumption of micro device manufacturing will increase as the complexity of the design increases. An environmental analysis conducted by Haapala et al. (2009) compared the environmental impacts of nickel phosphorus (NiP) electroplated diffusion brazing and nickel nanoparticle (NiNP) assisted diffusion brazing. They found that NiNP assisted diffusion brazing may be a more environmental friendly bonding process. Follow on work conducted by Brown et al., (2011) assessing environmental impacts of the manufacturing process flow for a microchannel device 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. For bonding, diffusion brazing was found to have higher environmental impacts than diffusion bonding. Thus, the combination of laser cutting and diffusion bonding outperformed other manufacturing scenarios explored. Brown et al., (2011) established a framework of the environmental assessment of microchannel device manufacturing, however, only consumables and raw materials were considered as mass inputs, tool replacement, and facility use was neglected. Also, their analysis focused on the type of environmental impacts and environmental impacts associated with each step, whereas the sources of the drivers of environmental impacts were not given.

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. Researchers have proposed economically viable and environmentally friendly techniques for microchannel device manufacturing (Allen and Jefferies, 2006), however, integrated economic and environmental understanding of the whole manufacturing process is still insufficient. In order to address the above limitations, a combined process-based economic and environmental assessment model has been developed (Gao et al., NDa). This model can provide users a more thorough understanding of microchannel device manufacturing by estimating the costs and environmental impacts of the processes under different manufacturing scenarios over a range of production volumes. Also, this manufacturing-oriented model can demonstrate the cost and environmental impact results for manufacturing related categories and process types, thus giving quantitative evidence for choosing between manufacturing alternatives and potential process improvements.

4.3 Research Method

The process-based economic and environmental impact assessment model is intended to estimate the overall costs and environmental impacts of alternative 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.

4.3.1 Cost model

The bottom-up process-based cost calculating method, which has been applied in prior studies (Lajevardi et al., 2011; Leith et al., 2010), is utilized in the cost model. Cost of microchannel device manufacturing is divided into seven cost categories: tool cost, facility cost, labor cost, maintenance cost, raw materials cost, consumables cost, and utilities cost. The cost of each category is determined by each manufacturing process and associated process steps. By summing up the cost of each category associated with each process step, total manufacturing cost can be estimated. In this model, cost relevant to factors like sales, interest, taxes, administrative activities, and profit are not considered in this model. Also, 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 Figure 4.1.

4.3.2 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 a products (or systems) (Goedkoop et al., 2009). To conduct an LCA, four steps are included in the study: defining the study goal and scope, conducting an inventory analysis, conducting an environmental impacts assessment, and interpreting the results (ISO, 2006). The scope of environmental assessment in this model is cradle-to-gate. The functional unit being

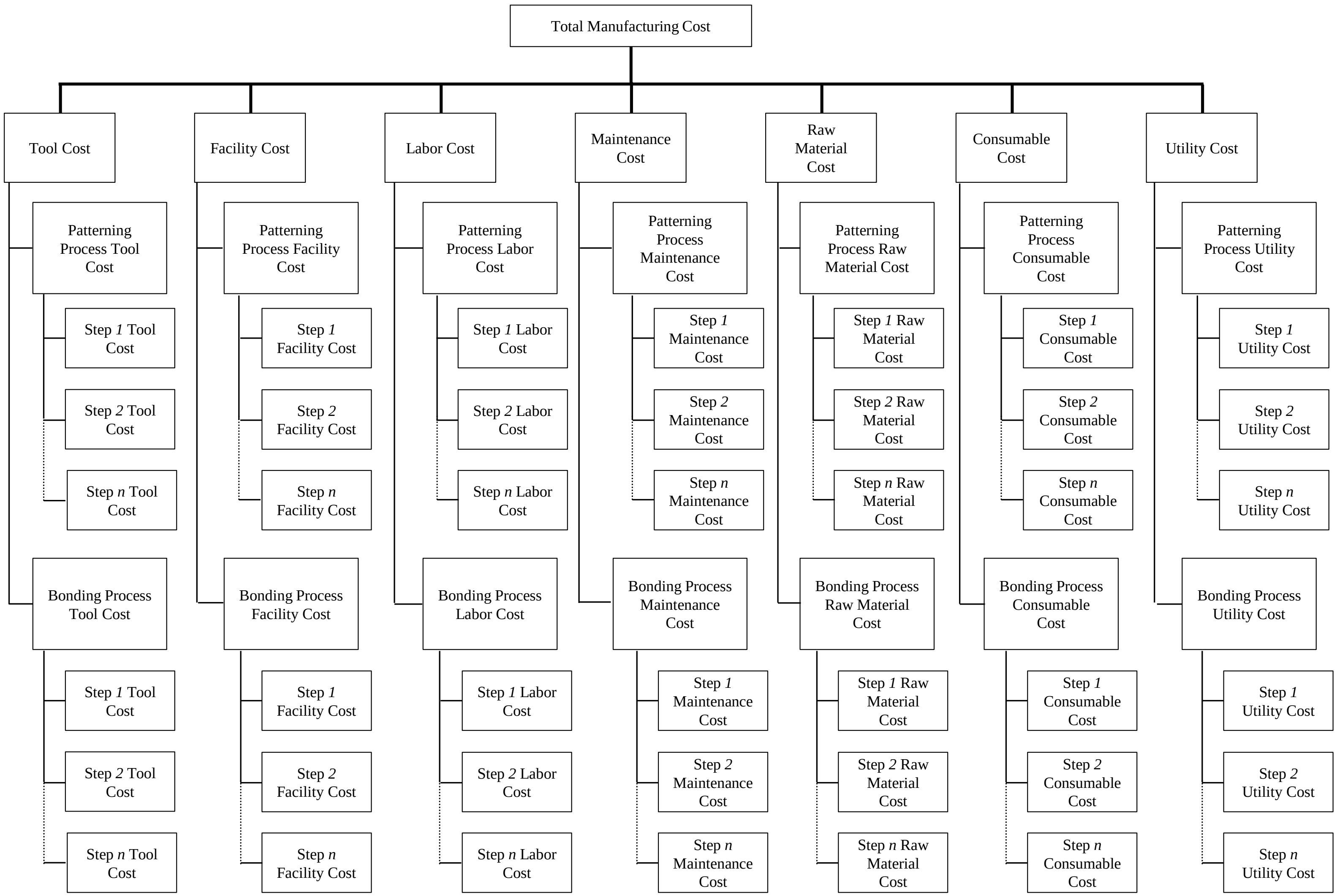


Figure 4.1. Bottom-up cost flow for microchannel device manufacturing

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. The environmental impacts are then divided into five impact 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 scores (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, 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. The hierachist archetype is chosen to weight the impacts, which assumes the timeframe of the product to be 100 years. The total manufacturing environmental impact score can be obtained by summing up the environmental impact score of each category. Environmental impact score flow is exhibited in Figure 4.2.

4.3.3 Modeling interface

The model is 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 Inputs sheet, where environmental impact parameters are stored. Calculation worksheets include the Process Calculation sheet, where all the cost calculations are performed; and an EI Calculation sheet where all 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 design, and input overall device design parameters. The user can calculate the results for default settings or recall the previous analysis. Cost and environmental impact results are calculated automatically and can be viewed in the results worksheet or in a PDF file.

By inputting the range of annual production rates for evaluation, the model will then 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, as well as for each process step. Environmental impact results are shown for five of the seven cost categories. To assist process analysis, costs and environmental impacts of each process are reported for each category.

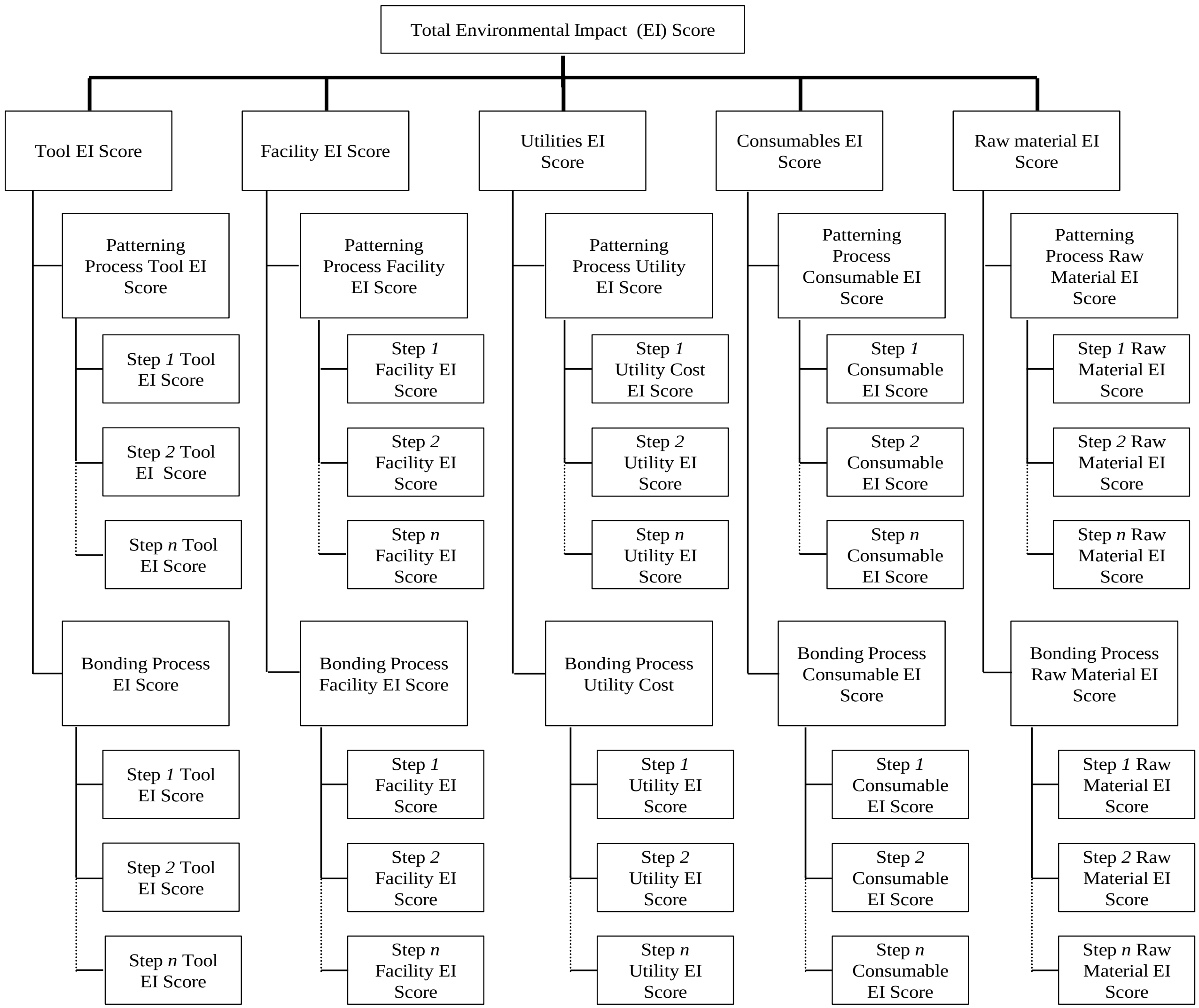


Figure 4.2. Process-based environmental impact score breakdown for microchannel device manufacturing

4.4 Application of the Method

The manufacturing of a microchannel heat exchanger called heat recovery unit (HRU) is chosen to demonstrate the application of the integrated cost and environmental impact assessment method.

