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Enhancing Energy and Resource Efficiency in Manufacturing Systems at the Process, Machine Tool and Facility Levels

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Enhancing Energy and Resource Efficiency in Manufacturing Systems at the Process, Machine Tool and Facility Levels

by

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Professor Masayoshi Tomizuka, Chair
Professor Sara Beckman
Associate Professor Duncan Callaway

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Abstract

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Energy and resource efficient manufacturing is becoming increasingly important due to scarcity of natural resources, stricter regulations and increasing customer demand for sustainable products. According to the Energy Information Administration, the industrial sector accounted for about one-third of total U.S. energy consumption in 2017. Research has shown that machine tool design is responsible for 40% of energy use while machining processes demand 22% of total energy consumption. The manufacturing sector is a significant contributor to environmental damage and resource use, and therefore there is ample opportunity for improving energy and resource efficiency. To address these issues, this dissertation proposes approaches to evaluate and quantify resource use of manufacturing across three hierarchical levels: process, machine tool, and production facility; these methods are used to assess current performance and provide effective approaches to reduce future resource consumption.

Depending on the scale of the system considered, different strategies can be applied to optimize the efficiency of manufacturing systems. In order to offer a systematic study, this dissertation is structured according to increasing system scale: First, at the individual process level, the design of experiments (DOE) method was applied to study the effect of the main machining parameter such as feed rate, spindle speed and drill diameter. A case study of drilling operations on multi-layer printed circuit boards (PCBs) was conducted to find the optimal cutting parameters for achieving high cutting performance that can avoid additional deburring process. A plan of experiments was performed to investigate the burr formation mechanism. In the end, a micro-drilling burr control chart was proposed for process planning.

The second part of this work focuses on machine tool level solutions. Changing the cutting parameters alone will not result in an optimal solution since there are other components in the production equipment that consume resources. Therefore, the scope moves from process planning to the machine tool level. A lot of studies tried to quantify the energy consumption of machine tools, but few of them have looked into other resources such as water. To fill this gap, a water footprint assessment of the milling machine tool was conducted, following ISO

14046 standards. A case study of face-milling on aluminum alloy was examined. The water inventory of a milling machine was calculated, and a water scarcity footprint was estimated to assess the associated impacts. Uncertainty analysis was conducted to assess the potential bias from different plant locations.

The third part of this work focuses on factory level solutions. Numerous studies have implemented value stream mapping to improve the production facility in terms of productivity, but energy information is often left out. Therefore, a construction of an environmental value stream map (E-VSM), which integrates environmental metrics into conventional value stream mapping, is presented. Through the construction of an E-VSM, a case study evaluates the performance of a cover glass manufacturing facility in China. Improvement strategies have been provided to increase productivity, as well as reduce environmental impacts. Uncertainty analysis was carried out to find out how geographic locations might affect the results.

This research has developed and evaluated effective approaches for the analysis of energy, water, and other resource use in manufacturing systems on different levels. The presented work allows manufacturers to better understand the resource consumption of manufacturing activities, and provides effective strategies to reduce the associated impacts.

To Yungkan, Athena, and Victoria.

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Chapter 1

Introduction

The United States is a highly developed and industrialized country. Figure 1.1 shows the industrial sector, which includes manufacturing, mining, agriculture, and construction, accounted for about one-third of total U.S. energy consumption in 2017. Manufacturing operations consume significant amounts of energy. According to the 2014 Manufacturing Energy Consumption Survey (MECS), manufacturing alone consumed 19045 trillion British thermal units (Btu). In the International Energy Outlook 2016 [16], worldwide industrial sector energy consumption is projected to increase by an average of 1.2%/year, from 222 quadrillion British thermal units (Btu) in 2012 to 309 quadrillion Btu in 2040.

Industrial activity has a large environmental burden associated with it. Manufacturing consumes both renewable and non-renewable materials, as well as significant amounts of energy, resulting in substantial stress on the environment. Machine drives, which are primarily electric motors, pumps, and fans, account for about half of the manufacturing sector's delivered electricity use and 8% of the sector's total fuel consumption. Their wide use across many industries results in a substantial impact on the demand placed on power grids.

ANSI/ISA-95.00.01-2000 [3], Enterprise-Control System Integration Part 1: Models and Terminology, describes the levels of functions and domains of control associated with manufacturing organizations. Using the equipment model hierarchy model prepared by the American National Standards Institute (ANSI), the physical layout of the factory can be organized into a hierarchical fashion as shown in Figure 1.2. A hierarchy of manufacturing can be categorized into five levels: enterprise, facility, production line, machine tool, and manufacturing process [25]. An enterprise is a collection of one or more facilities and may contain sites and areas. The enterprise is responsible for determining what products will be manufactured, at which sites they will be manufactured, and in general how they will be manufactured. At the facility level, it may contain multiple production lines. A geographical location and main production capability usually identify a facility, e.g., Berkeley City Manufacturing Facility. A production line is a logical organization of devices in the system that are acting in series or parallel to execute a specific activity, such as manufacturing a part or assembly. At the device level, a machine tool performs a unit process. A production line consists of a group of machine tools that is usually organized to achieve some special

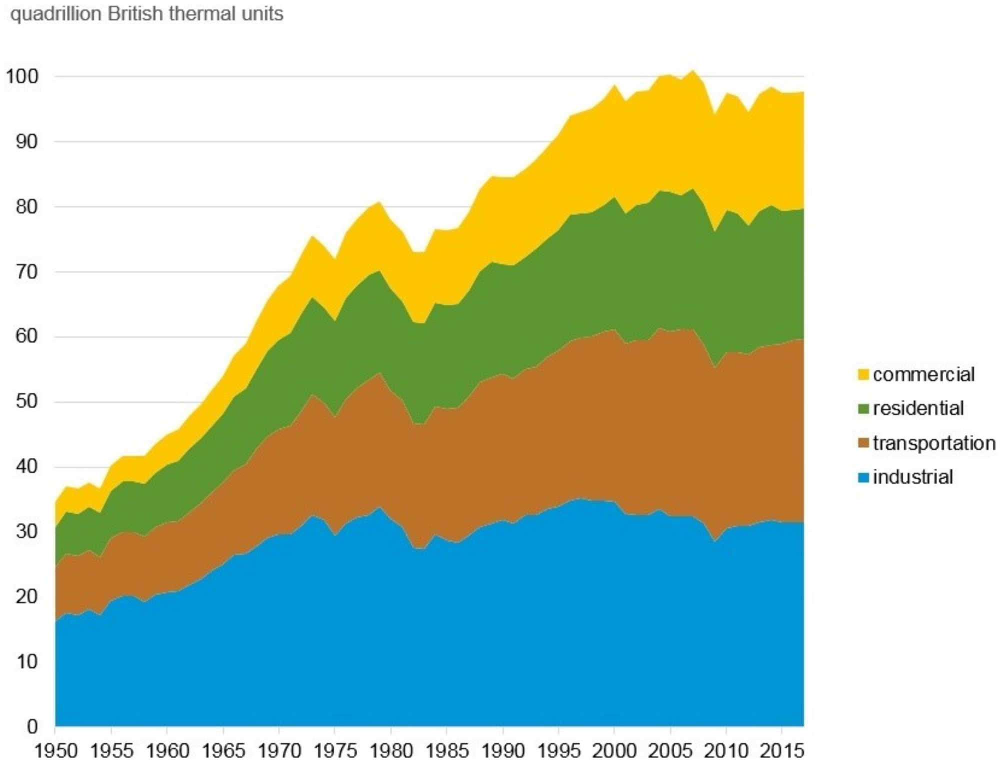


Figure 1.1: U.S. total energy consumption by end-use sector, 1950-2017 [26]

purpose. The major processing activity often identifies the production line, e.g., hydraulic cylinder assembly line. The supporting equipment of the unit process is included here, such as the cutting fluid circulating system. In this dissertation, only the lower three levels of the hierarchical model (production line, machine tool, manufacturing process/tool interfaces) are studied in detail. Chapter 2 presents previous research that has been conducted on energy and resource consumptions in manufacturing: (1) reviewing the existing tools and methods that support resource-related analysis (2) reviewing energy and resource efficiency research studies on three different levels of manufacturing systems, including process level, machine tool level, and facility level.

Depending on the scale of the considered system, different strategies can be applied to optimize the manufacturing system. In order to offer a systematic solution to manufacturers, the unit process level will be studied, starting with Chapter 3 which focuses on process parameter design. Chapter 3 aims to study the characterization of machine-material interactions and the identification of optimal machining parameters. Through experimental investigation, an industrial drilling problem will be explored.

However, changing the machining parameters alone will not result in the optimal solution for energy saving, since there are many components that contribute to energy consumption. Current environmental impact assessment of machining processes is limited. Life cycle as-

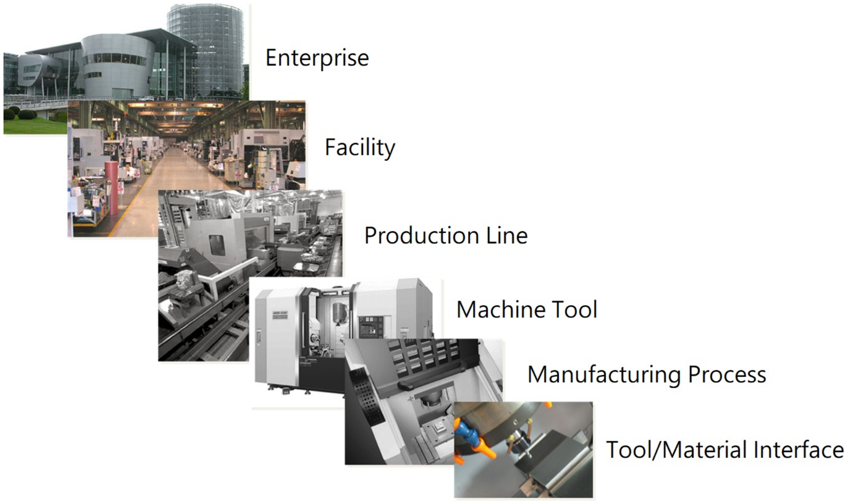


Figure 1.2: The spatial scope of manufacturing system (Derived from Dornfeld [23])

sessment aims at quantifying potential environmental impacts generated by human activities on a wide range of environmental issues. The water footprint is only a fraction of all those impact categories. Therefore, Chapter 4 aims to help the manufacturers preserve energy and water resources in the use of machine tools.

Machine tools do not operate independently; they make up manufacturing lines, work departments, and operate within the confines of a factory to produce a mixture of products. Deciding to reduce the machining time for one part in order to reduce energy consumption may unintentionally result in an increase in idle time and, consequently, idle energy consumption as well. In order to be more effective in suggesting sustainable manufacturing strategies, the scope of assessments must be widened to the factory level. Chapter 5 therefore aims to optimize production lines by implementing environmental value stream mapping (E-VSM). Since E-VSM was proposed, only a handful studies have addressed the applicability of E-VSM. This chapter concerns the application of E-VSM. This chapter studies process efficiency and environmental impact of shop floor - specially emphasis on cover-glass manufacturing facility in China. A case study will be presented which implemented environmental value stream mapping (E-VSM). By visualizing the information (e.g., customer demand, process time, defect rate) and material flows between stations, the study will provide effective strategies to reduce production wastes as well as environmental impact.

By presenting the optimization of process parameters, production equipment and factory operations, this dissertation will provide a cross-level study of energy and water in manufacturing and recommend effective methods that can be used beyond these case studies and industries to reduce environmental impact. By strategically building resource efficiency decision-making into production, manufacturers can achieve more strategic control over rising environmental costs.

Chapter 2

Background and Literature Review

This chapter begins by providing a brief overview of the tools and methods that can be used to perform a manufacturing analysis. The second section presents energy and resource efficiency studies in manufacturing.

2.1 Tools and Methods in Manufacturing

Over the past few decades, the growing concern about climate change and resource deprivation have increasingly changed the attitudes of industry towards the environment. Resource management in manufacturing has become increasingly important topic for industry and academia. For a shift toward resource efficient manufacturing, proper tools are required to model and assess resource consumption in a manufacturing environment. This section comprises the methods and tools available which mostly provide support in making energy related analysis and decisions in manufacturing environment.

Currently, many tools and methods exist that support resource-related analysis. According to the literature [70], these supporting tools and methods can be classified into four main groups: (1)modelling and analysis (2) emission calculation and sustainability (3) energy assessment (4) benchmarking (see Figure 2.1).

Manufacturing information modelling is the most important technique used for evaluating manufacturing processes. During the last decades several process modelling methodologies have been developed to understand, evaluate and optimize performance. Energy modelling and analysis is a challenging task due to the complexity of a machining system. Peng et al. [86] provided a brief review of energy modelling research in the machining domain, and presented two case studies to demonstrate the energy demand model of (1) a small 3-axis milling machine (2) an industrial production line. He et al. [42] proposed a modeling method to characterize the task-oriented energy consumption for manufacturing system that consists of several machine tools. Smith and Ball [100] developed guidelines for material, energy and waste process flow modelling, and illustrated its application in a case company.