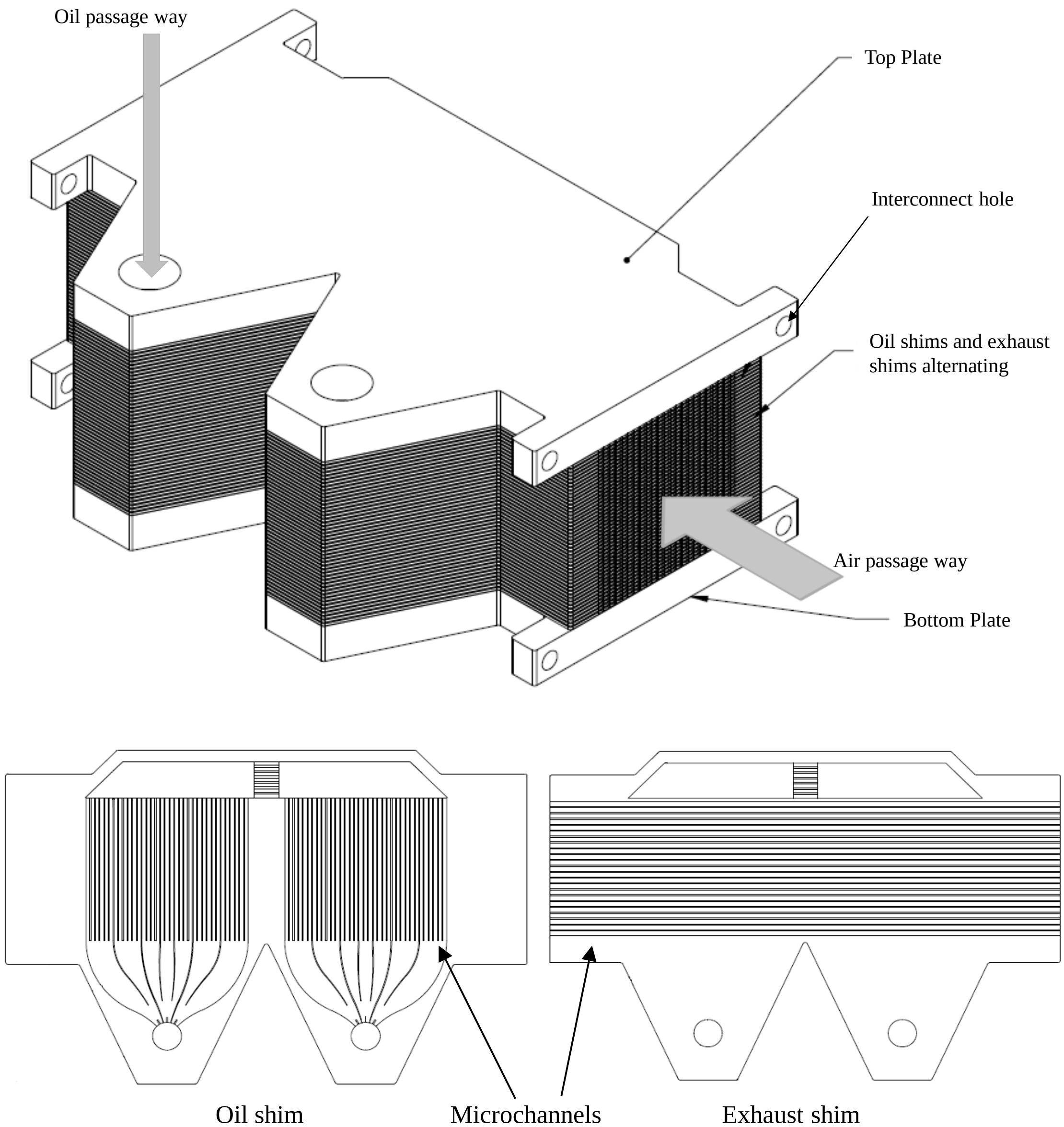


Figure 4.3. Design of heat recovery unit (HRU)

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. 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, which represents the cold fluid in the heat exchanger. The design of the device was reported by Gao et al. (NDa) and shown in Figure 4.3.

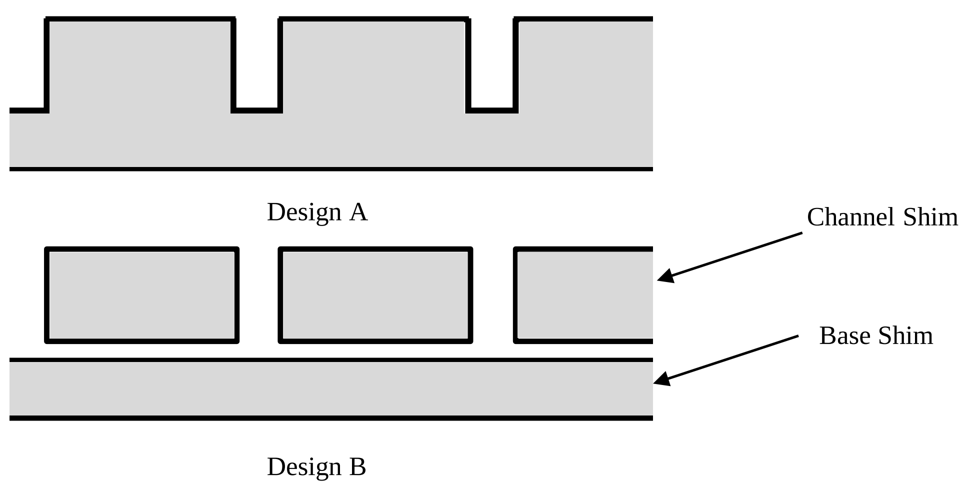


Figure 4.4. Two designs to make the channel geometry for exhaust air shim

There are two fundamental ways to fabricate the two shim designs. First, as shown in Design A of Figure 4.4, is to implement blind cut on a single laminae to make blind channels. The other, as illustrated in Design B of Figure 4, is to implement a through-cut on a shim to make a channel shim and then bond the channel shims to a base shim without any channels. In this case, four kinds of shim are needed to make one HRU device.

Photochemical machining (PCM) is modeled as patterning process for production of Design A, where blind channels are directly etched on the shims. Design B is applied for another patterning process, laser cutting, due to the challenges of making blind cuts using a laser. Three bonding techniques are chosen for bonding process: diffusion bonding, diffusion brazing, and laser welding. Therefore, as shown in Table 4.1, there are six manufacturing scenarios to the evaluated in terms of cost and environmental impacts to determine the most attractive strategy, as well as identifying key cost and environmental impact drivers and opportunities for potential cost and environmental impact improvements.

Table 4.1. Selected scenarios for HRU manufacturing

Scenario	Patterning Process	Bonding Process
1	Photochemical Machining	Diffusion Bonding
2	Photochemical Machining	Diffusion Brazing
3	Photochemical Machining	Laser Welding
4	Laser Cutting	Diffusion Bonding
5	Laser Cutting	Diffusion Brazing
6	Laser Cutting	Laser Welding

4.4.1 Photochemical machining (PCM)

As summarized by Gao et al. (NDa), steps modeling the PCM process includes: cleaning the metal surface for good etching condition, heating the panels to lamination process

Table 4.2. Material and energy input for photochemical machining (PCM)

Category Name	Material/Energy Type	SimaPro Process Name
Raw material	316 Stainless steel	X5CrNiMo18 (316)I
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

temperature, laminating dry films, laminating photomasks and exposing to ultraviolet light to harden select area, spraying chemicals to develop the pattern and wash out the unexposed area, etching patterns with chemicals in metal panel, stripping the photoresist, inspecting visual defects, dealing with metal etchant waste treatment, and the reclaim of metal etchant. Similarly, the model assumed that the whole surface of the stainless steel panel needs to be cleaned. Alkaline and acid chemical usage is assumed to be 0.11 L/m^2. Panel etch rate is assumed to be 0.1 mm/min.

4.4.2 Laser cutting

Table 4.3. Material and energy input for laser cutting

Category Name	**Material/Energy Type**	**SimaPro Process Name**
Raw material	316 Stainless steel	X5CrNiMo18 (316)I
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

A CO_2 laser machine is assumed to be used for the laser cutting process. Light powered by CO_2 travels through machine optics, focused by a lens, and ablates through-geometry including channels and holes on metal panels. Cycle time for laser cutting is based on a linear cutting rate of 350 cm/min. For the channel shim, cutting length is assumed to be the length of all the channels plus the perimeters of the holes and all other through cuts. For the base shims, cutting length is calculated as the perimeters of the holes and other through cuts. Detailed material and energy input information is illustrated in Table 4.3. Material assumptions are made based on commercially available data.

4.4.3 Diffusion bonding

Table 4.4. Material and energy input for diffusion bonding

Category Name	**Material/Energy Type**	**SimaPro Process Name**
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 bonding can be utilized to bond the etched panels and end plates into a monolithic panel stack. Shim cleaning is needed at the beginning of the process for degreasing and particulate removal. Afterwards, the cleaned panels are stacked and aligned in a fixture and bonded. During the bonding process, panel stacks will be heated to a bonding temperature of 980 ℃. The total bonding time is 42.7 hours, with a heating rate of 5 ℃/min, a cooling rate of 0.23 ℃/min, a holding time of 120 minutes, and a furnace load time of 30 minutes. Detailed material and energy input information is illustrated in Table 4.4.

Table 4.5. Material and energy input for diffusion brazing

Category Name	**Material/Energy Type**	**SimaPro Process Name**
Raw material	316 Stainless steel	X5CrNiMo18 (316)I
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

4.4.4 Diffusion brazing

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). 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 hold time of 60 min, and a furnace loading time of 30 min, with a bonding temperature of 880 ℃. Diffusion brazing includes electroless deposition of nickel-phosphorous (NiP), visual defect inspection, alignment of the panel stack in the fixture, loading the panel stack in the oven, and diffusion brazing. A clean and prepare process is needed prior to the NiP deposition. Detailed material and energy input information is illustrated in Table 4.5.

4.4.5 Laser welding

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 shims. Cycle time is determined based upon a linear weld rate of 350 cm/min. Laser welding includes cleaning and welding shims stack. Detailed material and energy input information is reported in Table 4.6.

4.4.6 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

Table 4.6. Material and energy input for laser welding

Category Name	Material/Energy Name	SimaPro Process Name
Raw material	316 Stainless steel	X5CrNiMo18 (316)I
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

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, electrical discharge machining (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.

Table 4.7. Mass and energy input for water jet cutting, EDM, and CNC

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	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

Detailed material and energy input information is presented in Table 4.7.

Labor cost, water, electricity, wastewater and sewer charges are assumed based on the rates in Portland, OR in 2013. Process parameters (e.g. tool and facility depreciation years, tool capital costs) are assumed to be the same as mentioned by Gao et al. (NDa). 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 the environmental impact model.

4.5 Results

Cost and environmental impacts estimates of the six manufacturing scenarios will be reported in this section, followed by analysis of results where 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.

4.5.1 Cost results

Per device cost estimates are reported for a range of production volumes in Table 4.8 for each manufacturing scenario. Projected trend lines for these results are shown in Figure 4.5. It can be seen that total manufacturing cost decreases with increasing production volume, most of the reduction occurs at lower production volumes. As the production rate increases from 20,000 to 500,000, the manufacturing cost for each scenario is comparatively constant. *Scenario 5*, with laser cutting as patterning process and diffusion brazing as bonding process, exhibits the lowest cost for each production volume. At production volumes of 2,000 and below, *Scenario 6*, a combination of laser cutting and laser welding, is estimated to have the highest cost. At higher production rates (5,000 and higher), however, *Scenario 3* has the highest cost, followed by *Scenario1*. This indicates *Scenario 6* becomes a more cost effective manufacturing method at higher production rates. A detailed cost analysis of each scenario is illustrated in the following sections.

Table 4.8. Manufacturing scenario cost comparison for different production volumes

Scenario	Production Volume (devices/year)								
	1,000	**2,000**	**5,000**	**10,000**	**20,000**	**50,000**	**100,000**	**200,000**	**500,000**
1	$1,521.88	$1,075.70	$840.26	$769.22	$728.65	$713.06	$704.98	$701.59	$700.60
2	$1,307.76	$908.11	$666.84	$588.85	$554.92	$544.15	$536.77	$533.37	$531.88
3	$1,555.86	$1,117.88	$854.69	$769.53	$735.73	$720.97	$713.11	$709.56	$708.13
4	$1,403.48	$969.34	$745.06	$676.41	$637.07	$623.25	$615.19	$612.00	$610.98
5	$1,189.98	$800.91	$581.74	$505.55	$472.25	$461.98	$454.36	$451.08	$450.14
6	$1,666.57	$1,126.79	$806.75	$712.59	$661.64	$644.10	$636.45	$631.74	$630.54

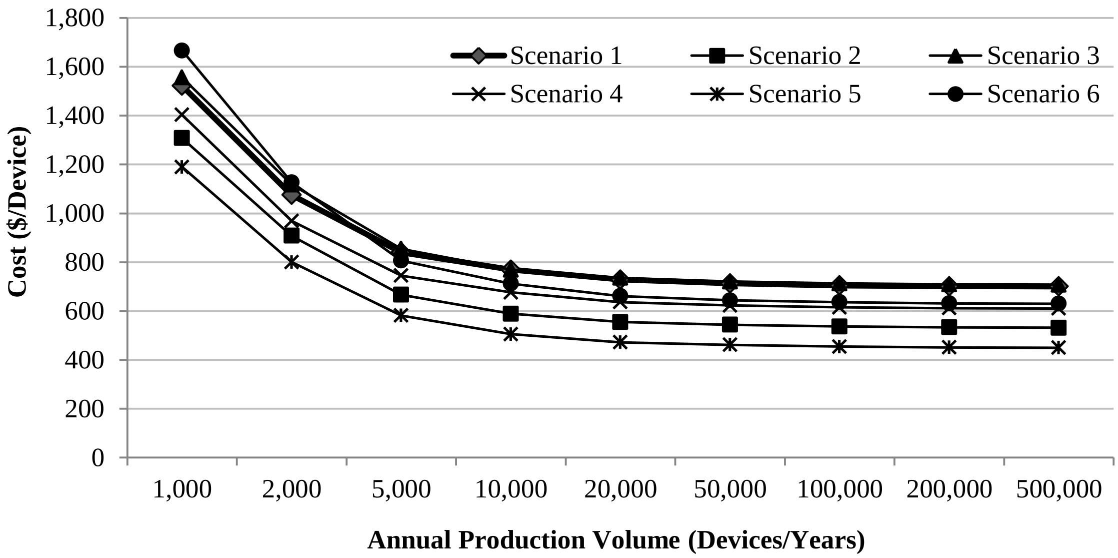
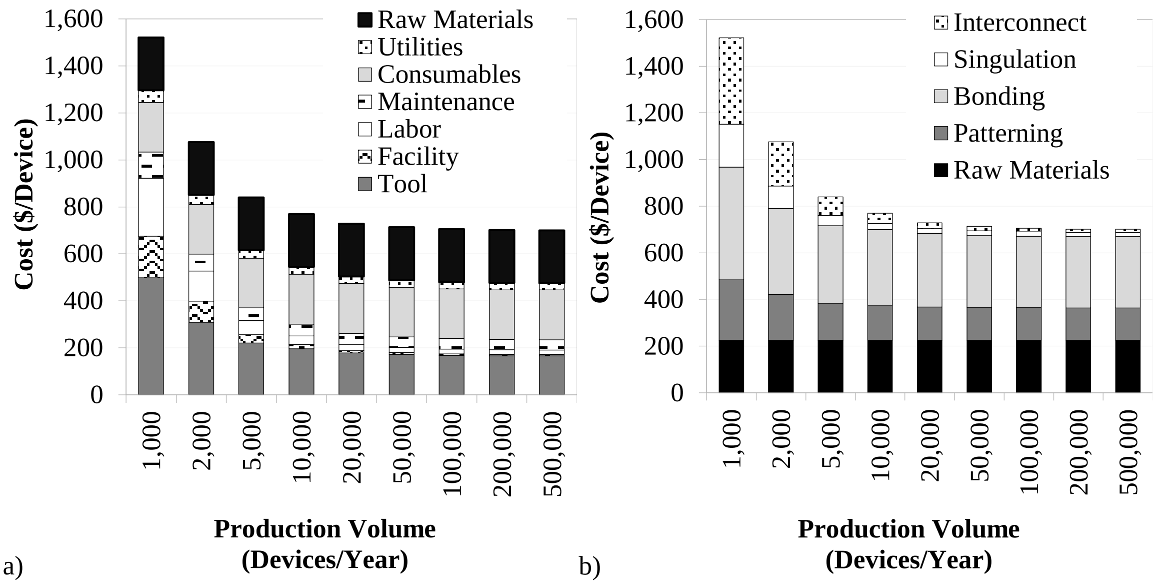


Figure 4.5. Cost of each scenario at different production volumes

4.5.1.1 *Scenario 1* cost results

Cost estimates for *Scenario 1* are illustrated in Figure 4.6. The manufacturing cost for one HRU decreases from $1,521.88 to $700.60 as the production volume increases from 1,000 to 500,000 HRUs per year. As shown in Figure 4.6a, where cost is broken down by cost categories, tool accounts for 32.71% of the total cost and is the largest cost driver at a production volume of 1,000 units. Labor and raw materials are also significant contributors at this production volume, and account for 16.18% and 14.79% of the total cost, respectively. However, as the production volume increases, tool cost, facility cost, utilities cost, maintenance cost, and labor cost decrease significantly, while raw materials costs and consumables costs are relatively constant. This is due to the assumption of raw materials and consumables are independent of production volume. Thus, at a high production volume of 500,000 HRUs per year, raw materials and consumables costs become the first and second cost contributors. Although decreasing significantly, the cost of tool still accounts for 23.65% of the total cost.



a) b)

Figure 4.6. Cost breakdown for *Scenario 1*: by a) Cost category and b) Process type and raw material

The cost breakdown by process type and raw materials is exhibited in Figure 4.6b. At low production rates, bonding, interconnect, and pattering processes are the top three drivers, account for 31.76%, 24.37%, and 17.05%, respectively. As production rates increase, the cost of interconnect and singulation processes drop significantly, from $370.87 and $182.96 at 1,000 devices per year to $12.66 and $18.04 at 500,000 devices per year, respectively. Comparatively, patterning cost and bonding cost remain more constant, dropping from $259.49 and $483.33 at 1,000 devices per year to $138.28 and $306.39 at 500,000 devices per year, respectively.

Since the total cost stabilized at a production volume of 20,000 HRUs per year and higher, Figure 4.7 displays the cost breakdown of each process by cost category at this production volume. As shown, consumables cost accounts for 90.52% of the patterning cost. As production volume increases, other costs decrease while consumables cost remains constant and become the major driver of patterning cost. For diffusion bonding, tool, consumables, and maintenance are the top three drivers, accounts for 52.00%, 21.66%, and 13.99% of the overall cost, respectively. This is due to the long bonding time required and the high tool capital cost. For singulation, consumables, tool, and the facility are all significant cost drivers, accounting for 37.00%, 22.71%, and 16.68% of overall cost, respectively. For the interconnect process, the significant cost drivers are tool, consumables, and the facility, each accounts for 28.54%, 25.15%, and 22.89%, respectively.

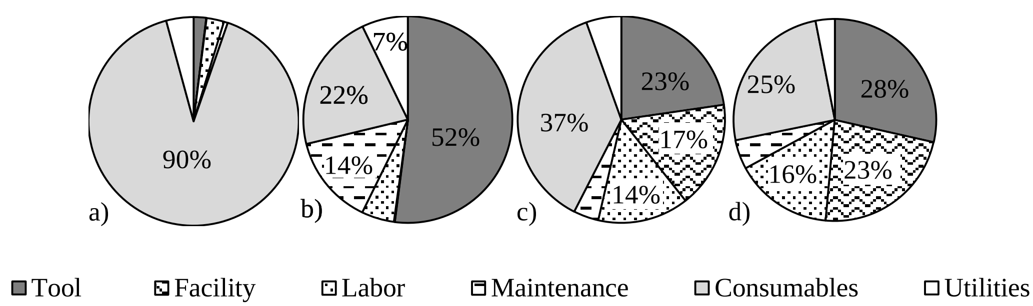


Figure 4.7. Cost breakdown for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes for *Scenario 1* (20,000 devices/year)

4.5.1.2 *Scenario 2* cost results

In *Scenario 2*, HRUs are patterned by PCM and then bonded by diffusion brazing.

As annual production volume increases from 1,000 to 500,000, the total manufacturing cost decreases, from $1,307.76 to $531.88. Figure 4.8a exhibits the cost breakdown for the defined cost categories. At a production volume of 1,000, tool, labor, raw materials, consumables, and facility costs are all significant, accounting for 24.06%, 21.30%, 17.21%, 16.37%, and 13.68%, respectively. Similar to *Scenario 1*, costs associated with tools and labor decrease tremendously while the cost of raw materials and consumables stays constant. Thus, at high production rate, raw materials and consumables become the main cost drivers, accounting for 42.30% and 40.26% of the total cost, respectively.

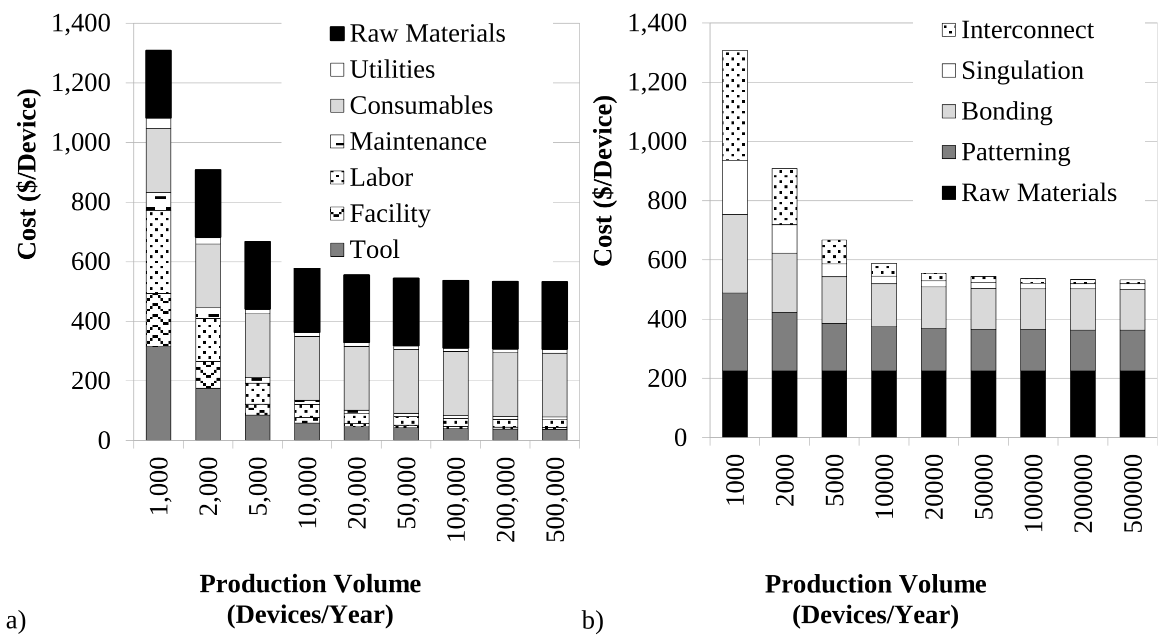


Figure 4.8. Cost breakdown for *Scenario 2* by a) Cost category and b) Process type and raw materials

Figure 4.8b demonstrates the cost breakdown by process type and raw material, where there is no difference of interconnect and singulation processes between *Scenario 1* and

Scenario 2. Patterning cost drops from $263.49 to $138.32 as production volume increases from 1,000 to 500,000. The minor variance of patterning cost between *Scenario 1* and *2* is due to the lower process yield assumed for diffusion brazing comparing to diffusion bonding. The cost of diffusion brazing is lower than diffusion bonding for each of the nine production volumes, decreasing from $265.21 to $137.64 as the production volume increases from 1,000 to 500,000. At a production rate of 1,000, interconnect, patterning and bonding are the top cost drivers, accounts for 28.38%, 20.15%, and 20.28% of the total cost, respectively, while at the production rate of 500,000, raw material, patterning, and bonding are the main contributors, accounting for 42.30%, 26.00%, and 25.88% of the total cost, respectively.

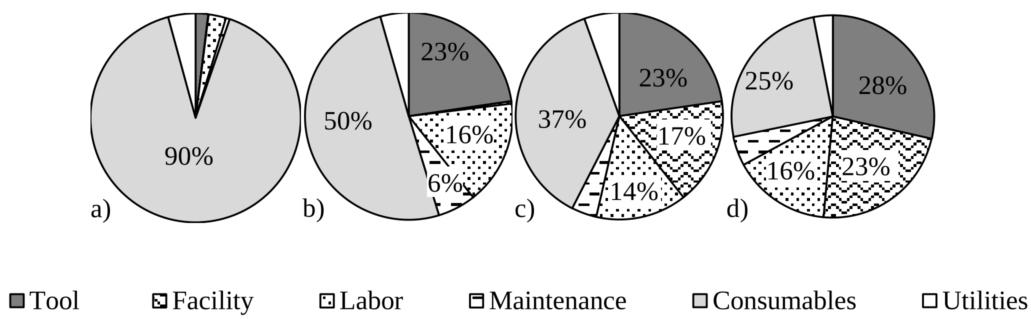
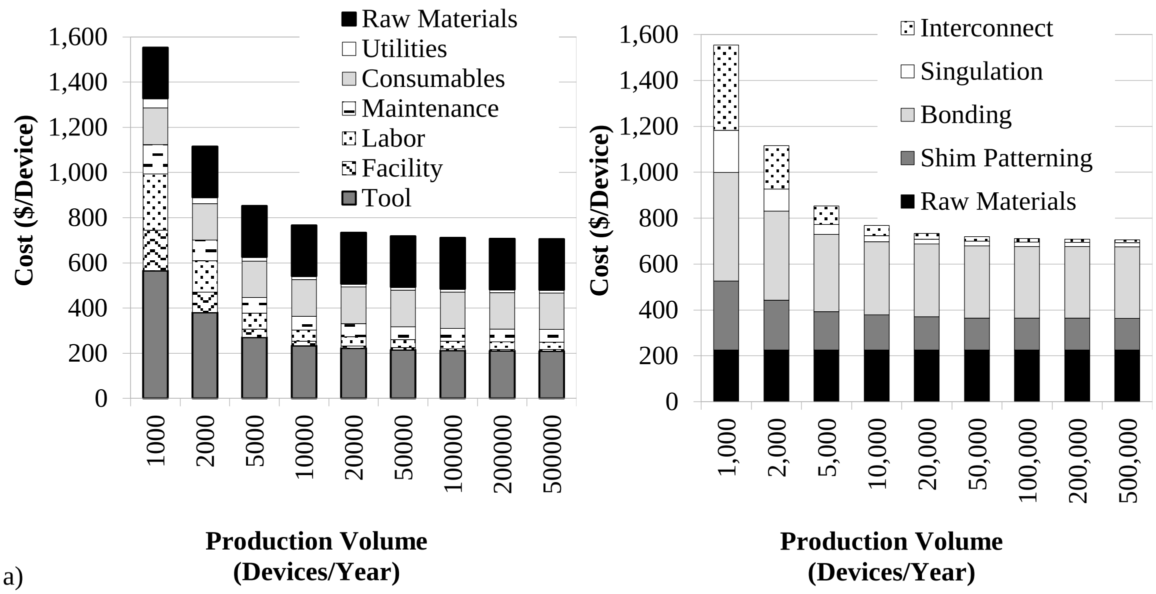


Figure 4.9. Cost breakdown for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes for *Scenario 2* (20,000 devices/year)

Cost stabilized at a production rate of 20,000 devices per year. At this point, the cost breakdown by cost category is shown in Figure 4.9. Distributions of cost categories are the same with *Scenario 1* for patterning, singulation, and interconnect processes since the same manufacturing processes are used. For bonding, consumables, tool, and labor are the top three drivers, accounting for 50.29%, 22.67%, and 16.27% of the overall cost, respectively.