A second group of methodologies concerns the emission calculation. Life cycle assessment

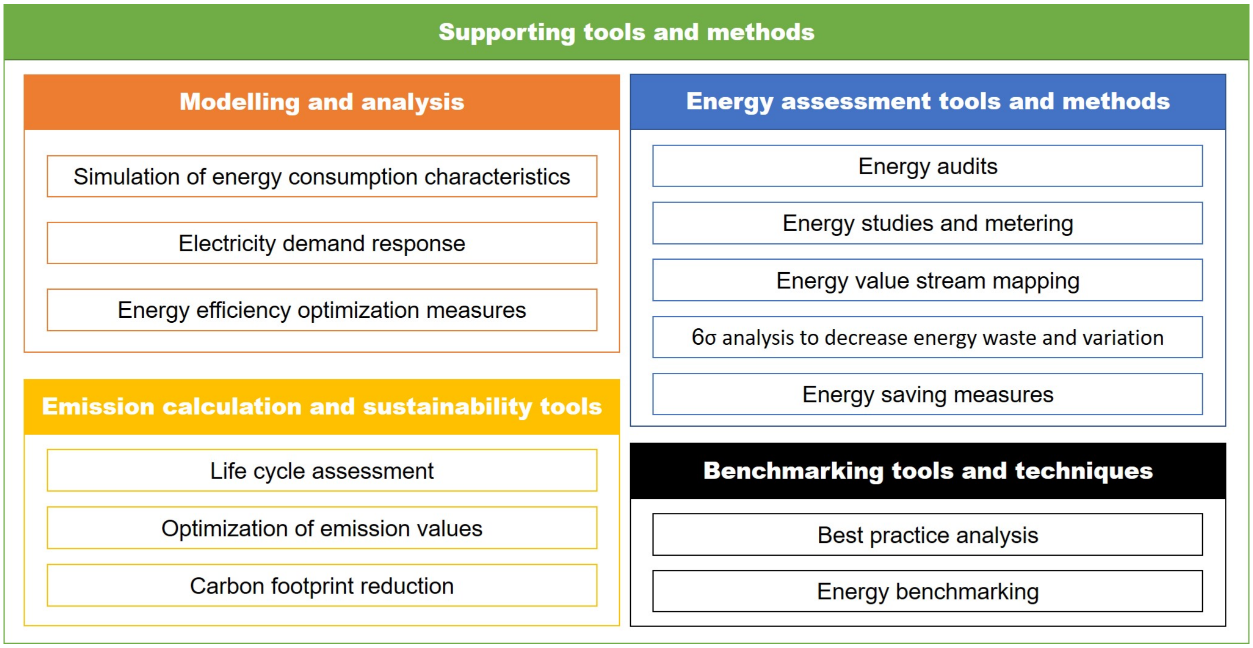


Figure 2.1: Supporting tools and methods in evaluating manufacturing processes (modified from [70])

is a very popular analysis for reporting environmental impacts of a product or service. It has been a powerful tool to assist manufacturers to evaluate the environmental impacts of the processes, and help stakeholders to make better choices. In the field of manufacturing systems, many studies reviewed the environmental impacts of manufacturing activities. Serres et al. [97] used SimoPro (7.1) to calculate the life cycle inventory of direct additive laser manufacturing, and its associated endpoint impacts. Faludi et al. [33] compared the environmental impacts between additive manufacturing and traditional machining through LCA. Kellens et al. [60] calculated the environmental impacts of three types of electrical discharge machining processes. Given that severe freshwater scarcity is a common phenomenon in many regions of the world, the LCA community has started pushing the development of comprehensive methods for water accounting. The water footprint concept was introduced by Hoekstra [45].

The third cluster of research studies explores the resource-related problems. These studies develop energy assessment models that include algorithms and architectures for process planning and scheduling. Value stream mapping (VSM) is a powerful tool that can be used to identify non-value-added activities and fulfill lean concepts. Muller et al. [79] presented energy value stream mapping which incorporates information about process energy consumption into traditional VSM. Papetti et al.[84] proposed resources value mapping to optimize the use of energy and resources. Other extended methods include Environmental VSM [89], Green VSM [18], Sustainable VSM [35].

The final cluster concerns benchmarking. Energy benchmarking can be applied on different levels of manufacturing (e.g. sector, country or process levels), depending on the research goal. There are few studies for benchmarking at plant and process levels, since these research attempts mostly focus on national and industrial sector levels. Laurijssen et al. [65] conducted energy benchmarking comparisons in 23 Dutch paper mills. Worrell and Price [110] developed an integrated benchmarking and energy savings tool for the iron and steel industry. Saygin et al. [96] provided a detailed overview of the energy use in energy-intensive sectors at country-level. However, existing studies solely focus on measuring energy use, ignoring positive or negative effects that energy saving may have on other environmental impacts such as emissions of pollutants.

2.2 Energy and Resources Use in Manufacturing

2.2.1 Process Level

Different strategies can be considered while aiming for the reduction of energy and resource use at the process level. The selection of process parameters can have a significant influence on energy and resource consumption. Mori et al. [77] showed that the energy consumption for drilling and face/end milling can be reduced by adjusting the cutting conditions, such as cutting speed, feed rate and cutting depth. Diaz et al. [19] explored the effect of the material removal rate on energy consumption by changing the feed rate, width of cut, or depth of cut. Newman et al. [80] addressed that energy consumption can be reduced using the optimum choice of cutting parameters. According to the literature [25], the optimization of process parameter settings can reduce energy consumption of the machine tool by 10%.

Beside the analyses of the influence of changed process parameters, tool path design can also increase the efficiency of machining processes. Kong et al. [63] showed that tool path design affects the processing time as well as energy consumption. Aramcharoen and Mativenga [4] assessed alternative toolpath design and identified opportunities for energy reduction.

2.2.2 Machine Tool Level

According to the study Market Report 2017 by the German Machine Tool Builders Association [5], the world production of machine tools represents EUR 71.7 billion. The increasing demand for machinery and production systems to be more energy-efficient is a relatively new challenge for machine designers. The International Organization for Standardization recently developed the first two parts of a new International Standard for the environmental evaluation of machine tools. ISO 14955-1 [56], Part 1: Design methodology for energy-efficient machine tools, addresses the energy efficiency of machine tools during their working life. ISO 14955-2 [57], Part 2: Methods for measuring energy supplied to machine tools and machine tool components, supports the energy-saving design methodology according to ISO 14955-1 by providing practical methods for measuring the energy supplied to machine tools.

Except the ongoing ISO efforts on environmental evaluation of machine tools, there are also many research studies on energy-efficient machine tools. Diaz et al. [20] analyzed the energy consumption and CO_2 emissions of two milling machine tools. Li et al. [66] investigated the energy consumption of 6 different machine tools. Figure 2.2 illustrates the power profile of an exemplary turning process. Mognol et al. [74] investigated the energy consumption of three rapid prototyping systems: Thermojet (3DS), FDM3000 (Stratasys) and EOSINT M250 Xtended (EOS). Balogun et al. [6] created an energy consumption model for turning and milling which includes the basic state, the ready state, and the idle state.

At the machine tool level, there is an ample research into life cycle assessment of production equipment, as well as energy reduction of machine tools. However, there are other important resources that needs more attention besides energy. Water, for instance, is an essential resource that needs more research attention. Zhao et al. [118] studied the water consumption of machine tools. The International Organization for Standardization recently established ISO 14046 [55] standard which specifies principles and guidelines of water footprint assessment. This newly published standard can help researchers better understand the environmental impacts of machine tools resulting from water use.

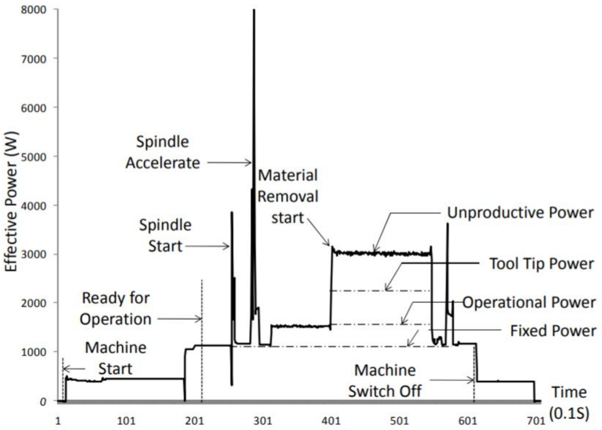


Figure 2.2: Power profile of a turning process [66]

2.2.3 Factory Level

Herrmann and Thiede [44] present a holistic view of a production facility. Figure 2.4 shows the energy and resource flows within a production facility. The influencing variables are the local climate at the production site and the exhausted air and waste emitted by production machines. Besides that, machine tools need energy, mostly electricity, and other resources such as compressed air and cooling water.

There is ample research into factory production planning and scheduling. Feng et al. [34] proposed a multi-objective optimization of a shop schedule which considers both productivity and energy. Zhang et al. [117] analyzed the trade-off between electricity cost and carbon

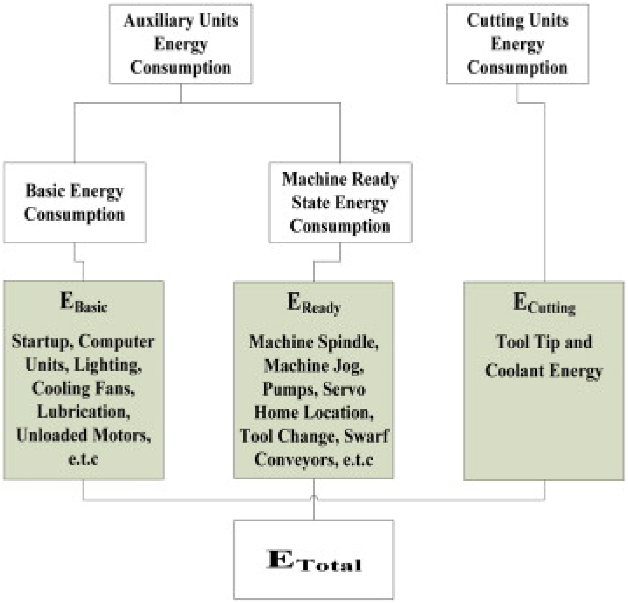


Figure 2.3: Machine tool electrical consumption estimation model [6]

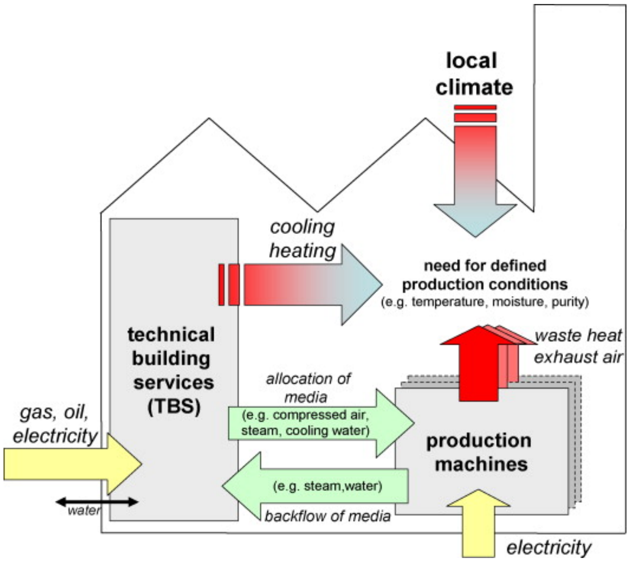


Figure 2.4: Energy and resource flows in a production facility [44]

footprint emissions using flow shop scheduling. Yan et al. [113] explored the potential of energy saving for shop floor management, and proposed a multi-level optimization method for energy-efficient shop scheduling.

At the factory level, many research studies have shown successful improvements in reducing energy consumption through facility scheduling. However, the energy models of machine tools adopted in these scheduling methods are simplified in many ways. Additionally, the integration from factory level to machine tool level is largely absent from the literature but offers a continuum of benefit that can be progressively exploited [95].

Chapter 3

Optimization of Machining Parameters in Drilling Printed Circuit Boards

3.1 Background

As miniaturization continues to propel the industry, fabricating electronics and manufacturing printed circuit boards (PCBs) is becoming more challenging. The shrinking feature sizes of electronics often increases the number of layers used in PCBs, and requires manufacturing process tolerances to be reduced. The hole drilling process occurs when the PCBs have already gained a high value. Drilling burrs cause several problems for product quality and functionality. The deburring process is especially difficult due to bad accessibility and tight tolerances. Since the scale of drilling burrs in PCB manufacturing processes is small, they are usually difficult to remove. It is estimated that deburring and edge finishing on precision components constitute 30% of the cost of the finished part [38]. The formation of drilling burrs has several undesirable features with regard to product quality and functionality. Therefore, reducing burrs is very important in micro-drilling. This chapter investigates the drilling burr formation mechanism, selects optimum drilling process parameters to minimize burr size at the production stage, and develops a micro-drilling control chart to predict and control drilling burrs.