4.5.1.3 *Scenario 3* cost results

In *Scenario 3*, HRUs are patterned by PCM and then bonded by laser welding. As the annual production volume increases from 1,000 to 500,000, the total manufacturing cost decreases, from $1,555.86 to $708.13. Figure 4.10a exhibits the cost breakdown by cost category. Similar to *Scenario 1* and *Scenario 2*, cost of raw materials and consumables are insensitive to the change in production volume while other costs decreases tremendously with the increasing production volume. At a low production rate of 1,000 HRUs per year, tool, raw materials, and consumables costs are top cost drivers while at high production rate, tool, labor, and raw materials costs are the top three cost drivers, accounts for 36.38%, 15.92%, and 14.46% of the overall cost, respectively. At a production rate of 500,000 HRUs per year, raw materials, tool, and consumables are the main contributors, accounting for 31.78%, 29.66%, and 23.18%, respectively. Figure 4.10b demonstrates the cost breakdown by process where there is no variation in interconnect and singulation processes between *Scenario 1*, *Scenario 2*, and *Scenario 3*.The patterning process cost drops from $301.14 to $138.37 as the production volume increases from 1,000 to 500,000. The minor difference for the patterning process is because of the different process yield assumed for laser welding. The bonding process, which is performed with laser welding, is the most significant cost driver for all of the nine production volumes. Per device cost drops from $475.67 to $313.84 while the production rate increases from 1,000 to 500,000 HRUs per year.



a)

Figure 4.10. Cost breakdown for *Scenario 3* by a) Cost category and b) Process type and raw materials

Cost estimates stabilized at a production rate of 20,000 devices per year. At this point, the cost breakdown by cost category is shown in Figure 4.11. Distributions of cost categories are the same as *Scenario 1* and *Scenario 2* for patterning, singulation, and interconnect processes since the same manufacturing processes are used for these Scenarios. For bonding, tool, maintenance, and labor are the top three drivers, accounting for 63.03%, 16.96%, and 10.69% of the overall cost, respectively. Due to the nature of laser welding, the cost is influenced by the length of welding path - a longer welding path results in higher cost. Thus, the cost of laser welding will change with the design of shim.

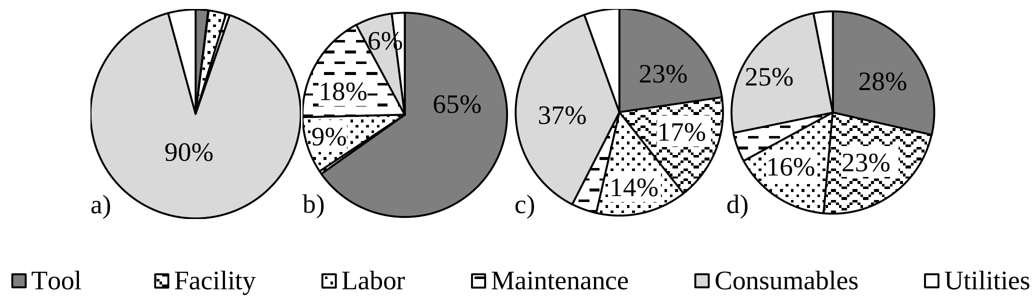
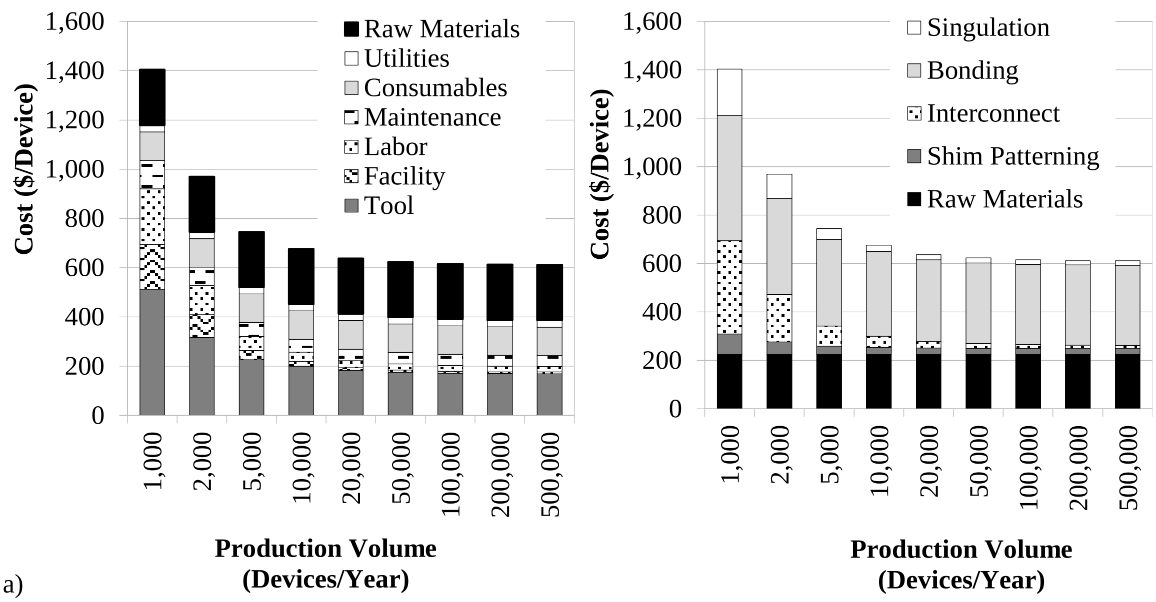


Figure 4.11. Cost breakdown for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes for *Scenario 3* (20,000 devices/year)

4.5.1.4 *Scenario 4* cost results

Figure 4.12 demonstrates cost estimates of a HRU for *Scenario 4*, which is assumed as laser cutting and diffusion bonding. With the increase of annual production volume from 1,000 to 500,000 devices, manufacturing cost decreases from \$1,403.48 to \$610.98. Figure 4.12a exhibits the manufacturing cost breakdown by cost category. At a production volume of 1,000 HRUs per year, tool, labor, and raw material, account for 36.49%, 16.15%, and 16.03% of the overall cost, respectively, and are the top three cost drivers. At a production volume of 500,000 devices per year, raw materials, tool, and consumables become the top cost contributors, and account for 36.83%, 27.68%, and 18.91% of the total cost, respectively. Figure 4.12b shows the cost breakdown by process types and raw materials, where the bonding process is the biggest cost driver at each production volume. As the production volume increases, cost of bonding process drops from \$518.45 to \$330.64. Although diffusion bonding is also used for *Scenario 1*, its cost in *Scenario 4* is slightly higher due to the nature of laser cutting, which doubles the number of shims required. Laser cutting demonstrates its excellent cost advantages as a patterning process. Compared to PCM, estimated to be from $279.91 per device at 1,000 HRUs per year to $138.87 per device at 500,000 HRUs per year, laser cutting costs are $83.64 per device at 1,000 HRUs per year and the cost decreases to $23.75 per device at 500,000 HRUs per year. There is no variation of interconnect and singulation processes between *Scenario 4* and previous scenarios.



a)

Figure 4.12. Cost breakdown for *Scenario 4* by a) Cost category and b) Process type and raw materials

The cost of one HRU starts to stabilize at a production rate of 20,000 devices per year. At this point, the cost breakdown by cost category is shown in Figure 4.13. Distributions of cost categories are the same as *Scenario 1* for bonding, singulation, and interconnect processes. For patterning processes, consumables, tool, and utilities are the top three drivers, accounting for 60.24%, 22.02%, and 9.63% of the overall cost respectively.

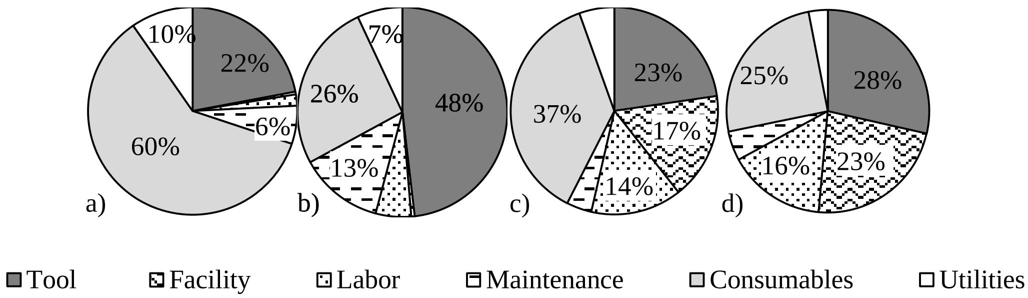


Figure 4.13. Cost breakdown for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes for *Scenario 4* (20,000 devices/year)

4.5.1.5 *Scenario 5* cost results

As shown in Figure 4.14, as the production volume increases from 1,000 to 500,000 devices per year for *Scenario 5*, which assumes laser cutting and diffusion brazing, total cost decreases from $1,189.98 to $450.14. Figure 4.14a demonstrates the manufacturing cost breakdown by cost category. At a production volume of 1,000 HRUs per year, tool, labor, and raw materials, with cost estimates of $322.61, $264.88, and $225.01, respectively, are the top three cost drivers. At a production volume of 500,000 HRUs per year, raw materials and consumables become the top and major cost drivers, with their cost estimate at $225.01 and $112.89, respectively. In Figure 4.14b, cost is broken down by process type and raw materials. At a low production rate, interconnect, bonding, and raw materials account for large amount of the cost. Per device interconnect and singulaton costs drop significantly with the increasing of production rates. Comparatively, patterning cost and bonding cost stayed more constant, dropping from $85.75 and $303.02 at 1,000 devices per year to $23.56 and $170.06 at 500,000 devices per year, respectively. The cost for diffusion brazing as a bonding process is higher in

Scenario 5 than that in *Scenario 2*, due to a doubling in the number of shims by using Design B for laser cutting. This increase the cost also accounts for additional stacking activities and consumables.

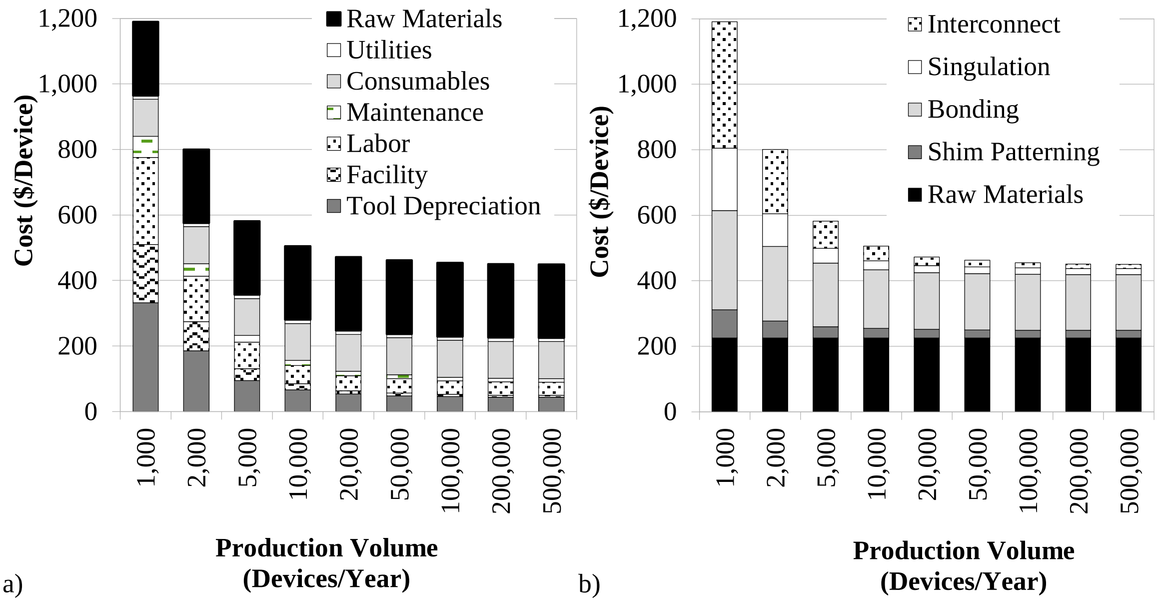


Figure 4.14. Cost breakdown for *Scenario 5* by a) Cost category and b) Process type and raw materials

Cost of one HRU starts to stabilize at a production rate of 20,000 devices per year. At this

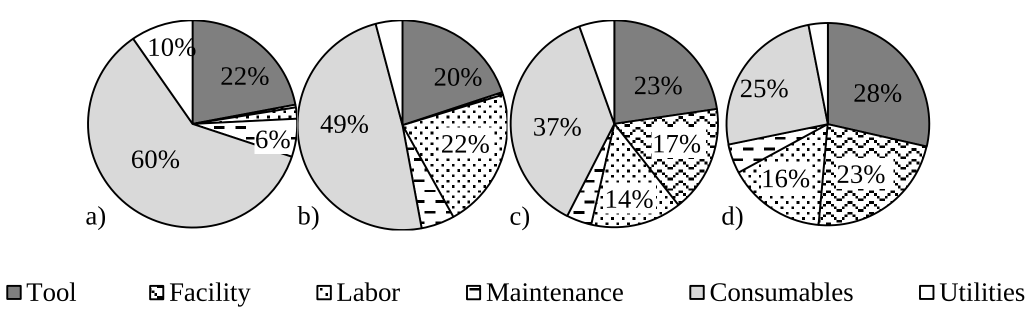
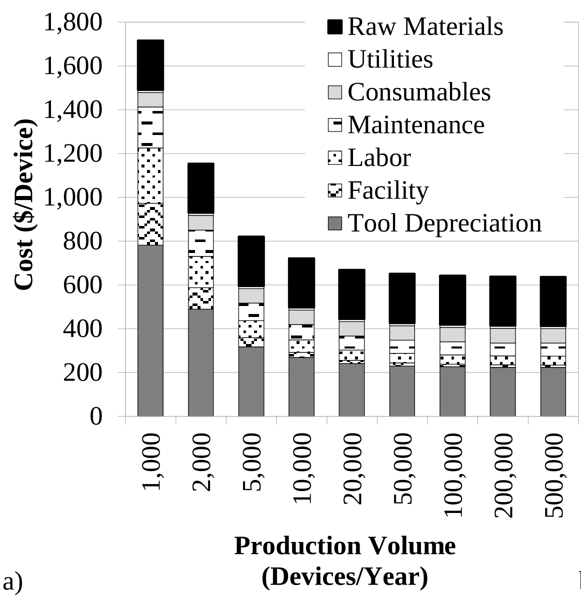


Figure 4.15. Cost breakdown for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes for *Scenario 5* (20,000 devices/year)

point, the cost breakdown by cost category is shown in Figure 4.15. Distributions of cost categories are the same as *Scenario 2* for bonding, singulation, and interconnect processes. For patterning processes, the results are consistent with those in *Scenario 4*.

4.5.1.6 *Scenario 6* cost results

As shown in Figure 4.16, for *Scenario 6*, which assumes laser cutting and laser welding, manufacturing cost decreases from $1,666.57 to $630.54 with an increase in production volume from 1,000 to 500,000. Figure 4.16a demonstrates the manufacturing cost breakdown by cost category. At a low production volume of 1,000 HRUs per year, tool, raw materials and labor, with cost of $781.29, $225.01, and $201.70 respectively, are the top three cost drivers.



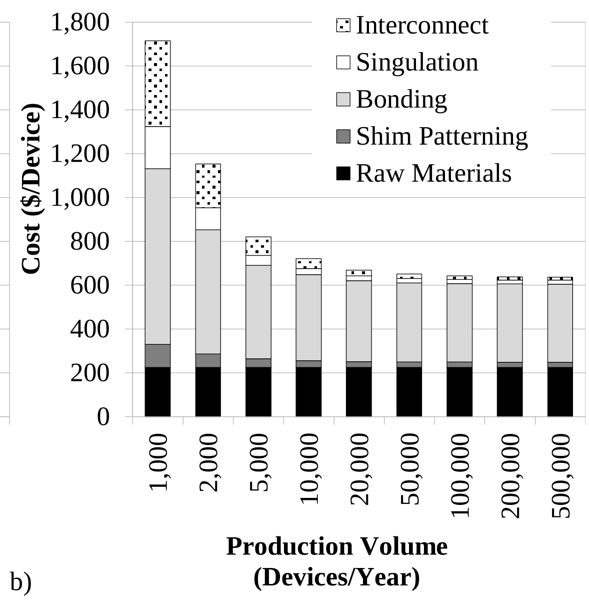


Figure 4.16. Cost breakdown for *Scenario 6* by a) Cost category and b) Process type and raw materials

At a production volume of 500,000 devices per year, raw material and tool, with costs of \$225.01 and \$222.93, respectively, become the top and major cost drivers. In Figure 4.16b, cost is broken down by process types and raw materials. At a low production rate, the bonding process is the top cost driver, accounting for 47.02% of overall cost. Interconnect and singulaton process costs drop significantly as seen for other scenarios with increasing production rate. Comparatively, patterning cost and bonding cost stayed more constant, dropping from \$103.90 and \$783.62 at 1,000 devices per year to \$23.56 and \$35.05 at 500,000 devices per year, respectively.

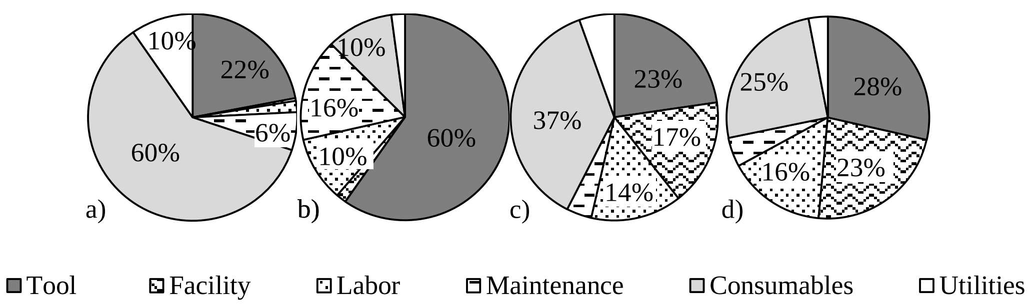


Figure 4.17. Cost breakdown for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect processes for *Scenario 6* (20,000 devices/year)

Cost of one HRU starts to stabilize at a production rate of 20,000 devices per year. At this point, the cost breakdown by cost category is shown in Figure 4.17. Distributions of cost categories are the same as *Scenario 3* for bonding, singulation, and interconnect processes. For patterning processes, results are consistent with those in *Scenario 4* and *Scenario 5*. By using laser cutting as a patterning process, the number of shims to be bonded is doubled. Thus, since the cost of laser welding as a bonding process is driven by the welding length, laser welding in *Scenario 6* is more costly than *Scenario 3*.

Table 4.9. Cradle-to-gate environmental impact per device (Pts/HRU) at different production volumes

Scenario	Production Volume (devices/year)								
	1,000	**2,000**	**5,000**	**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	1,764.90	1,764.88
3	288.40	283.33	280.27	279.43	278.93	278.68	278.63	278.61	278.59
4	2285.46	2284.09	2283.38	2283.16	2283.05	2283.00	2282.98	2282.97	2282.96
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

4.5.2 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 4.9. 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 of the six scenarios are compared in Figure 4.18 for a production volume of 500,000 devices. 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 for a production volume of 500,000 devices.

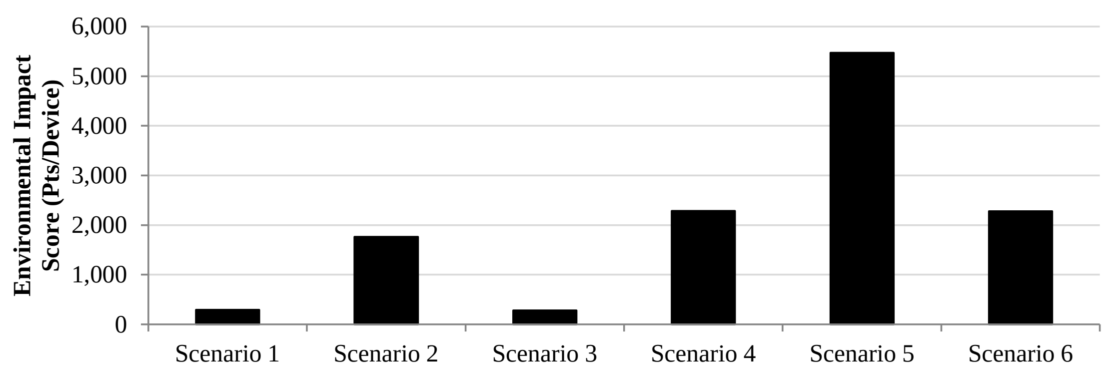
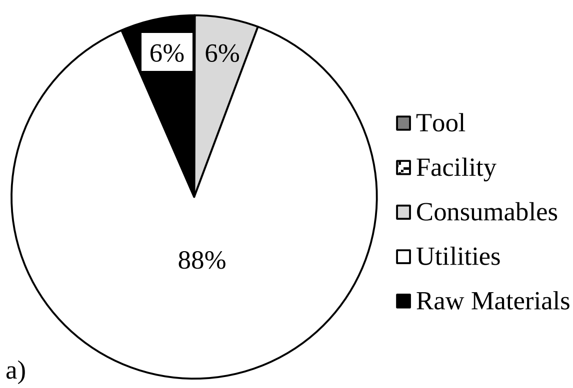


Figure 4.18. Environmental impact assessment of the six scenarios at a production volume of 500,000 HRUs per year

4.5.2.1 *Scenario 1* environmental impact results

As indicated by Figure 4.19a, where environmental impact score is broken down by impact category, utilities dominates (87.82%) the total impacts. Raw material 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 the change of 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. Figure 4.19b exhibits the environmental impact score breakdown by process type.



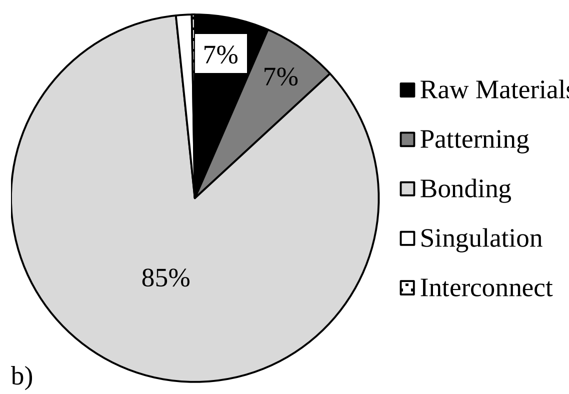


Figure 4.19. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 1* at production rate of 500,000 HRUs per year

The bonding process, with an environmental impact score of 251.53 Pts/device, accounts for 85.21% of the total impacts. The patterning process and raw materials, with impact scores of 19.58 Pts and 19.20 Pts, account for 6.63% and 6.51%, respectively. Detailed analysis of each process is illustrated in Figure 4.20, where the environmental impact score for each process is broken down into previous defined categories.

It can be seen that consumables account for 67.55% of the environmental impacts for the patterning process, followed by utilities, which account for 32.22% of the environmental impacts. For the bonding process, utilities account for 99.39% of the total impacts. For singulation and interconnect process, utilities are the major contributors, while consumables are also significant drivers for both processes. Figures 4.19 and 4.20 indicate that the major environmental driver of *Scenario 1* is utilities 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.