According to the printed circuit board report by Lucintel in 2018, the global PCB market is expected to reach an estimate $80.1 billion by 2023 [67]. As people's demand for IT products is growing, the demands for circuit boards will keep growing. Lucintel forecast that the average growth rate for global PCB market value from 2018 to 2023 is 3.3%. Previous research has focused on drilling burr formation of steel. Min et el. [73] have done comprehensive experiments and developed a drilling burr control chart for low alloy steel. Watanabe et al. [105] have studied the correlation between radial run-out and the hole quality in drilling PCBs. Dornfeld et al. [22] have investigated the effects of tool geometry as well as process conditions on drilling burr formation. Both drilling process and PCB structure design have been studied extensively. However, research efforts on the drilling process of multilayer PCBs are still lacking. This chapter aims to fill the gap by developing a Drilling Burr Control Chart (DBCC) of the PCB drilling process. The presented research employed Taguchi method to determine the best combination values of drill diameter, spindle speed, and feed to minimize burr height.

3.1.1 What are PCBs

A PCB is a thin plate made of one or more layers of insulating board (also known as substrate), which supports electronic components and connects them electrically, using conductive pathways, tracks, or signal traces. PCBs are used in almost every kind of electronic device, ranging from toys to sophisticated radar systems.

There are three major types of PCB construction: single-sided, double-sided, and multi-layered. In single-sided construction, all components are placed on one side of the board. Double-sided PCBs are used when the number of components is too large to allow single-sided construction within the designated space. A multi-layered board has several printed circuit layers separated by layers of insulation. The electronic components on the surface are connected through plated holes drilled down to the appropriate circuit layer, which simplifies the circuit. Figure 3.1 shows how a multi-layer PCB is made. The most common substrate used for PCBs is glass fiber reinforced epoxy resin with copper foil bonded to the surface. Drilling processes create the holes for the electronic components to be placed on PCB surfaces.

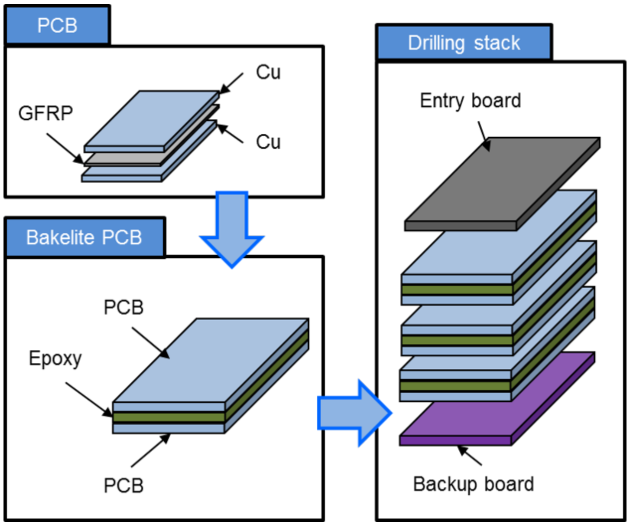


Figure 3.1: Printed circuit board (PCB)

3.1.2 The PCB Fabrication Process

A PCB consists of electronics circuits that are created by mounting electronic components on a non-conductive board, and where conductive connections are created between the laminate layers. Figure 3.2 shows the manufacturing process of PCBs. The beginning step of any PCB manufacture is the design. The designer lays out a blue print for the PCB that fulfills all the requirements. After finalizing the design, a special printer called a plotter is used to print the design of the PCB. It produces a film that shows the details and layers of the board. And then, the cleaned copper panel is coated with a layer of photosensitive film. The film receives a blast of ultraviolet light which hardens the photoresist materials through the translucent parts of the film, and defines the copper pattern. An etching process is used to remove unwanted copper from the board. Holes are drilled into the PCB to help with the alignment and the electrical connections within multilayer PCBs. Then, the PCB goes to plating and other processes in outer layer image transfer. This study will be focused on the drilling process and the following deburring process.

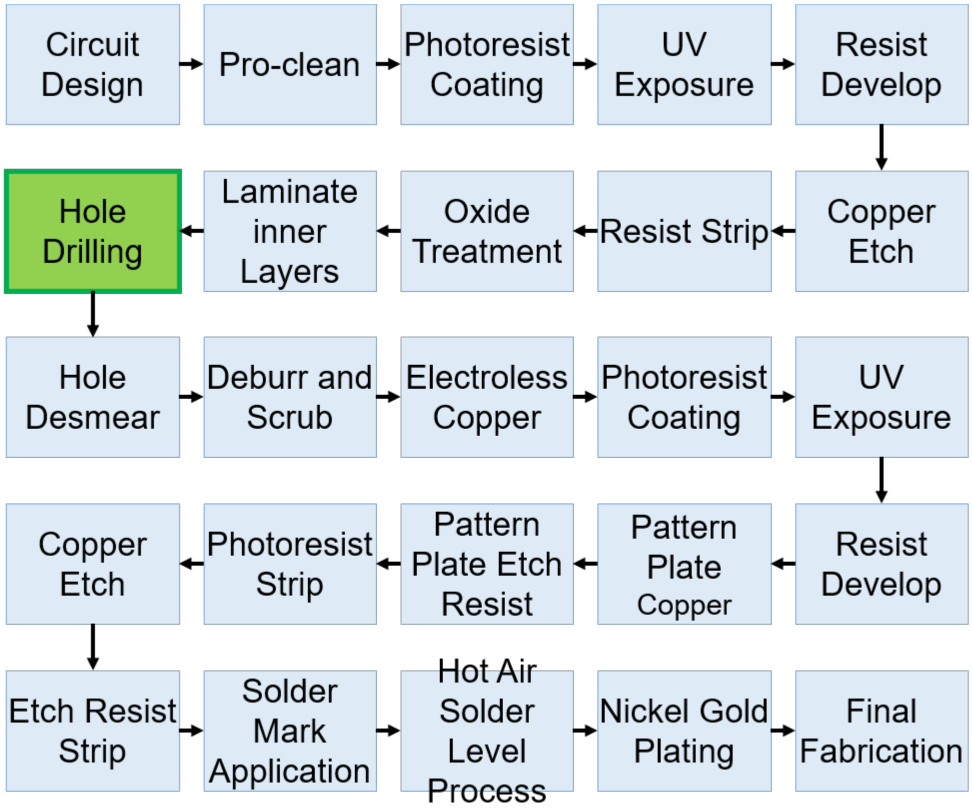


Figure 3.2: Process flow diagram for PCB manufacturing

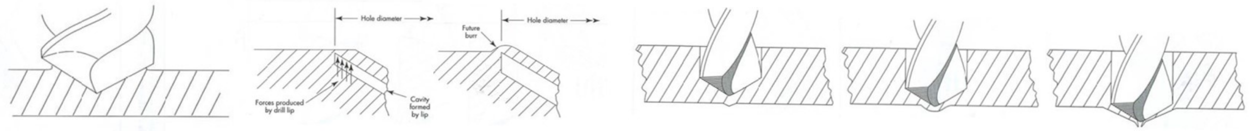
3.2 Micro-drilling Process

The holes through the PCB are used for either electro-connection among layers or mounting boards together. For the former, the inside surfaces of the holes are plated with copper to provide a conductive circuit from one side of the board to the other. For mounting the boards together, non-conducting holes are first plugged to keep them from being plated. Then the plugs are taken out and the boards are connected with components. There are plenty of machining processes that can achieve the required hole quality, including laser, plasma, and chemical machining. Mechanical drilling remains the most popular method, because it delivers higher quality as well as greater productivity [115].

Since the drilling process influences the shape of burrs and therefore the deburring process, it plays an important role in reducing the cost of PCB production. According to a PCB manufacturing company in Korea, the deburring process can be removed if the burr height is less than 1% of the hole diameter. Therefore, the aim of this study is to find the optimal machining conditions reduce burr height and thus to avoid deburring process.

3.2.1 Burr Formation Mechanism

Understanding the formation of drilling burrs is especially important to be able to minimize the burr or reduce the energy consumption for deburring. A burr consists of plastically deformed material, generated on the part edge during machining. The drilling process produces burrs on both entrance and exit surfaces of a workpiece. Therefore, drilling burrs can be classified as entrance burrs and exit burrs [72]. The drilling burr that forms at the entrance of the hole can be a result of tearing, a bending action followed by clean shearing, or lateral extrusion. If one thinks of the drill lip as a lathe tool entering the hole, it looks similar to Figure 3.3a. The burr that is formed when a sharp drill exits the workpiece is a Poisson burr resulting from rubbing at the margins of the drill. When a normal or worn out drill exits the workpiece, the drill pierces the workpiece and pushes out the uncut material which results in a rollover burr as shown in Figure 3.3b [38].



(a) Burr formation on entrance surface

(b) Burr formation on exit surface

Figure 3.3: Burr formation mechanism [38]

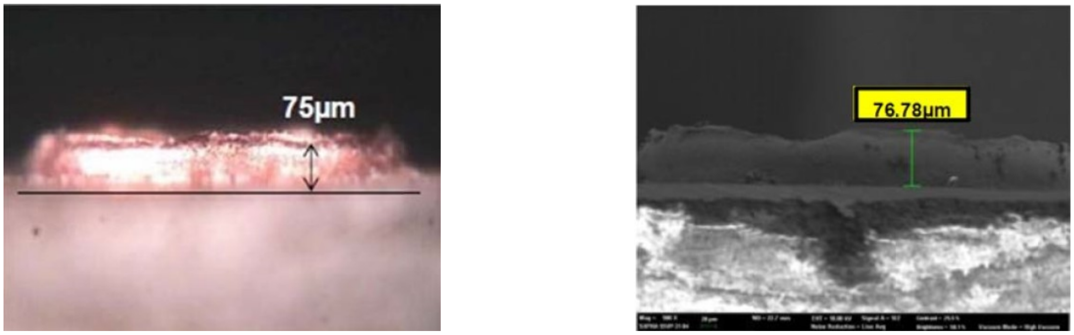
The drilling burr formation reflects the complex interaction of many factors, among the most important of which are listed in Table 3.1. Since the materials being drilled are PCB, the material category is fixed. To reduce the drilling burr, the design of geometry, drilling process conditions and other factors will be focused upon. The basic parameters are feed rate, drill size, and spindle speed, which will be optimized in this study.

Category	**Parameters**
Drill geometry	Drill diameter, point geometry, point angle, helix angle, lip relife angle
Material properties	Hardness, strain-hardening characteristics, ductility, tensile toughness, temperature, and strain rate dependence of properties
Drilling process	Cutting speed, feed
Others	Tool wear, tool material

Table 3.1: Parameters affecting drilling burr formation (modified from [72])

3.2.2 Burr Measurement

The optical microscope CAMSCOPE model SV-32 was used for measuring the burr height. The optical microscope cannot focus on the bottom and the top of the burr at the same time due to its high resolution. One reference line was drawn at the bottom of the burr, and the other reference line was drawn on the tip of the burr parallel to the first line, as shown in Figure 3.4a. The burr height was measured by calculating the distance between the two reference lines [7]. An optical microscope is generally easy to use and fast, but it cannot be used for burr heights less than 25 μm.



(a) Optical microscope

(b) SEM

Figure 3.4: Burr measurement using different types of equipment

The other measurement method used in this study is scanning electron microscopy (SEM). The scanning electron microscope uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens [11]. The signal that derives from electron-sample interactions reveals information about the sample including external morphology, chemical composition, and crystalline structure. For burr heights larger than 25 μm, SEM and optical microscopes give good matching results. But the accuracy of the optical microscope drops for burr heights smaller than 25 μm. This study has used both measuring techniques to measure the burr heights.

3.2.3 Research Methodology

The major process parameters which influence the burr size and shape observed in experiments are feed and spindle speed. It is reasonable to represent possible ranges of operating conditions for drilling by use of a burr control chart derived from experimental data on burr formation for varying speeds and feeds [24]. The drilling burr control chart (DBCC) for aluminum alloys was first developed by Jinsoo Kim in the Laboratory for Manufacturing and Sustainability at UC Berkeley [62]. Previous research studies have focused on steel, however few of them have investigated multi-layer materials like PCBs. This section concerns the development of a DBCC for PCBs that quantifies the effect of feed rate and spindle speed on the burr height and type. Table. 3.2 presents the research methodology and describes actions taken to investigate drilling burr problems of PCBs.