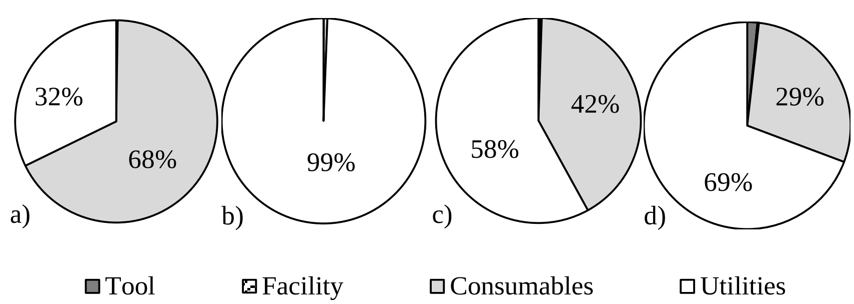


Figure 4.20. Categories of environmental impact categories for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect process for *Scenario 1*

4.5.2.2 *Scenario 2* environmental impact results

Results for a production rate of 500,000 HRUs per year are exhibited in Figure 4.21. As indicated by Figure 4.21a, where environmental impact score is broken down by impact category, consumables and utilities are major contributors, accounting for 60.22% and 38.68% of the overall impacts respectively. Figure 4.21b displays the environmental impact breakdown by process type and raw materials. The bonding process, with an environmental impact score of 1721.24 Pts, dominates (97.53%) the total impacts. The patterning process and raw materials, with impact scores of 19.58 Pts and 19.20 Pts, account for 1.11% and 1.09%, respectively. Detailed analysis of each process is illustrated in Figure 4.22, where the environmental impact score for each process is broken down into the selected categories.

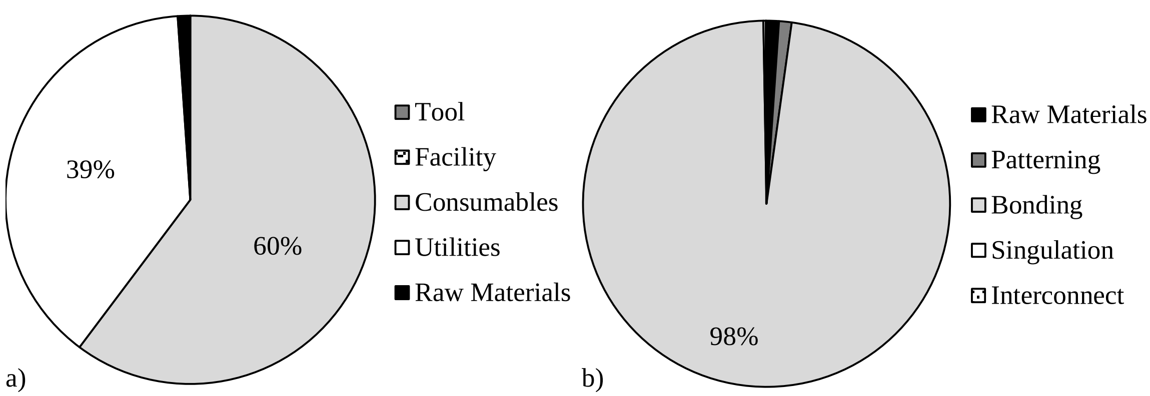


Figure 4.21. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 2* at production rate of 500,000 HRUs per year

Consistent with the results of *Scenario 1*, consumables and utilities account for 67.55% and 32.22% of the overall environmental impacts respectively for patterning process. Singulation and interconnect processes have the same environmental impacts as for *Scenario 1*. For the bonding process, which is done with diffusion brazing, consumables and utilities are the major contributors to environmental impacts, account for 60.87% and 39.13% of the total impacts. From Figures 4.21 and 4.22, it can be seen that the major environmental driver of *Scenario 2* is the bonding process where consumables and utilities have significant impact. It can be interpreted that although a comparatively lower bonding temperature and shorter bonding time is required for diffusion brazing, a cycle time of 25.3 hours and bonding temperature of 880 ℃ is still significant, and consumes a large amount of water and electricity. Besides that, consumables are required for each shim, which also contribute to the environmental impact.

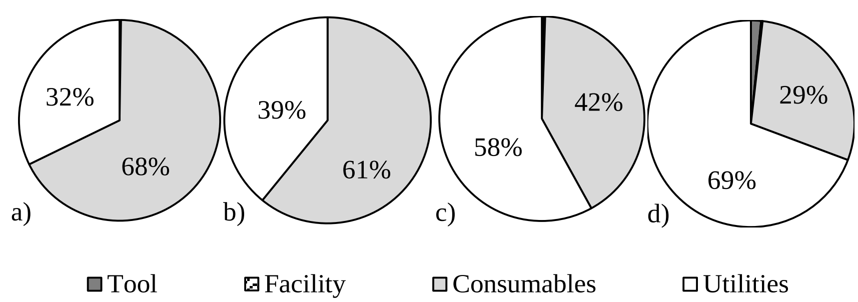


Figure 4.22. Categories of environmental impact categories for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect process for *Scenario 2*

4.5.2.3 *Scenario 3* environmental impact results

With a patterning process of PCM and bonding process of laser welding, *Scenario 3* demonstrates the lowest environmental impacts compared to other scenarios. Results for a production rate of 500,000 HRUs per year are exhibited in Figure 4.23. As indicated by Figure 4.23a, where environmental impact score is broken down by impact category, consumables, utilities, and raw materials are major contributors, accounting for 64.68%, 28.32%, and 6.89% of the overall impacts, respectively. Figure 4.23b exhibits the environmental impact score breakdown by process type and raw materials. The bonding process, with an environmental impact score of 234.96 Pts, accounting for 84.34% of the total impacts. The patterning process and raw materials, with impact score of 19.57 Pts and 19.20 Pts, accounts for 7.03% and 6.89% of the overall impacts, respectively. Detailed analysis of each process is illustrated in Figure 4.24, where the environmental impact score for each process is broken down into the selected categories.

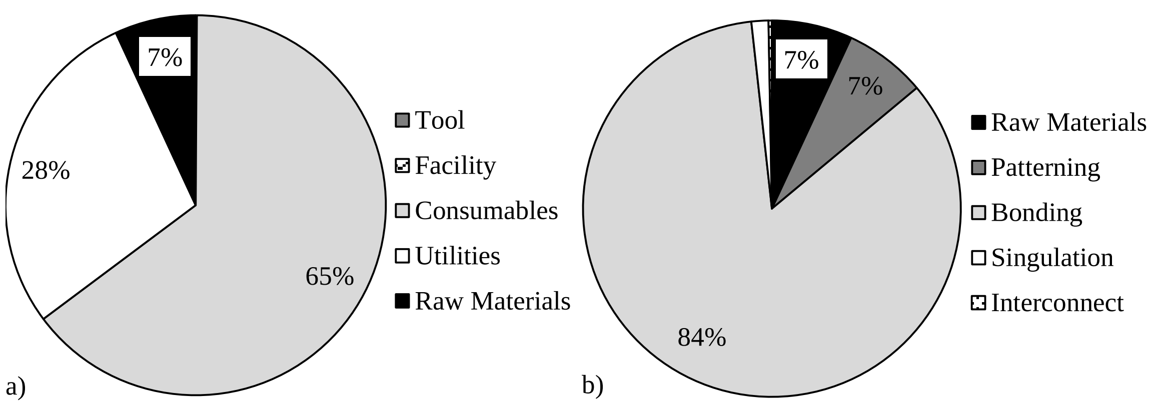


Figure 4.23. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 3* at production rate of 500,000 HRUs per year

Results for the patterning, singulation, and interconnect processes are consistent for *Scenario 1*, *Scenario 2*, and *Scenario 3* since the same manufacturing processes are utilized. Environmental impacts of the bonding process, which is accomplished with laser welding, are primarily driven by utilities and consumables, which account for 70.25% and 29.66% of the total impacts, respectively. Figures 4.21 and 4.22 indicate that *Scenario 3* is more environmental friendly than *Scenario 1* and *Scenario 2* due to use of laser welding as bonding process.

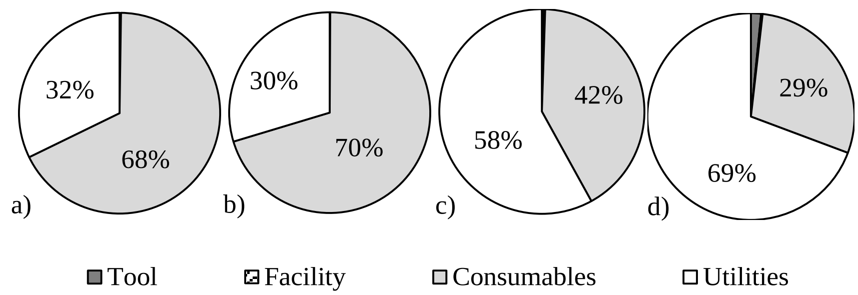


Figure 4.24. Categories of environmental impact categories for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect process for *Scenario 3*

4.5.2.4 *Scenario 4* environmental impact results

Results at a production rate of 500,000 HRUs per year are exhibited in Figure 4.25 for *Scenario 4*. As indicated by Figure 4.25a, where the environmental impact score is broken down by impact category, consumables and utilities are major contributors, and account for 87.62% and 11.52% of the overall impacts, respectively. Figure 4.25b displays the environmental impact score breakdown by process type and raw materials. The patterning process, with an environmental impact score of 2006.40 Pts, accounts for 87.86% of the total impacts. The bonding process, with an impact score of 253.07 Pts, accounts for 11.08% of the overall environmental impacts. The impacts of diffusion bonding are 0.61% higher in this scenario than for the same process used in *Scenario 1* because twice many shims is needed for patterning using laser cutting. Detailed analysis of each process is illustrated in Figure 4.26, where the environmental impact score for each process is broken down into the selected categories.

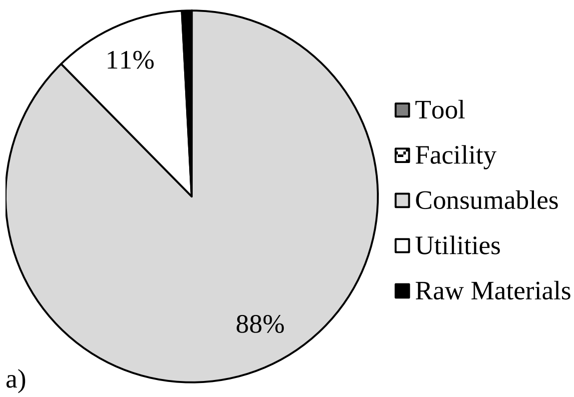


Figure 4.25. Environmental impact breakdown by a) Impact category and b) Process type and raw material for *Scenario 4* at production rate of 500,000 HRUs per year

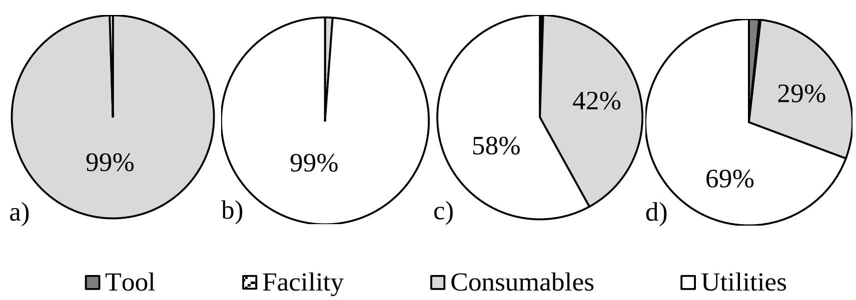


Figure 4.26. Categories of environmental impact categories for a) Shim patterning, b) Bonding, c) Singulation, and d) Interconnect process for *Scenario 4*

Results for bonding, singulation, and interconnect processes are consistent with *Scenario 1*, due to the same manufacturing process utilized. The environmental impacts of the patterning process, which is done with laser cutting, are primarily driven by consumables, which account for 99.49% of the total impacts. Figures 4.25 and 4.26 indicate that the high environmental impact score of *Scenario 4* is mainly caused by the consumables utilized in laser cutting.

4.5.2.5 *Scenario 5* environmental impact results

It can be seen from Table 4.9 and Figure 4.18 that *Scenario 5* has the most significant environmental impact among the six scenarios. Results at a production rate of 500,000 HRUs per year are exhibited in Figure 4.27. As indicated by Figure 4.27a, where the environmental impact score is broken down by impact category, consumables and utilities are major contributors, accounting for 74.78% and 24.86% of the overall impacts, respectively. Figure 4.27b displays the environmental impact score breakdown by process type and raw materials. The bonding process, with an impact score of 3440.01 Pts, accounts for 62.88% of the overall environmental impacts. The patterning process, with an environmental impact score of 2006.39 Pts, accounts for 36.68% of the total impacts. It can be seen that the environmental impact score of diffusion brazing almost doubled comparing to the same manufacturing process utilized in *Scenario 2*. This is because of Design B is used for laser cutting as a patterning process, which doubles the number of shims required. It also doubles the amount of consumables needed for diffusion brazing, resulting in a more significant environmental impacts for diffusion brazing in *Scenario 5*. Detailed analysis of each process is illustrated in Figure 4.28, where the environmental impact score for each process is broken down into the selected categories.

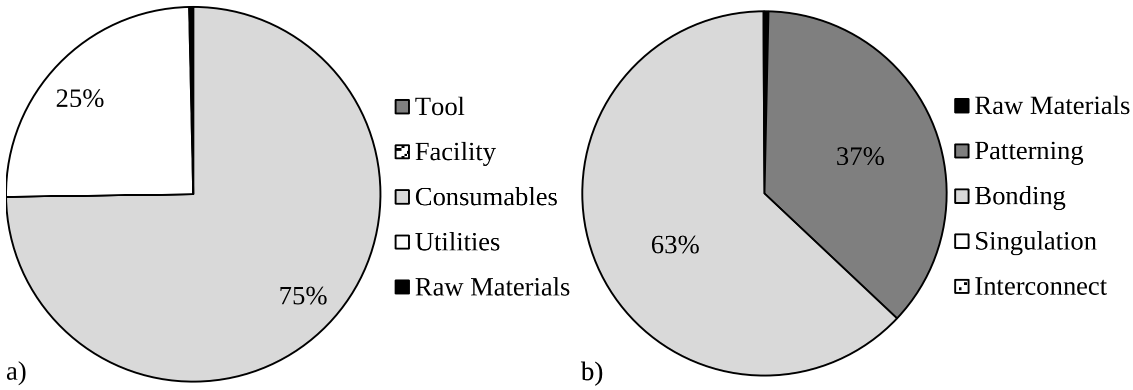


Figure 4.27. Environmental impact breakdown by a) impact category and b) process type and raw material for *Scenario 5* at production rate of 500,000 HRUs per year

Results for bonding, singulation, and interconnect processes are consistent with *Scenario 2*, while patterning process is consistent with *Scenario 4*. Due to the same manufacturing process utilized, although the total environmental impact score of the bonding process is increased, the composition and distribution of the processes is still the same.

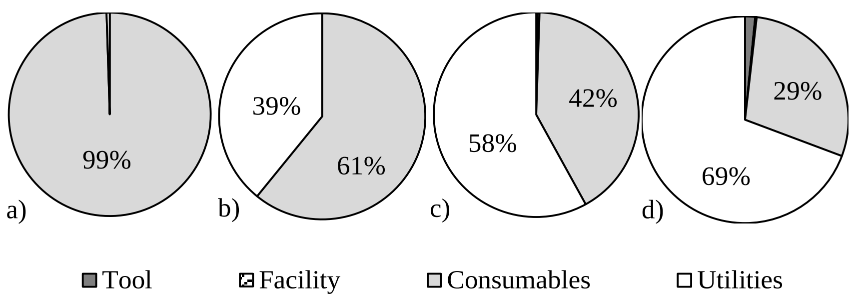
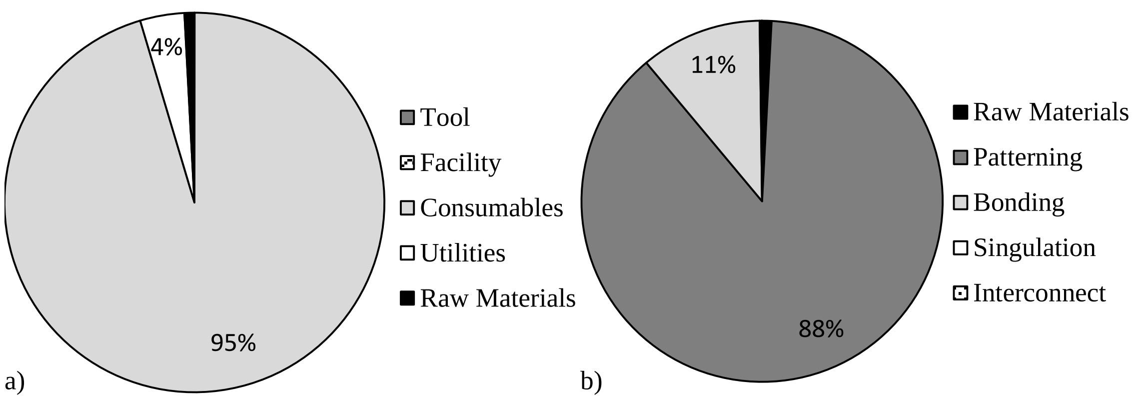


Figure 4.28. Categories of environmental impact categories for a) shim patterning, b) bonding, c) singulation, and d) interconnect process for *Scenario 5*

4.5.2.6 *Scenario 6* environmental impact results

Environmental impact results at a production rate of 500,000 HRUs per year are exhibited in Figure 4.29 for *Scenario 6*. As indicated by Figure 4.29a, where the environmental impact score is broken down by impact category, consumables are the major contributors, accounting for 95.37% of the overall impacts. Figure 4.29b displays the environmental impact score breakdown by process type and raw materials. The patterning process, with impact score of 2006.07 Pts, accounts for 88.08% of the total environmental impacts. Environmental impacts of other processes are comparatively minor. It can be seen that the environmental impact score of laser welding increases compared to the same manufacturing process utilized in *Scenario 3*, due to the number of shims being doubled by utilizing Design B in laser cutting, which increases the total length of welding path, thus increase its environmental impacts. Detailed analysis of each process is illustrated in Figure 4.30, where the environmental impact score for each process is broken down into the select categories.



a) b)

Figure 4.29. Environmental impact breakdown by a) impact category and b) process type and raw material for *Scenario 6* at production rate of 500,000 HRUs per year

Environmental impact results for patterning, singulation, and interconnect processes are consistent with *Scenario 5*. The composition and distribution of bonding process in *Scenario 3* and *Scenario 6* are consistent.

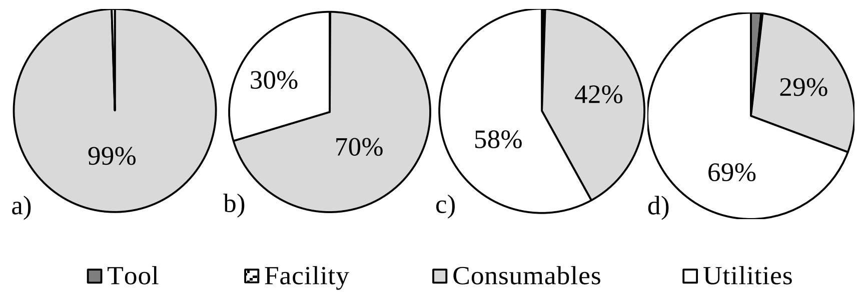


Figure 4.30. Categories of environmental impact categories for a) shim patterning, b) bonding, c) singulation, and d) interconnect process for *Scenario 6*

4.6 Discussion

Six scenarios for HRU manufacturing were analyzed and compared using the cost and environmental impact assessment method preciously developed in this research (Gao et al., NDa). For each of the six scenarios, it was found that per unit cost and environmental impacts decreased as the production volume increased. *Scenario 5*, which assumed 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 5,000 HRUs per year or higher. At lower production volumes (1,000 and 2,000 HRUs per year), *Scenario 3* was the second most costly scenario, after *Scenario 6* (laser cutting and laser welding). At the process level, laser cutting and diffusion brazing were the lowest cost for patterning and bonding process respectively, however, they were also most environmental impactful patterning and bonding process. PCM was a more environmental friendly patterning process comparing to laser cutting, while laser welding was a more environmental friendly bonding process compared to diffusion bonding and diffusion brazing. They are not cost efficient compared to the other patterning and bonding processes, however, especially for high production volumes (5,000 HRUs per year or higher). For laser cutting and laser welding, for which cost and environmental impact are driven by cutting path length, results can be influence by the design of device. 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, value judgment of the decision maker is needed to choose an appropriate manufacturing scenario.

Table 4.10. Primary cost and environmental impacts drivers for each process at production rate of 20,000 devices per year

Process	Primary Cost Driver	Primary Environmental Impact Driver
Photochemical Machining	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

Table 4.10 summarizes the primary driver to cost and environmental impacts of each process. Consumables are primary driver to cost and environmental impacts for PCM, laser cutting, and diffusion brazing. Consumables are also the primary contributor to cost of singulation and environmental impacts of laser welding. Tool is primary cost driver for diffusion bonding, laser welding, and electrical discharge machining. Utilities are primary driver to environmental impacts of diffusion bonding, singulation, and electrical discharge machining. This provides clues for potential process improvements that by incorporate changes to the primary drivers, a more economically viable and environmentally friendly microchannel device manufacturing process may be achieved.

4.7 Conclusions

A combined process-based economic and environmental assessment model was introduced to provide decision makers a more thorough understanding of the manufacturing costs and environmental impacts of microchannel devices. Given the process parameters and geometry information for a microchannel device, the model can estimate the total cost and environmental impacts of associated manufacturing process flow. By illustrating cost and environmental impacts of microchannel device manufacturing at different production volumes and breaking down the results by process types, cost and environmental impact categories, evidence can be given for selecting among manufacturing alternatives and for identifying potential improvement opportunities to achieve a lower cost and less environmentally impactful manufacturing processes. The modeling methodology for estimating cost and environmental impacts was described, followed by application of the methodology to assess several scenarios for producing a microchannel heat recovery unit (HRU) to demonstrate the use of the model. A graphical user interface (GUI) was also created to help users manipulate the model.

This work presents a unique combined cost and environmental impact assessment for evaluating microchannel device manufacturing. Compared to prior work, more detailed calculations for cost and environmental impact assessment were illustrated. Unlike conventional environmental impact analysis, impacts scale with production volume, and results are shown for manufacturing processes and categories related to manufacturing systems (i.e., tools, facility, utilities, consumables, and raw materials). Thus, this manufacturing-oriented economic and environmental assessment model for microchannel device manufacturing can benefit decision makers by providing quantitative evidence for processes selection and potential process improvements, and drive the microchannel device manufacturing to produce more sustainable, lower cost and less environmentally impactful products.

While the model establishes a framework for economic and environmental impacts of microchannel device manufacturing, limitations must be addressed. In the economic assessment model for example, factors like interest, tax, profit, and management factors are not considered. The cost of raw materials and consumables is assumed independent of production volume which does not account for economics of scale effects. Although labor and maintenance are considered as cost categories, they are not completely addressed in environmental impact assessment. Standard methods do not yet exist to estimate the environmental impacts of labor. Due to the lack of information, environmental impact of other maintenance is not considered, the tool material composition is assumed as iron and steel. For tools with unknown weight, weighs are calculated based on footprint and a density assumption. Finally, to assist users decision making, cost and environmental impact weighting approaches should be incorporated to the model framework to further facilitate robust decision making.

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CHAPTER V

CONCLUSIONS

5.1 Summary

Characterized as innovative and efficient, microchannel process technology (MPT) exhibits significant advantages in heat transfer. To justify high volume production of configurations validated as prototypes, and to select from among the plethora of manufacturing techniques according to sustainable manufacturing requirements, an evaluation of the manufacturing economics and environmental impacts is needed.

An integrated process-based economic and environmental assessment model is developed for microchannel device manufacturing. Given the process parameters and geometry information for a microchannel device, cost and environmental impacts of the associated manufacturing process flow can be estimated quantitatively, thus provides a more thorough understanding of the microchannel device manufacturing. By illustrating cost and environmental impacts of microchannel device manufacturing at different production volumes and breaking down the results by process types, cost and environmental impact categories, evidence can be given for selecting among manufacturing alternatives and for identifying potential improvements opportunities to achieve lower cost and less environmentally impactful manufacturing processes. The modeling methodology for estimating cost and environmental impacts was described, followed by application of the methodology to assess several scenarios for producing a microchannel heat recovery unit

(HRU) to demonstrate the use of the model. A graphical user interface (GUI) was also created to help users manipulate the model.