Steps	**Goal**
Define scope	Investigate opportunities for drilling process improvement through lean principles; Identify important factors
Collect data	Plan parameters & design experiments
Construct current state	Conduct experiments & evaluate results
Identify areas for improvement	Develop DBCC
Design future state	Predict new settings of parameters using DBCC

Table 3.2: Research methodology

3.3 Result and Discussion

3.3.1 Design of Experiment

Drilling experiments with different feed rates (f), spindle speeds (n) and 400μm, 600μm and 800μm diameter drills (d) were conducted. Figure 3.5 shows the microdrill bits used in the experiment manufactured by Neotis Korea Inc.. The specification of the micro drill bits is listed in Table 3.3. Figure 3.6a shows a 3-axis stage manufactured by Justek Inc., Korea, along with a high-speed spindle manufactured by Westwind that are used for the PCB drilling experiment. The PCB drilling experiments were carried out at room temperature, 22 °C, without additional cooling applied to the work piece.

Helix angle	35°
Point angle	130°
1st relief angle	15°
2nd relief angle	30°

Table 3.3: Specification of drill bit

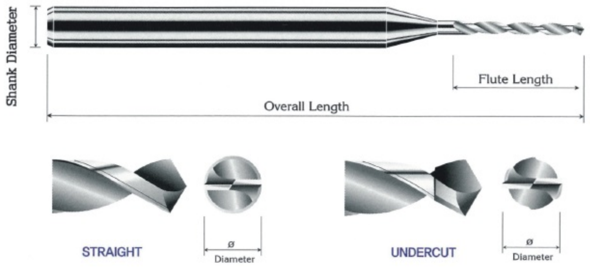
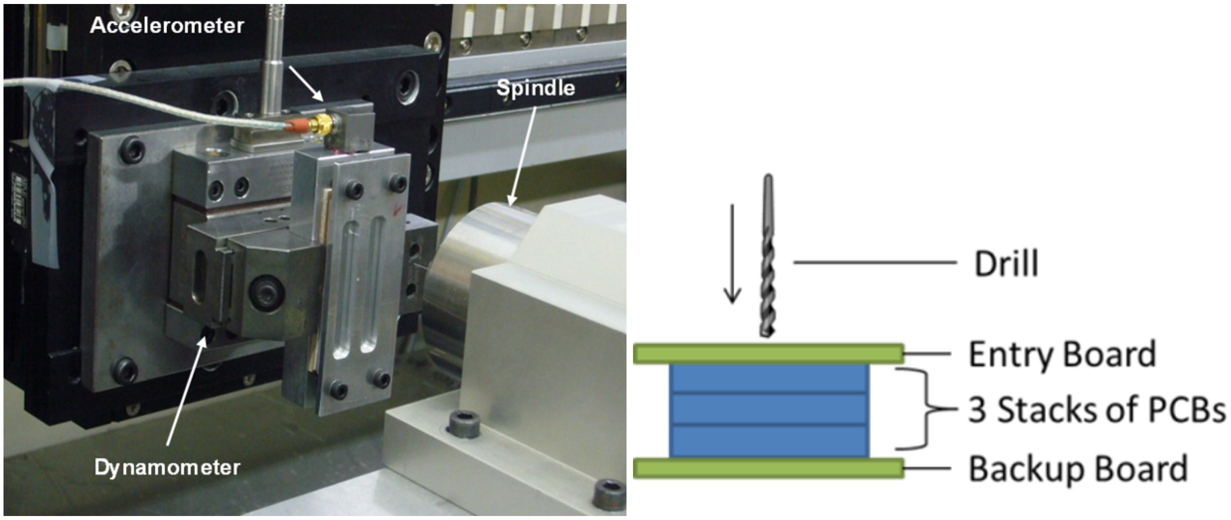


Figure 3.5: Drill bit for microdrilling [7]



(a) Experiment Setup (b) Schematic Diagram of Drilling Process

Figure 3.6: Drilling experiment setup

Figure 3.6b shows the schematically simplified experiment setup. Three stacks of PCBs were drilled with an entry board and a backup board. The entry board is made of aluminum. It not only protects the copper surface, but it widely suppresses the burr that is formed where the drill-bit enters [8]. The backup board is made of wood. It allows space for the drill bit itself to continue through the workpiece without damaging the fixture or the drill. Most drilling processes create a burr on both entrance and exit surfaces [22]. The exit burr was much larger in size and is the main concern in this study.

The three controlled factors that are considered important to the drilling process are spindle speed (n), feed rate (f), and drill diameter (d). The design of experiments (DOE) technique was utilized to characterize the drilling process, as well as to optimize the drilling process, that is, to find the settings of the important factors that result in desirable values of the burr height [76].

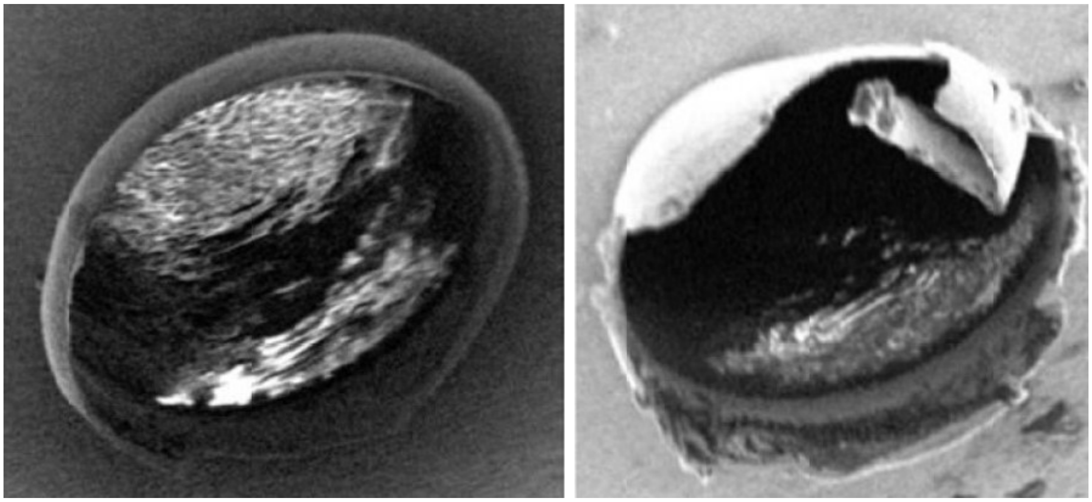
For each drill bit size, three sets of experiments were conducted:

- Case I: Varying spindle speed, maintaining infeed
- Case II: Varying infeed, maintain spindle speed
- Case III: Varying both spindle speed and infeed

A spindle speed of 90000 min^{-1} and infeed rate of 40 mm/s are standard protocol used in the PCB manufacturing industry. As the drill diameter increases, the spindle speed and feed rate decrease. The range of machining parameters will be chosen based on the industrial protocol for PCB manufacturing.

3.3.2 Classification of Burrs

In PCB drilling processes, the burr shape is extremely important, since the quality of the hole and the burr size are determined by it. A series of experiments is conducted to classify burrs into two categories. One is the uniform burr which has a relatively small burr height as shown in Figure 3.7a. The other is the transient burr which has a relatively large burr height and a non-uniform burr shape, as shown in Figure 3.7b.



(a) Uniform burr (b) Transient burr

Figure 3.7: SEM images of drilling burrs for 400μm

3.3.3 The Development of Drilling Burr Control Chart

A dimensionless feed parameter of drilling, $\mathrm{F_n}$, is equal to the feed rate (f) divided by the tool diameter (d) (Equation 3.1). $\mathrm{F_n}$ is calculated by Equation 3.1 and it is the horizontal axis of the chart. The thrust force directly affects the amount of the plastic deformation of the material at the final stage of the drilling process and, as a result, influences burr formation. It is known that an increase in the feed rate in drilling tends to increase the thrust force [62].

$$F_n = \frac{f}{d} \tag{3.1}$$

Along the vertical axis the cutting speed parameter, S, is defined as the product of drill diameter (d), spindle speed (n), and a constant (K), as shown in Equation 3.2. Depending on the cutting speed, the amount of heat generated at the cutting edge changes greatly, influencing some properties of the workpiece material. It also affects the rate of tool wear, especially for the corner wear which is believed to have a large influence in drilling burr formation [62].

$$\begin{gathered} S = K \times n \times d \\ K = 10^{-5} \end{gathered} \tag{3.2}$$

A series of experiments were done to construct the drilling burr control chart (DBCC). Table 3.4, Table 3.5 and Table 3.6 show the experiments performed for 400μm drill, 600μm drill and 800μm drill respectively. Experiments were performed to determine the relationship between the drilling parameters and the burr height. The three independent variables in the experiments were spindle speed, infeed and drill diameter. The dependent variable was burr height. Three drilling trials were conducted for each set of experiments. For each experiment performed, the parameters Fn and S were calculated, respectively.

Figure 3.8 shows the DBCC of PCB which can be used to predict the type of burr produced by different drilling conditions. In accordance with the classification of burr shape, burr height, and tool breakage, the regions in the burr chart are classified into uniform burr, transient burr, preferred burr, drill breakage, and critical burr height regions. The thick line denotes the boundary between uniform and transient burr types.

Table 3.4: Experiment results for 400μm drill

(a) Experimental Plan 1 (Varying Spindle Speed)

Run	Drill Diameter (μm)	Spindle Speed (N, min^{-1})	Feed (mm/sec)	Drill		DBCC	
				OK	Broken	S	Fn
1	400	90000	30	✓		0.36	0.05
2	400	80000	30	✓		0.32	0.056
3	400	70000	30	✓		0.28	0.064
4	400	60000	30	✓		0.24	0.075
5	400	50000	30	✓		0.2	0.09
6	400	40000	30	✓		0.16	0.1125
7	400	30000	30	✓		0.12	0.15
8	400	20000	30	✓		0.08	0.225
9	400	10000	30		✓	0.04	0.45
10	400	9000	30		✓	0.036	0.5

(b) Experimental Plan 2 (Varying Feed Rate)

Run	Drill Diameter (μm)	Spindle Speed (N, min^{-1})	Feed (mm/sec)	Drill		DBCC	
				OK	Broken	S	Fn
1	400	90000	30	✓		0.36	0.05
2	400	90000	40	✓		0.36	0.067
3	400	90000	50	✓		0.36	0.083
4	400	90000	60	✓		0.36	0.1
5	400	90000	70	✓		0.36	0.117
6	400	90000	80	✓		0.36	0.133
7	400	90000	90	✓		0.36	0.15
8	400	90000	100		✓	0.36	0.167
9	400	90000	110		✓	0.36	0.183
10	400	90000	120		✓	0.36	0.2

(c) Experimental Plan 3 (Varying Spindle Speed and Feed Rate)

Run	Drill Diameter (μm)	Spindle Speed (N, min^{-1})	Feed (mm/sec)	Drill		DBCC	
				OK	Broken	S	Fn
1	400	90000	30	✓		0.36	0.05
2	400	80000	40	✓		0.32	0.075
3	400	70000	50	✓		0.28	0.107
4	400	60000	60	✓		0.24	0.15
5	400	50000	70	✓		0.2	0.21
6	400	40000	80	✓		0.16	0.3
7	400	30000	90	✓		0.12	0.45
8	400	20000	100	✓		0.08	0.75
9	400	10000	110		✓	0.04	1.65
10	400	9000	120		✓	0.036	2

Table 3.5: Experiment results for 600μm drill

(a) Experimental Plan 1 (Varying Spindle Speed)

Run	Drill Diameter	Spindle Speed	Feed	Drill		DBCC	
	(μm)	(N, min^{-1})	(mm/sec)	OK	Broken	S	Fn
1	600	90000	30	✓		0.54	0.033
2	600	80000	30	✓		0.48	0.038
3	600	70000	30	✓		0.42	0.043
4	600	60000	30	✓		0.36	0.05
5	600	50000	30	✓		0.3	0.06
6	600	40000	30	✓		0.24	0.075
7	600	30000	30	✓		0.18	0.1
8	600	20000	30	✓		0.12	0.15
9	600	10000	30		✓	0.06	0.3

(b) Experimental Plan 2 (Varying Feed Rate)

Run	Drill Diameter	Spindle Speed	Feed	Drill		DBCC	
	(μm)	(N, min^{-1})	(mm/sec)	OK	Broken	S	Fn
1	600	90000	30	✓		0.54	0.033
2	600	90000	40	✓		0.54	0.044
3	600	90000	50	✓		0.54	0.055
4	600	90000	60	✓		0.54	0.067
5	600	90000	70	✓		0.54	0.078
6	600	90000	80	✓		0.54	0.089
7	600	90000	90	✓		0.54	0.1

(c) Experimental Plan 3 (Varying Spindle Speed and Feed Rate

Run	Drill Diameter	Spindle Speed	Feed	Drill		DBCC	
	(μm)	(N, min^{-1})	(mm/sec)	OK	Broken	S	Fn
1	600	90000	30	✓		0.54	0.033
2	600	80000	40	✓		0.48	0.05
3	600	70000	50	✓		0.42	0.071
4	600	60000	60	✓		0.36	0.1
5	600	50000	70	✓		0.3	0.14
6	600	40000	80	✓		0.24	0.2
7	600	30000	90	✓		0.18	0.3
8	600	20000	100	✓		0.12	0.5
9	600	10000	110		✓	0.06	1.1

Table 3.6: Experiment results for 800μm drill

(a) Experimental Plan 1 (Varying Spindle Speed)

Run	Drill Diameter	Spindle Speed	Feed	Drill		DBCC	
	(μm)	(N, min^{-1})	(mm/sec)	OK	Broken	S	Fn
1	800	90000	30	✓		0.72	0.025
2	800	80000	30	✓		0.64	0.028
3	800	70000	30	✓		0.56	0.032
4	800	60000	30	✓		0.48	0.038
5	800	50000	30	✓		0.4	0.045
6	800	40000	30	✓		0.32	0.056
7	800	30000	30	✓		0.24	0.075
8	800	20000	30	✓		0.16	0.113
9	800	10000	30	✓		0.08	0.0.225
10	800	9000	30	✓		0.07	0.25
11	800	5000	30		✓	0.04	0.45

(b) Experimental Plan 2 (Varying Feed Rate)

Run	Drill Diameter	Spindle Speed	Feed	Drill		DBCC	
	(μm)	(N, min^{-1})	(mm/sec)	OK	Broken	S	Fn
1	800	90000	30	✓		0.72	0.025
2	800	90000	40	✓		0.72	0.033
3	800	90000	50	✓		0.72	0.042
4	800	90000	60	✓		0.72	0.05
5	800	90000	70	✓		0.72	0.058
6	800	90000	80	✓		0.72	0.067
7	800	90000	90	✓		0.72	0.075

(c) Experimental Plan 3 (Varying Spindle Speed and Feed Rate

Run	Drill Diameter	Spindle Speed	Feed	Drill		DBCC	
	(μm)	(N, min^{-1})	(mm/sec)	OK	Broken	S	Fn
1	800	90000	30	✓		0.72	0.025
2	800	80000	40	✓		0.64	0.038
3	800	70000	50	✓		0.56	0.054
4	800	60000	60	✓		0.48	0.075
5	800	50000	70	✓		0.4	0.105
6	800	40000	80	✓		0.32	0.15
7	800	30000	90	✓		0.24	0.225
8	800	20000	100	✓		0.16	0.375
9	800	10000	110	✓		0.08	0.825
10	800	9000	120		✓	0.072	1

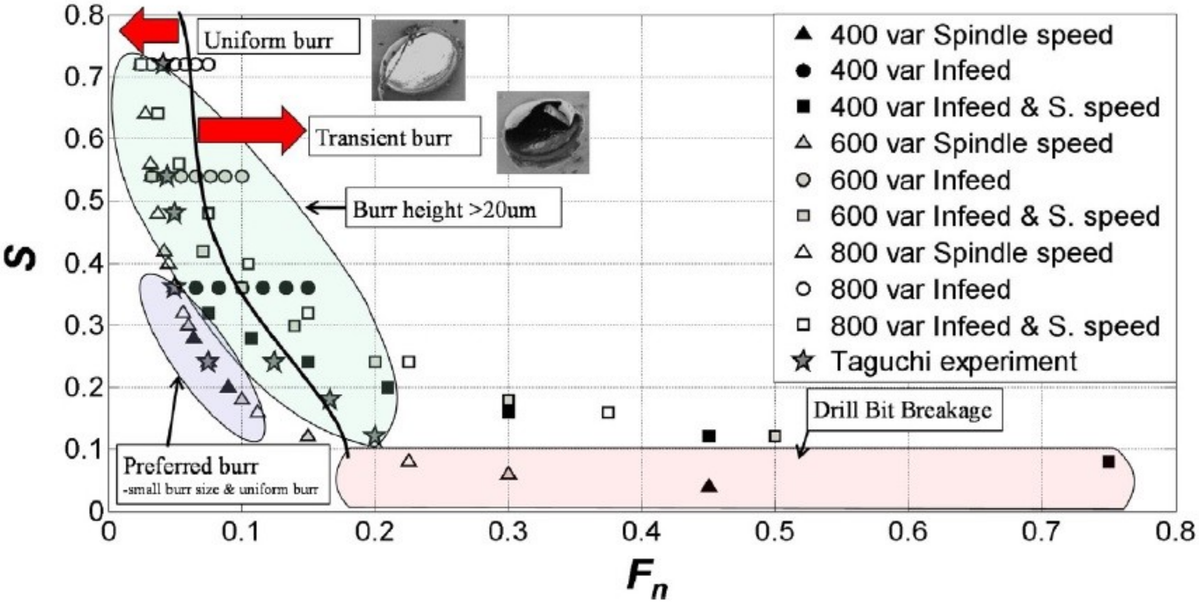


Figure 3.8: Drilling burr control chart for PCBs [7] [50]

Under the same drilling conditions, smaller drill bits produced larger burrs; on the contrary, larger drill bits produced smaller burrs. The preferred burrs, that is, uniform burrs with small burr height are highlighted in the DBCC. Based on the experiments, the burrs created from the PCB drilling process are strongly dependent on the product of spindle speed and diameter. If increasing productivity by using high spindle speed is desired, then a small drill diameter is needed to obtain uniform burrs.

Determining drilling process operating conditions is a good place to start in order to identify opportunities that reduce drilling burrs, and reduce drilling-related costs. The benefits of implementing a DBCC includes greater process reliability and improved overall performance.

3.3.4 Discussion

As described in this chapter, the burr height is related to numerous parameters. The workpiece material, which is selected according to product requirements, as well as tool materials and geometry are standardized. Parameter design, the focus of this chapter, was performed by determining what process parameters (drill diameter, spindle speed, feed) most affect the product manufacturing and then designing them to give the specified target quality of products, namely burr height. The DBCC presented here is designed to help manufacturers to predict burr formation and select optimal cutting conditions to minimize burr size. The DBCC provides information regarding what type of burr forms on the two-dimensional cutting conditions space.

Chapter 3 presented issues related to drilling burrs in PCBs and explored the formation mechanism for entrance and exit burrs. So far, most work done in drilling processes was on metallic materials; this chapter offers potential for research of multi-layer materials. Future studies might, for example, look for trends in drill geometry. Drill geometry influences cutting force, hole accuracy and, therefore, burr formation. The major components of drill geometry are point angle, helix angle, length of chisel edge, and lip relief angle. Future study should better characterize the drill bit geometry and determine the relationship between different point angles and burr size.

Chapter 4

Enhancing Water Use Efficiency in Machine Tools: Characterization and Recommendations

4.1 Introduction

According to the latest study done by the United Nations, 19% of the world's freshwater withdrawals are used by industry. Manufacturing activities especially place a significant amount of burden on the environment in the form of resource consumption and pollution. When assessing the environmental performance of products, attention is usually drawn to the energy consumption throughout a product's lifespan or greenhouse gases emissions. However, water consumption and pollution have often been neglected, regardless of the fact that its impacts can be substantial. This chapter aims to fill this knowledge gap by conducting a thorough water footprint assessment of machining tools.

The research presented in this chapter outlines a methodology for calculating the water footprint of a machine tool, which follows the newly established ISO 14046 standards. The study begins with water inventory accounting, which considers all the input resource flows into the machine tools. Next, a midpoint impact assessment is conducted to assess the water scarcity impacts. An uncertainty analysis is performed to disclose the potential bias associated with plant locations. This research identifies the appropriate parameters and metrics to address water flows within a machine tool, and provides a conceptual framework to calculate the water consumption of machining processes and its associated impacts. Using the proposed framework, a case study of the face milling process has been conducted to measure the water consumption and the resulting impacts.

4.1.1 Water Use in Manufacturing

According to the World Economic Forum (WEF), water crises have been among the top five global risks in each of the last eight years [15]. The WEF reports that 44 percent of people currently live in areas of the world that are water stressed, and, if present trends continue, water scarcity will affect the livelihoods of one-third of the world population by 2025[14]. Water use in the United States in 2015 was estimated to be about 322 billion gallons per day. Thermoelectric power and irrigation remained the two largest uses of water in 2015 [21]. Industrial withdrawal represents a significant portion of total water use. U.S. industrial water use is estimated to be more than 18.2 billion gallons per day [30]. This number only accounts for direct water withdrawal, not including water use from the public water supply. Although industrial water withdrawals account for just five percent of total water withdrawals in the United States, thermoelectric power water withdrawals account for 49 percent. Electricity generating technologies use water for different processes, depending on their configuration. Water is a critical resource for the drilling and mining of natural gas, coal, and uranium. Thermal electricity technologies consume a substantial amount of water for cooling. As for non-thermal renewable technologies, hydroelectric facilities use the water stored in dams to spin turbines to produce electricity. Although hydroelectricity creates no emissions to the air, reservoir evaporation represents a substantial loss of available water. Wind systems do not require water for cooling, and do not release emissions that pollute the air. Unlike traditional forms of electricity generation, using wind to produce energy has fewer effects in the environment.

Water is essential for a range of industrial processes and support functions, facility operations, and as an ingredient for many products. The regional and seasonal differences in water availability can lead to shortage. According to the Organization for Economic Co-operation and Development (OECD) [27], global water demand is projected to increase by 55%, mainly due to the growing demand from manufacturing and thermal electricity production (+140%). Figure. 4.1 shows that global water demand for manufacturing will increase by 400% from 2000 to 2050 which is much larger than any other sector.

Machining processes consume natural resources as input streams and generate intense heat during the cutting process due to excessive shearing caused by plastic deformation and friction [87]. The machining process is one of the most widely practiced material shaping processes used in the form of turning, milling, drilling and grinding operations. Therefore, a key first step toward reducing industrial water usage is to conduct a water footprint assessment of the machine tool.

4.1.2 Previous Research

In the early 1990s, the concept of the ecological footprint was introduced by William Rees and Mathis Wackernagel [91] [104] at the University of British Columbia. It is a measure of human impact on the Earth's ecosystem. With respect to water resources, a separate indicator - the water footprint - was introduced by Hoekstra [45] at the International Expert

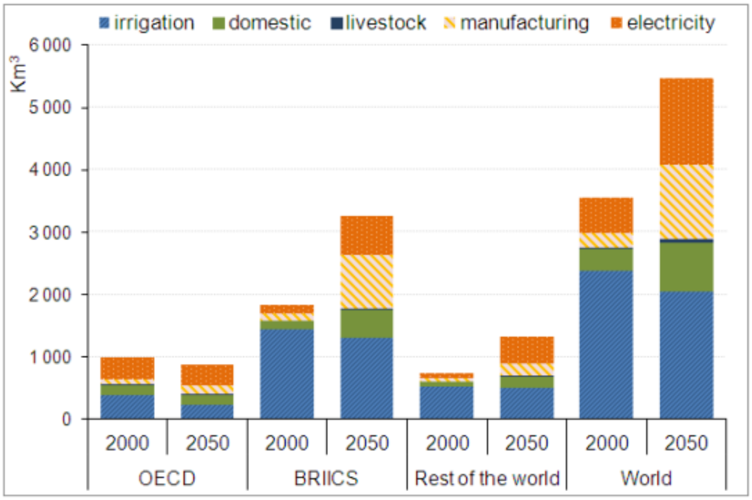


Figure 4.1: Global water demand: 2020 and 2050 [27]

Meeting on Virtual Water Trade. Currently, two main approaches exist to assess the water footprint of a product, process, or organization: the water footprint network (WFN) and ISO 14046. The first approach originates from the virtual water concept presented by Hoekstra. It has been gradually developed into the WFN [46], a guideline to assess water footprints of all sorts of products and services. The methodology developed by WFN is a volumetric measure of water consumption. The second approach was developed by the International Standard Organization (ISO). ISO 14046 [55] specifies the principles, requirements and guidelines of assessing and reporting water footprints. In ISO 14046, a water footprint is defined as a metric that quantifies the potential environmental impacts related to water by following the concept of life cycle analysis. Figure 4.2 shows the previous research works in the field of water footprint methodologies and industrial applications.