5.2 Conclusions

As a result of the work conducted in this research, several conclusions can be drawn:

- The cost per device decreases asymptotically as the production volume increases. At low production rates, tool depreciation, labor, raw materials and consumables are significant cost drivers, while at high production rates, raw material, consumables and tools account for majority of the cost. These latter costs are insensitive to increasing production volume on a per-device basis.
- Overall environmental impact per device decreases as the production volume increases, however, the level of decrease is minor. At all production rates, utilities and consumables are the main contributors to the environmental impacts of microchannel device manufacturing.
- Microchannel heat recovery unit (HRU) manufacturing *Scenario 5*, which assumed laser cutting and diffusion brazing, was shown to have the lowest cost, but exhibited the highest environmental impacts. *Scenario 3*, which assumed photochemical machining (PCM) and laser welding, exhibited the lowest environmental impact, but had comparatively high cost.
- PCM outperformed laser cutting in environmental impact assessment, however, it was a more expensive patterning process. Diffusion brazing exhibited the lowest

cost among the three bonding process candidates, however, its environmental impact was the highest. Due to the fact that the cost and environmental impacts of laser cutting and laser welding are dependent on the tool path length, results can vary for a specified microchannel device function based upon the design.

- Cost and environmental impacts results obtained using this model can be integrated using weighting methods to facilitate process selection. An illustrative example is provided in Appendix B, along with a brief discussion of approaches that have been developed in prior work.

5.3 Contributions

This work represents several unique contributions to the research community that build upon prior work reported in the literature:

- Based on prior research, this is the first reported work that demonstrates the calculations for the bottom-up process-based cost modeling method for microchannel device manufacturing in detail. This will enable other researchers to more broadly apply these methods in future work. Automation for exploring a range of production volumes is realized by designing a graphical user interface for the spreadsheet model.
- The environmental impact assessment approach proposed in this work is the first reported process-based manufacturing-oriented environmental impact assessment method that analyzes the environmental impacts for a range of production

volumes with impact breakdowns for tools, utilities, consumables, raw materials, and facilities. Given this breakdown, the primary sources of environmental impacts can be identified.

- This is the first known model for microchannel device manufacturing which can benefit decision makers by providing quantitative evidence of manufacturing cost and environmental impact for assisting process selection and identifying potential process improvements. This can enable the microchannel device manufacturing industry to produce lower cost and less environmentally impactful products, while working to achieve a more sustainable future.

5.4 Research Limitations

While the model establishes a framework for economic and environmental impacts of microchannel device manufacturing, limitations remain that must be addressed by future work. In the economic assessment model for example, factors like interest, tax, profit, and management factors are not considered. The cost of raw materials and consumables is assumed independent of production volume, which does not account for economies of scale effects. Although labor and maintenance are considered as cost categories, they are not specifically addressed in environmental impact assessment modeling. Standard methods do not yet exist to estimate the environmental impacts of labor, while information about the maintenance activities for the equipment, systems, and facilities considered is unknown. Tool material composition is assumed to be iron and steel; this equipment will also require plastics, electronics, and other materials and components. For tools with unknown weights, weights are calculated based on the tool footprint and a "density" (kg/m^2) assumption.

5.5 Opportunities for Future Research

Due to the limitations of the work reported in this thesis, several opportunities for future research exist:

- The cost model proposed in this research only accounted for the process-based manufacturing cost, which is the foundation of a company's cost control and decision making, however, it fails to reflect real-world manufacturing. In order to improve the model for a more comprehensive estimation, considerations like interest rates, taxes, profits, and management costs should be incorporated. This will require an analysis of the cash flow of microchannel device manufacturing and a study of company strategy.
- In order to achieve more comprehensive environmental impact assessment for manufacturing processes, impacts of labor and maintenance need to be included. To address the environmental impacts caused by labor, a method to characterize and quantify the possible environmental impacts caused by the labor is required. To address the environmental impacts caused by maintenance, a study of tool information is needed to clarify the specific maintenance for each tool so that maintenance environmental impacts can be estimated. By doing this, a more accurate estimate of tool environmental impacts can also be achieved.

- A manufacturing process cannot be guaranteed to be cost-effective and environmentally friendly simultaneously. When facing a trade-off between cost and environmental impacts, value judgment from a decision maker is needed. To incorporate a decision maker's preferences into the model framework, cost and environmental impact weighting methods are needed. An approach to normalize and weight the environmental impact and cost should be developed. Alternatively, other multi-objective decision making approaches could be explored.

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APPENDICES

Appendix A. Spreadsheet graphical user interface

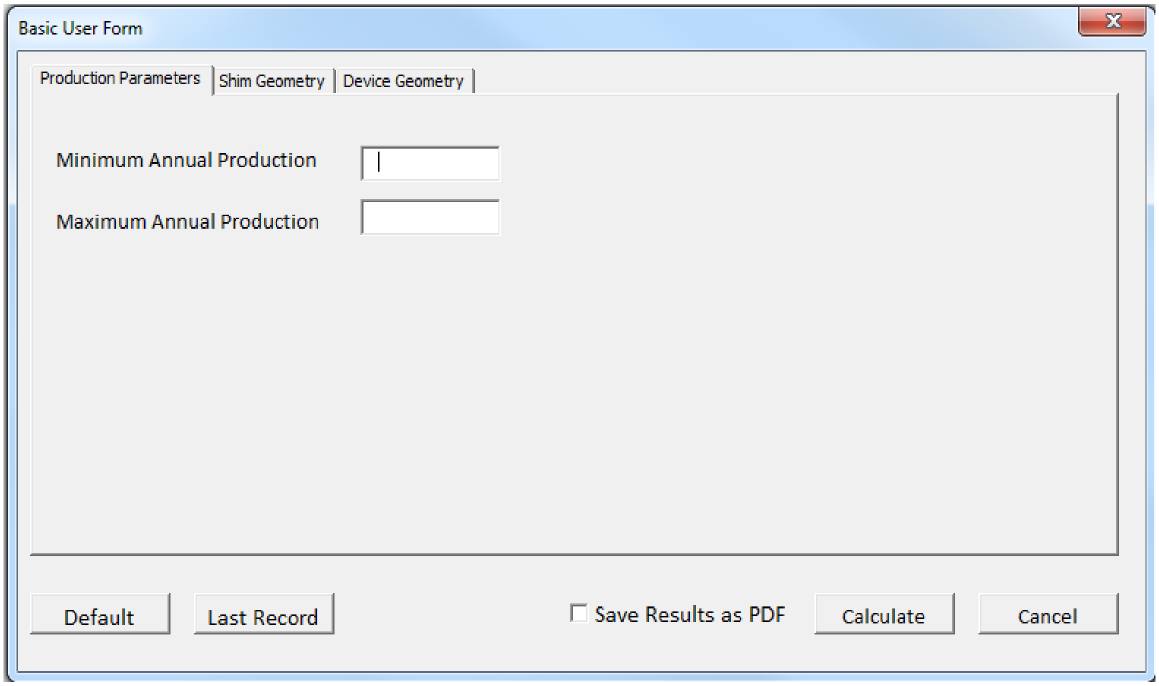

Figure A.1. Production parameter tab of graphical user interface

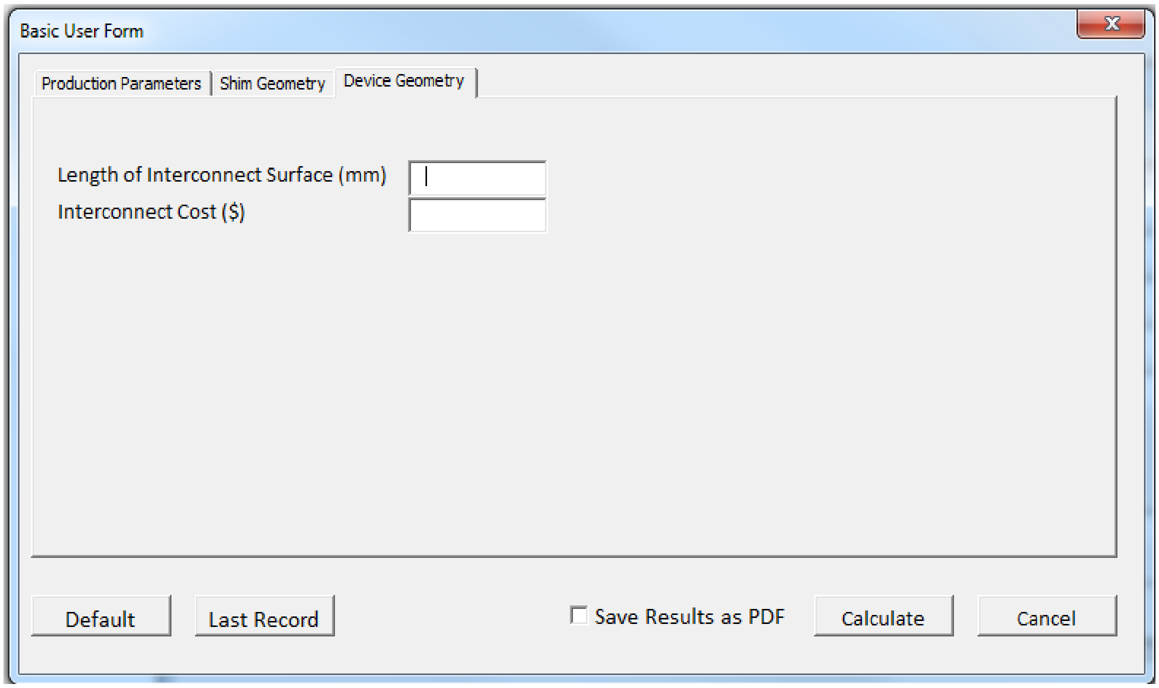

Figure A.2. Device geometry tab of graphical user interface

Appendix B. Weighting approach example

To facilitate manufacturing process comparison and selection, cost and environmental impact results obtained can be integrated according to decision makers' preferences with a weighting method. Weighting methods have been developed in prior work to incorporate multiple criteria into decision making. Approaches include the Analytical Hierarchy Process (AHP), developed by Thomas Saaty in 1980 (Saaty, 1980), and the PROMETHEE method, proposed by Brans and Vincke (1985) (Pohekar and Ramachandran, 2003), among others. Following is a simple decision making method that can be utilized for this model, where normalization and weighting are included.

- Normalization: In order to integrate cost (e.g., dollars) and environmental impacts (e.g., ReCiPe Points), a normalization process is needed to convert the cost and environmental impacts into a common unit. This can be realized by choosing a baseline scenario and normalizing the data based on the ratio of one over another.
    - First, choose one from among the scenarios of interest as the baseline scenario, and acquire the cost and environmental impact score at a selected production volume. This production volume is determined based on decision makers' interest (e.g., the knee of manufacturing cost, the high end of production volume estimated, or production capacity). For example, the decision maker may be interested in comparing *Scenario 1* and *Scenario 2* for HRU manufacturing at a production volume of 20,000,

where cost per device starts to stabilize. Table B.1 gives an example of acquired data.

Table B.1. Cost and environmental impacts of *Scenario 1* and *Scenario 2* at a production volume of 20,000 devices/year

	Scenario 1	**Scenario 2**
Cost ($/Device)	728.65	554.92
Environmental Impacts (Pts/Device)	295.45	1765.16

- The normalized data (N) of one scenario is calculated as a ratio of the cost/environmental impacts of the scenario over the selected base scenario. Table B.2 illustrates the normalized data for Table B.1, where *Scenario 1* is chosen as base scenario.

Table B.2. Normalized cost and environmental impacts of *Scenario 1* and *Scenario 2* at a production volume of 20,000 devices/year

	Scenario 1	**Scenario 2**
Cost ($/Device)	1.00	0.76
Environmental Impacts (Pts/Device)	1.00	5.97

- Weighting: In order to incorporate users' preference of cost or environmental impacts into the decision making, a weighting method is needed.
    - Weighting scores can be assigned to cost (W_c) and environmental impacts (W_{EI}) according to decision makers' judgment, where

$$W_c + W_{EI} = 1 \tag{B.1}$$

$0 \leq W_c \leq 1.0$, and $0 \leq W_{EI} \leq 1.0$.

    - To get a single score (N) where cost and environmental impacts are integrated, weight of cost (W_c) and environmental impacts (W_{EI}) can be applied by multiplying the weight by the normalized cost (N_c) and environmental impacts (N_{EI}) as follows:

$$N = W_c * N_c + W_{EI} * N_{EI} \tag{B.2}$$

Table B.3. Weighting result of *Scenario 1* and *Scenario 2* at a production volume of 20,000 devices/year

	Weighting score	**Scenario 1**	**Scenario 2**
Cost ($/Device)	0.7	0.70	0.53
Environmental Impacts (Pts/Device)	0.3	0.30	1.79
Single score	-	1.00	2.32

Table B.3 exhibit the weighting results where a 0.7 weight score is assumed for cost and a 0.3 weight score is assumed for environmental impacts. According to the result, *Scenario 1* outperforms *Scenario 2* at such circumstance. The method described above can only be utilized by comparison between two Scenarios.