A significant body of literature has emerged since the guidelines were released. Ogaldez et al. [81], studied the water footprint of machining processes using volumetric indicators. Zhang et al. [117] used the method of bibliometrics to analyze the water footprint research published between 2006 and 2015. Pervaiz et al [87] reviewed the water consumption of metal cutting processes. Zhao et al. [118] studied the water inventory of machining processes including turning milling and drilling processes. Yet, when assessing the environmental performance of products, attention is usually drawn on the energy consumed along a product's lifespan or the emission of greenhouse gases. In contrast, the consumption of water has often been neglected even though its environmental impact can be substantial. Previous research studies use life cycle assessment (LCA) to evaluate manufacturing processes. LCA is the most commonly used method for characterizing environmental impacts. In LCA, only data on water inputs and outputs were collected, and water use accounting was performed. Characterizing water usage is not enough. A thorough investigation or water footprint assessment of the machine tool is also necessary. More comprehensive research needs to be conducted that considers both quantity and quality. Water use and impacts have to be

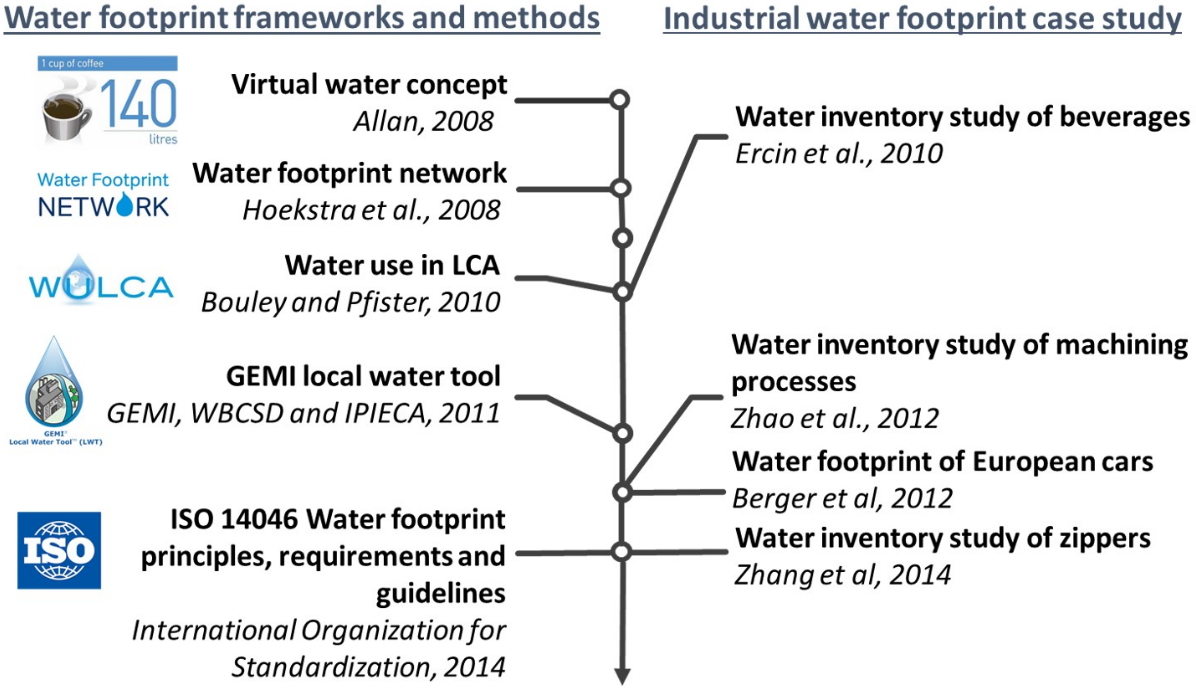


Figure 4.2: Timeline of water footprint research

considered locally.

Since the inception of water footprints, many methods have been proposed to assess the water impacts in manufacturing systems. A recent highlight was the publication of an ISO standard specially dedicated to water footprint assessment. On the application side, Zhao et al. [118] tried to quantify the water consumption of machining processes, but the impacts associated with water consumption remain untouched. The proposed research will come to fill this gap with a more comprehensive assessment that considers both consumption, related impacts, and regional issues.

4.2 Case Study: Water Footprint Assessment of a Milling Machine

The research framework will follow ISO 14046 standards and thus it will be compatible to other life cycle assessment (LCA) research work. As a pilot project, milling process will be studied to understand the water footprint impact. Since the milling process is one of the most versatile and commonly used manufacturing processes in industry, the framework and the results will be generalizable to other machining processes.

Figure 4.3 shows the research framework of this study. A water footprint assessment (WFA) according to ISO 14046 shall include the four phases of life cycle assessment: the

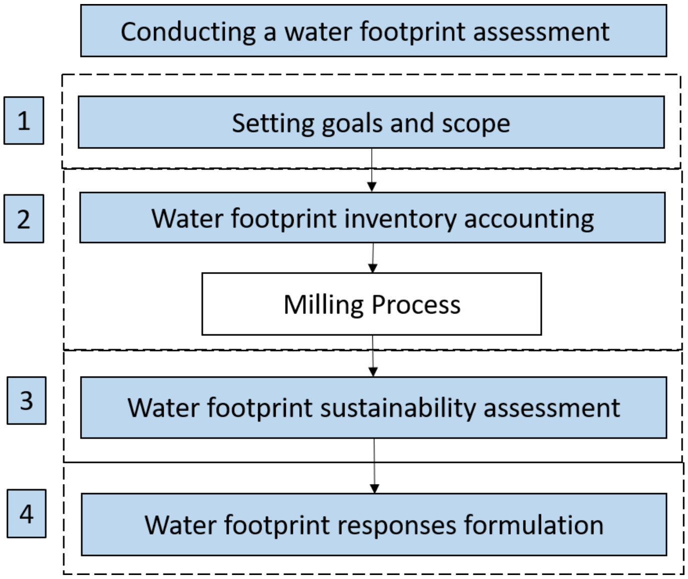


Figure 4.3: A schematic research framework for water footprint assessment

goal and scope definition, the water footprint inventory analysis, the water footprint impact assessment and the interpretation of results. In the first phase of WFA, the goal and scope of the study will be determined, including selecting a functional unit and defining boundaries of the product system. Following the water footprint inventory analysis, the input and output flows to the systems will be studied and quantified. Next, the impacts and damages of the milling process will be calculated. The last step is the interpretation of the results, in which hotspots will be identified and recommendations will be provided.

4.2.1 Goal and Scope Definition

The objectives of the study are to: (a) generate a quantitative and qualitative LCA-based water footprint assessment of the milling machine; (b) identify hotspots of the milling process; (c) explore the spatial variation of water footprints on the milling process; and (d) provide scientific advice to decision makers regarding machine tool water management.

A functional unit is a key element that provides a reference to which all the data in the system boundary are normalized. In this study, the functional unit is milling 100 pieces of aluminum alloy under flood cooling. The workpiece is a rectangular block of 200 mm $\times 100$ mm $\times 50$ mm (L $\times W \times H$), as shown in Figure 4.4. From the dimensions (200 mm $\times 100$ mm $\times 50$ mm) and the density (2712 kg/m^3), the weight of the workpiece is 2.712kg. The workpiece is machined down to 48 mm thickness with a 50 mm diameter 5-tooth cutter (Sumitomo SRF 50 RS) [101]. The detailed energy consumption calculations are based on using a Jeenxi Technology 4-axis CNC machine (JHV 1500). All direct water resource consumption (e.g., cutting fluid requirement), and energy inputs were based on this functional unit.

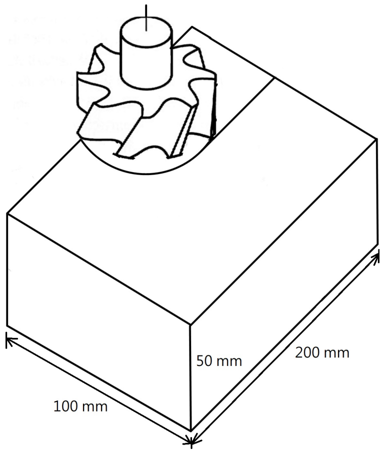


Figure 4.4: Part design for water footprint quantification

The system flow diagram in Figure 4.5 represents the different activities performed during the milling process. The overall system includes activities such as tool preparation, material removal, and cleaning, among others. Water is mainly used in the preparation of cutting fluids. Besides the preparation of cutting fluids, extra water is supplied to the system to compensate for the water loss from evaporation as well as work piece carry-off. Besides cutting fluids, electricity, cutting tools and other consumables are used in the milling process. The production of energy and materials requires a significant amount of water, which corresponds to indirect water usage.

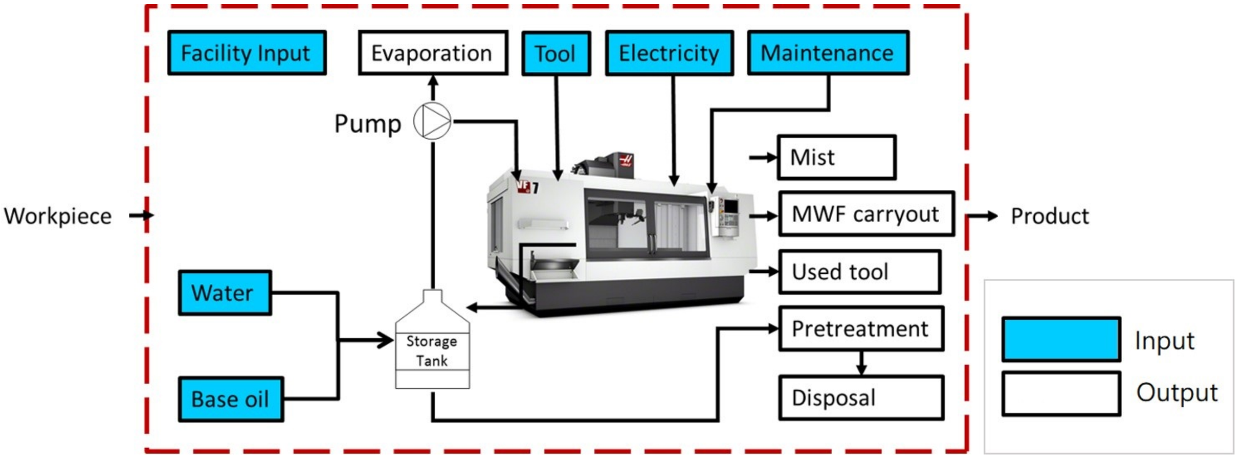


Figure 4.5: Boundary conditions of a milling machine

4.2.2 Water Inventory Accounting

Water footprint of machine tool electricity consumption

The production of energy requires a significant amount of water. This section will calculate the energy consumption of the machine tool. The machining conditions and the cutting parameters are listed in Table 4.1. In the following paragraphs, each cutting parameter will be discussed carefully.

Cutting Conditions	
Cutting Diameter (D)	50 (mm)
Cutting Speed (V)	120 (m/min)
Feed per tooth (f_t)	0.3 (mm/tooth)
Spindle Speed (N)	764 (rpm)
Number of teeth	5
Feed rate (f_r)	1146 (mm/min)
Depth of cut (d)	2 (mm)
Width of cut (w)	100 (mm)
Volume removal rate (VRR)	114650 (mm^3/min)
Rapid traverse(horizontal)	30 (m/min)
Rapid traverse(vertical)	24 (m/min)

Table 4.1: Specification of JHV CNC machine and milling parameters

Figure 4.6 shows two types of milling operations: peripheral milling and face milling. In peripheral milling, the axis of the tool is parallel to the surface being machine. In face milling, the axis of the cutter is perpendicular to the surface being milled. In this study, face milling will be explored.

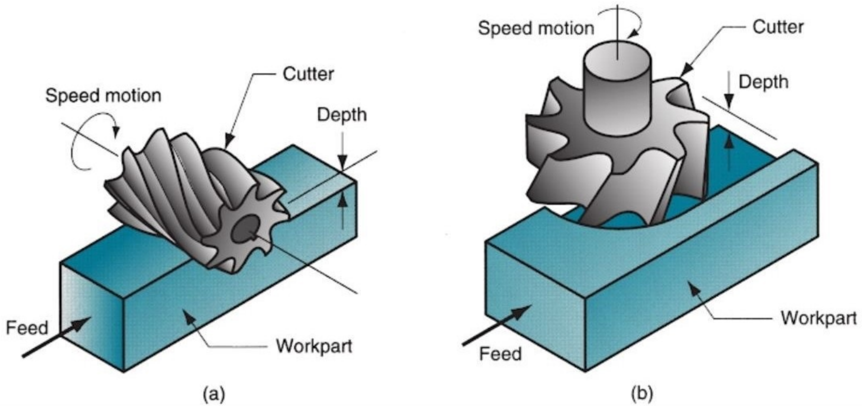


Figure 4.6: Types of milling processes: (a) peripheral milling and (b) face milling [40]

There have been several approaches developed to estimate electricity consumption of machining processes [108] [90]. In this study, Unit Process Life Cycle Inventory (UPLCI) tools will be used to calculate the energy consumption of a milling machine. Overcash et al [83] developed UPLCI tools that capture a wide range of manufacturing processes. Since the UPLCI model is parameterized, it can be used to predict changes in energy and material flows when machining different materials under different cutting conditions.

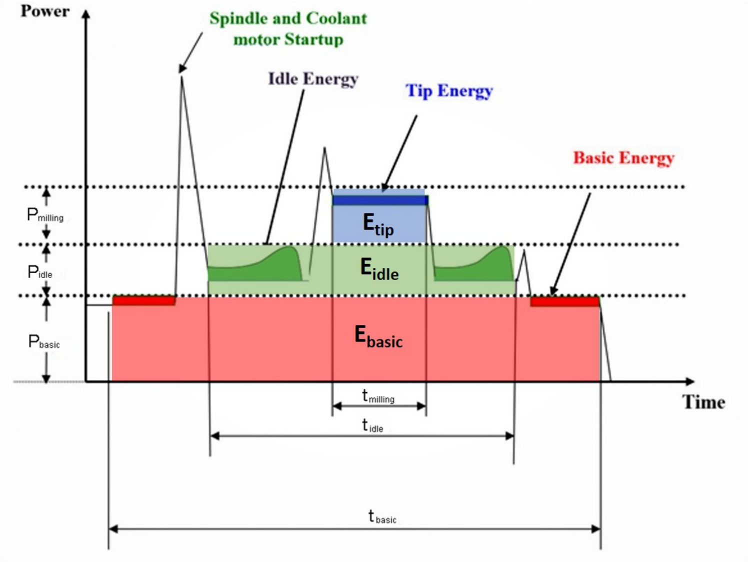


Figure 4.7: Power profile and energy consumption of machine tools (modified from [83])

Figure 4.7 shows there are three power levels: basic, idle and tip power. The ”basic” corresponds to the processes of loading/unloading, positioning, and securing a new workpiece onto the machine; ”idle” corresponds to the processes of the cutting tool approaching and retracting from the workpiece ”milling” corresponds to the actual material removal process. Each power level is an incremental power, not the absolute total power. After the power measurement has been carried out, three different power levels of the milling cycle can be calculated. For example, to calculate tip power, the power measured during milling period must have basic and idle power subtracted to obtain the tip power. Similarly, there are three time periods which correspond to three distinct levels of the power profile.

According to UPLCA [83], the electricity consumption of machining processes can be estimated using Equation 4.1. The total machining energy, $\mathrm{E}_{\mathrm{total}}$, is the sum of the three power levels: tip energy ($\mathrm{E}_{\mathrm{tip}}$), idle energy ($\mathrm{E}_{\mathrm{idle}}$), and basic energy ($\mathrm{E}_{\mathrm{basic}}$).

$$\begin{aligned} E_{total} &= P_{milling} \times t_{milling} + P_{idle} \times t_{idle} + P_{basic} \times t_{basic} \\ &= E_{tip} + E_{idle} + E_{basic} \end{aligned} \tag{4.1}$$

where power and time are illustrated in Figure 4.7

In the following, three subgroups of milling energy consumption will be discussed and quantified. Starting with $E_{milling}$, time for milling a cross sectional area of width of cut 100mm and depth of cut 3mm will be:

$$t_{milling} = \frac{L + 2L_c}{f_r} = \frac{200 + 2 * 25}{1146} \times 2 = 0.436\ (min) = 26.17\ (sec) \tag{4.2}$$

where L is the length of the workpiece to be machined, L_c is the extent of the current first contact with the workpiece, and f_r is the feed rate of the workpiece.

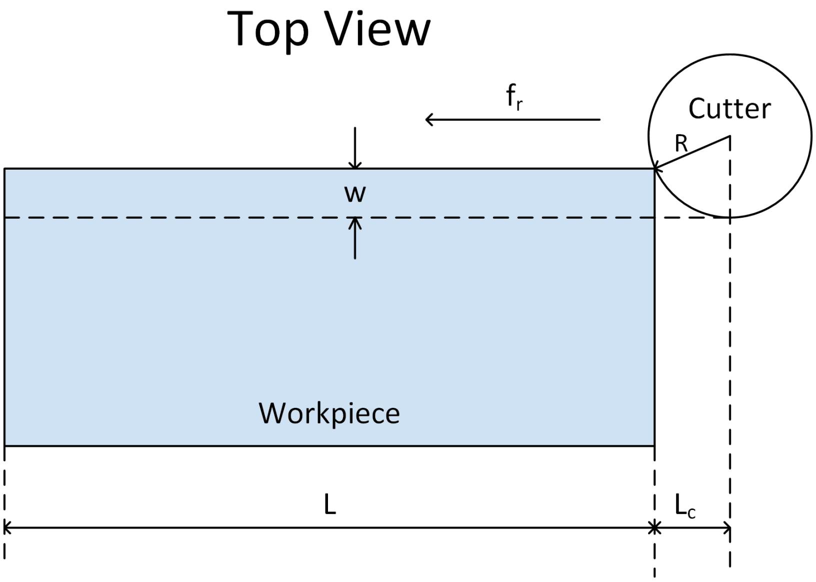


Figure 4.8: Face milling operation

Figure 4.8 shows the top view of the face milling process. From Pythagorean's Theorem, L_c can be calculated:

$$L_c = \sqrt{w(D - w)} \tag{4.3}$$

where w is the the width of the cut, D $(2 \times R)$ is the diameter of the cutter and L is the length of the work piece. Here, since the face milling is centered exactly, $L_c = D/2 = 25$ mm

The cutting speed, V, is the speed of the rotating tool at the point of contact on the workpiece. The rotational speed of the spindle, N, can be calculated using Equation 4.4. The recommended cutting speed for Aluminum alloys is 120-140 m/min [59]. In this study, the cutting speed assumed to be 120 m/min.

$$N = \frac{V}{\pi \times D} = \frac{120000}{\pi \times 50} = 764.33\ (rev/min) \tag{4.4}$$

where V is the cutting speed and D is the diameter of the cutter

Feed per tooth, $\mathrm{f_t}$, is the thickness of chip material that each cutting edge of a tool removes with one pass. The feed per tooth is determined from:

$$\begin{aligned} f_t &= \frac{V}{N \times Number\ of\ teeth} \\ f_r\ (mm/rev) &= f_t\ (mm/tooth) \times Number\ of\ teeth\ per\ one\ revolution \end{aligned} \tag{4.5}$$

V and f_t are estimated from the material properties. From the literature [83], f_t varies from 0.28 to 0.56 for aluminum alloy. In this study, f_t is assumed to be 0.3 (mm/tooth).

Feed rate, f_r, is the rate at which the cutting tool and the workpiece move in relation to one another. The feed rate is the product of feed per tooth (f_t), spindle speed (N) and number of teeth.

$$f_r = f_t \times N \times Number\ of\ teeth = 0.3 \times 764 \times 5 = 1146\ (\frac{\text{mm}}{\text{min}}) \tag{4.6}$$

The volume material removal rate (VRR) for a given width of cut and depth of cut is:

$$VRR = w \times d \times f_r = 100\ (\text{mm}) \times 3\ (\text{mm}) \times 1146\ (\frac{\text{mm}}{\text{min}}) = 3438000\ (\frac{\text{mm}^3}{\text{min}}) \tag{4.7}$$

where w is the width of the cut, d is the depth of the cut.

The specific cutting energy (Up) is 0.98 $W/mm^3 persec$, from UPLCA database [59].

$$\begin{aligned} P_{milling} &= volume\ removal\ rate \times Specific\ cutting\ energy\ (Up) \\ &= (w \times d \times f_r) \times Up \\ &= (100 \times 2 \times 1146.5) \times \frac{0.98}{60} \\ &= 3.74\ (kW) \end{aligned} \tag{4.8}$$

$$\begin{aligned} E_{milling} &= t_{milling} \times P_{milling} \\ &= t_{milling} \times volume\ removal\ rate \times specific\ cutting\ energy \\ &= \frac{L + 2 \times L_c}{f_r} \times (w \times d \times f_r) \times Up \\ &= 26.7 \times 3.74 \\ &= 98.0\ (kJ) \end{aligned} \tag{4.9}$$

The handling time includes the air time of the cutter moving from home position to approach point, approach, overtravel, retraction after milling, and traverse, if needed to perform an other cut in the same work piece. Before milling on the workpiece, the first thing to be done is setting the ordinate axes of the machine with respect the workpiece. The milling cutter is set to be an offset of 25mm above the workpiece. Handling Time is the time required for the cutter to move from home position to an approach point (25mm) above the workpiece. Time for handling:

$$\begin{aligned} t_{handling} &= Air\ time\ + Approach/overtravel\ times\ + retraction\ times \\ &= t_{a1} + t_{a2} + t_{a3} \end{aligned} \tag{4.10}$$

The time required for the cutter to move from the home position to the approach point (25mm) is essentially milling in air. The air time of the milling cutter as it moves from the home position to the approach point at a horizontal traverse rate is:

$$t_{a1} = \frac{25}{traverse\ speed} = \frac{25\ (mm)}{500\ (mm/sec)} = 0.05\ (sec) \tag{4.11}$$

The horizontal traverse speed is based on a Jeenxi Technology 4-axis CNC machine.

The approach and overtravel distances can be assumed to be 5 to 10 mm. In this case, we assume them to be 8 mm. After reaching the approach distance 8mm from the workpiece, it reaches the workpiece at feed rate, f_r and after cutting the workpiece the cutter travels an overtravel distance of 8mm.

$$t_{a2} = \frac{(approach + overtravel)}{f_r} = \frac{(8+8)\ (mm)}{1146\ (mm/min)} = 0.014\ (min) = 0.84\ (sec) \tag{4.12}$$

After reaching the overtravel point, the mill retraces back to an offset position at a faster rate called the horizontal traverse rate. Retract time is

$$t_{a3} = \frac{\text{retract distance}}{\text{traverse speed}} = \frac{(10+200+10)}{30000} = 0.44\ (sec) \tag{4.13}$$

The average idle power of automated CNC machines is between 1200 and 15000 watt.

$$\begin{gathered} P_{idle} = P_{spindle} + P_{coolant} + P_{axis} \\ where\ P_{coolant} = 1\ kW; P_{spindle} = 4\ kW; P_{axis} = 5\ kW \end{gathered} \tag{4.14}$$

The assumed values are from the CNC manufacturing companies [59]. Therefore, the idle power for the milling process is:

$$\begin{aligned} P_{idle} &= P_{spindle} + P_{coolant} + P_{axis} \\ &= 4 + 1 + 5 = 10\ (kW) \end{aligned} \tag{4.15}$$

The idle time is the sum of the handling time and the milling time, as shown in Figure 4.7. Handling time is the air time of the cutter moving from home position to the approach point, retraction after milling, and traverse. The total idle time for a cut is:

$$t_{idle} = t_{handling} + t_{milling} = t_{a1} + t_{a2} + t_{a3} + t_{milling} = 1.33 + 26.7 = 28.0\ (sec) \tag{4.16}$$

Total idle energy for the drilling process is the product of total idle time and idle power, as shown in Equation 4.17.

$$\begin{aligned} E_{idle} &= P_{idle} \times t_{idle} \\ &= 10 \times 28 \\ &= 280\ (KJ) \end{aligned} \tag{4.17}$$

The basic power of a machine tool is the demand under running conditions in stand-by mode. There is energy-consuming peripheral equipment, such as numerical control, lightning. There is no relative movement between the tool and the workpiece, but all components are still running at no load power consumption.

The basic time t_{basic} is the sum of loading/unloading time, cleaning time, handling time, and milling time. Loading and unloading times can be estimated quite accurately for a particular machine tool and workpiece-holding device if the weight of the workpiece is known [36]. In this case, the weight of the workpiece is 2.4 kg, and the workholding device is a vise. Based on Fridriksson's study, the workpiece loading and unloading times are 12 seconds each. After the milling process, the time required to clean the machine with pneumatic cleaners is assumed to be 25 seconds.

$$\begin{aligned} t_{basic} &= t_{load/unload} + t_{cleaning} + t_{handling} + t_{milling} \\ &= (12 + 12) + 25 + 28 = 77\ (sec) \\ &where\ t_{handling} + t_{milling} = t_{idle} \end{aligned} \tag{4.18}$$

The basic power of the machine can be assumed as the 25% of the machine maximum power in the manufacturer specifications. Therefore, the power consumed during the basic process is

$$P_{basic} = 7.5kW \tag{4.19}$$

Energy consumed during this process is,

$$E_{basic} = P_{basic} \times t_{total} = 7.5 \times 77 = 578\ (kJ) \tag{4.20}$$

The basic time for the process is the sum of idle time, which includes machining time, and load/unload time.

$$T_{basic} = t_{basic} + t_{idle} \tag{4.21}$$

In summary, the energy required for a milling machine to mill one functional unit is:

$$E_{machining} = e_{milling} + e_{idle} + e_{basic} = 98 + 280 + 578 = 956\ (kJ) \tag{4.22}$$

Fuel Type	% [2]	gal/MWh [68]
Nuclear	19	672
Hydro	7	4491
Solar	1.6	26
Wind	6	0
Geothermal	0.4	1760
Biofuel	1.5	553
Natural gas	35	826
Coal	27	687
Oil	1	0

Table 4.2: National electricity generation profile 2018 and associated water consumption

Water footprint of facility

Manufacturing facilities often use water to change or maintain temperature, and to clean equipment. These non-value-added activities should also be considered while calculating the water footprint of a machine tool. The amount of water required for the various end uses differs by industry and by facility. Water use in most industries can be classified into the following broad end uses: (1) Production processing (2) Auxiliary processes e.g., pollution control (3) Cooling and heating e.g., cooling tower (4) Indoor domestic use e.g., restroom, kitchens (5) Outdoor water use e.g., landscape irrigation.

To account for facility water use, U.S. EPA statistics data will be used as a proxy. EPA created ENERGY STAR Portfolio Manager to track and examine energy and water use of commercial buildings across the United States [32]. The median indoor water use for offices is 13 gallons/worker/day. Assume the machine tool needs one worker to operate the machine. According to the Bureau of Labor Statistics, the average American works 8.56 hours per day. The facility water use can be estimated:

$$\begin{aligned}\text{Facility water use per worker} &= \frac{t_{basic}}{\text{Daily operating hours}} \times \text{Daily indoors water use per worker} \\ &= \frac{77\ (sec)}{8.56 \times 60 \times 60\ (sec)} \times 13\ (\text{gallons}) \ = 0.032\ (\text{gallons})\end{aligned} \tag{4.23}$$

Water footprint of cutting fluids

Metalworking fluids (MWFs) are used as coolants and lubricants in metal cutting and forming to extend the life of tools and achieve faster production rates. A tank holds a certain volume of the cutting fluid that is pumped through a pipe or nozzle to the cutting area. The area is completely flooded by the cutting fluid. The fluid then returns to the tank, is filtered, and is recirculated through the system [48]. In this study, oil-based cutting fluids are used. Hoffman et al. [47] recommended cutting fluids for milling operation on various materials . For aluminum alloys, soluble oil composed of 96% water with 4 % mineral oil will be used.

Conventional oil recovery technologies have a major effect on water consumption. Water is used in the production of bitumen from oil sand, and it is used as a coolant in refiners. Wu et al. [111] provides water consumption by recovery technology. According to Peachey [85], the oil sands industry used an average of 4 gallons of freshwater to produce 1 gallon of bitumen oil including upgrading.

The cutting fluids may be consumed in-process or evaporate in the case of water. A total daily fluid loss of 5% to 20% may occur from the combination of evaporation, spills, mist, and carry-out on chips and workpieces [12]. To incorporate all these factors, a fixed percentage (5%) of the cutting fluid loss is assumed [119]. Although cutting fluids are reused and recirculated over a period of time, cutting fluids ultimately deteriorate and must be replaced. To maintain proper functionality, cutting fluid needs to be replaced periodically. It is assumed that 55 gallons of cutting fluid must be replaced every other week [13]. Assuming cutting fluid is used for 204 hrs, then cutting fluid loss is 55 gallon/(204*60) per minute, which is 17g per min. The cutting fluid is prepared by using 96wt.% water and 4wt.%oil, so the cutting oil loss is 0.68g cutting oil/min. Since the milling time is 26 seconds, the cutting fluid consumption can be calculated:

$$\begin{aligned}&\text{Mass loss of the water} = 17\ (\frac{\text{g}}{\text{min}}) \times 0.96\ (wt.\%) \times \frac{26}{60}\ (\text{min}) = 7.07g\ water\\&\text{Mass loss of the cutting oil} = 17\ (\frac{\text{g}}{\text{min}}) \times 0.04\ (wt.\%) \times \frac{26}{60}\ (\text{min}) = 0.30g\ cutting\ oil\end{aligned} \tag{4.24}$$

Types	Assumptions	Sources
Production	Soluble oil (96% water + 4% oil)	Peachey [85] Wu [111] Hoffman [47]
Loss	5% of the tank volume	Zimmerman [119] Iowa Waste Reduction Center [12]
Replacement	55 gallons of cutting fluids/two weeks	Clarens [13]

Table 4.3: Water inventory data sources for metalworking fluids

In summary, the water inventory data for the metalworking fluids included in this study were compiled from several sources with similar boundary conditions. The assumptions and supplemental water footprint inventory data sources are listed in Table 4.3.

Cutting tool usage

Milling processes require replacement of cutting tools over a period of time. The tool life is the actual machining time that a newly sharpened tool satisfactorily works prior to it becoming necessary to remove it for replacement or reconditioning. Tool life will be affected by many factors, such as cutting forces, infeed speed, spindle speed etc. The milling cutters used for face milling aluminum alloys are a modular style of construction, as shown in Figure 4.9. The blade is fixed on the cutter body by a mechanical fixing mechanism, e.g., clamp screw. During the milling process, when a certain blade wears, the corresponding blade can be replaced without replacing the whole milling cutter. Since the replacements are small, for the simplification of the calculation, the milling cutters are not considered in this study.

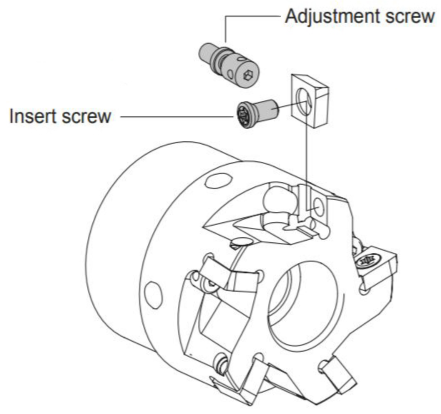


Figure 4.9: Sumitomo milling cutter [101]

Part Cleaning

Because cutting fluid is generally carried on the machined components, cleaning of the processed component should be arranged immediately. Parts-washing operations are among the largest consumers of water. Steps involved in aqueous cleaning including degreasing, rinsing, dragging out, and final rinsing [53]. However, the importance of cleaning and the impacts of cleaning is highly dependent on the product being made. This highly diversified cleaning methods, both in terms of the amount of water and type of cleaning, make general quantitative and qualitative analysis of the cleaning process difficult. Therefore, the cleaning process is not considered in this study.

Results: Water Inventory Accounting

This section presented the water inventory results of milling process. There are five inputs to the milling process system: electricity consumption, facility energy resources usage, cutting fluid consumption, cutting tool usage, and part cleaning. Given the reasonable assumptions mentioned in the previous sections, only three major areas will be studied: electricity consumption, facility energy resources usage, and cutting fluid consumption. Figure 4.10 depicts the water inventory results calculated for the milling process. Total water consumption of the milling process is 1.07 Liters. The water inventory is largely associated with the electricity consumption of machining process, which accounts for 88% of freshwater consumption. The facility energy use is smaller but remains significant. The water footprint associated with cutting fluids usage is the smallest. This estimation is based on secondary data. More primary process level data and capture of the significant water consumption profile of parts cleaning would improve the estimates.

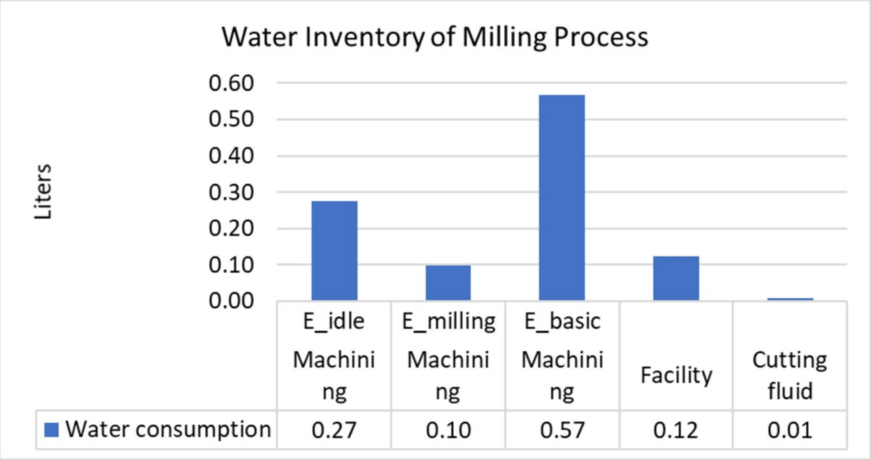


Figure 4.10: Inventory of freshwater consumed for machining, facility use, and cutting fluids

4.2.3 Water Scarcity Footprint

Water footprint inventory analysis is a phase of water footprint assessment involving compilation and quantification of inputs and outputs related to water for products, processes or organizations [55]. However, the inventory results do not address regional issues. If the milling process takes place in the areas that present high water scarcity, the freshwater consumption impacts can be significant. In the impact assessment, the inventory result is analyzed for environmental impacts. For example, manufacturing a product may consume a known volume of water; in the impact assessment phase, the water scarcity impact from the consumption of water is calculated. This section applies a consensus-based midpoint water scarcity footprint, consistent with the ISO 14046 standard, to determine the associated water deprivation potential.

Table 4.4: Existing water footprint impact assessment methodologies

Midpoint		Endpoint	
Category	Method	Category	Method
Scarcity	Water stress index [88]	Human health	Pfister [88]
Scarcity	AWaRe [10]	Human health	Motoshita [78]
Scarcity	Swiss Ecoscarcity [37]	Human health	Boulay [9]
Scarcity	WFN [46]	Ecosystem	Pfister [88]
Degradation	Ecotoxicity [92]	Ecosystem	Habafiah [41]
Degradation	Acidification [43]	Ecosystem	Zelm [116]
Degradation	Human Toxicity [92]	Resources	Pfister [88]

When calculating the results of a water footprint assessment, there are many different impact assessment methods, as shown in Table 4.4. A midpoint method looks at the impact earlier along the cause-effect chain. On the other hand, endpoint results are usually shown as impact on human health, ecosystem quality, and resource depletion. In this case study, midpoint methods will be use. Since data gaps and assumptions would stack up along the cause-effect chain, midpoint methods will be used to avoid higher statistical uncertainty.

In 2017, the top five machine tool consuming countries are: China, the United States, Germany, Japan and Italy [54]. Therefore, the water scarcity footprint of milling processes in those top five countries will be evaluated. Water use in LCA (WULCA) group provides aggregated CFs for specific countries corresponding to a period of one year. A consensus-based method called Availible WAter REmaninging (AWARE) is used to calculate the water scarcity footprint (WSF) as a water use midpoint indicator. AWARE is calculated on per area basis in a watershed. The impact category used to quantify the water consumption from the milling process is water scarcity footprint reported in liters world equivalent per mega joule of gas (L world eq/MJ). Water degradation and quality aspects in milling process are outside the scope of this study.

To calculate WSF, first the total water consumption of the process was calculated, in liters of water per workpiece. Based on the inventory results from previous section, the milling process consumes 1.07 liter of water. The countries identified and the associated CFs are collected from AWARE [112]. The AWARE indicators are based on the inverse of the AMD (availability minus demand), which represents the relative available water remaining per area in a watershed [10]. The WSF of milling process in different plant location can be calculated, using the formula below:

$$Water\ Scarcity\ Footprint = Water\ consumption \times CF_{AWARE} \tag{4.25}$$

The WSF calculated varies from 0.63 to 46.27 (m^3 world eq) following the AWARE method. Both the CF and the inventory play a role in the resulting water scarcity footprint. To effectively reduce freshwater consumption impacts, besides reducing the amount of water

Table 4.5: Characterization Factors (CFs) of top five machine tools consuming countries

Country	CFs	inventory	WSF (m^3-world eq)
China	42.47	1.07	45.47
United States	33.13	1.07	35.47
Germany	1.31	1.07	1.40
Japan	0.59	1.07	0.63
Italy	43.21	1.07	46.27

consumed, the choice of plant location is also very crucial. Given the water scarcity footprint changes significantly, it is important to get specific information on the geographical location of processes and raw materials in order to avoid overestimation or underestimation of results.

4.3 Discussions

4.3.1 Uncertainty Analysis

Finally, models at the machine tool level inherit large uncertainties which have to be communicated transparently to allow for proper decision-making. Due to the cumulative effects of model imprecision, input uncertainty or data variability, a systematic procedure to quantify the uncertainty of the results needs to be performed. In addition to these default CFs also modified CFs have been applied allowing for a sensitivity analysis.

Figure 4.11 depicts the water inventory accounting using different country electricity profiles. Water consumption was calculated based on US EIA data in 2014, with the result that water consumption varies from 0.68 liters per workpiece in Germany to 1.57 liters per workpiece in China. These results will then be used to calculate WSFs for the five countries.

Two water scarcity footprint methods will be compared: water stress indices (WSIs) [88] and AWARE indicators [10]. Although both methods develop scarcity indicators that are used as midpoint CFs in water footprint assessment. Pfister [88] developed the WSI indices, based on the ratio of the total annual freshwater withdrawals to the hydrological availability. On the other hand, AWARE indicators are based on the inverse of the AMD (availability minus demand). The water scarcity footprint of milling processes will be calculated using country level CFs for both the WSI and AWARE method. The WSF calculated through the AWARE method has been introduced in Equation 4.25. The WSF also can be calculated using WSI method:

$$Water\ Scarcity\ Footprint = Water\ Inventory \times WSI \tag{4.26}$$

Figure 4.12a shows the WSF results using AWARE method. Japan and Germany have the smallest impacts toward water resource deprivation. Figure 4.12 shows the WSF results using WSI method. Among two impact assessment methods, Germany remains the lowest

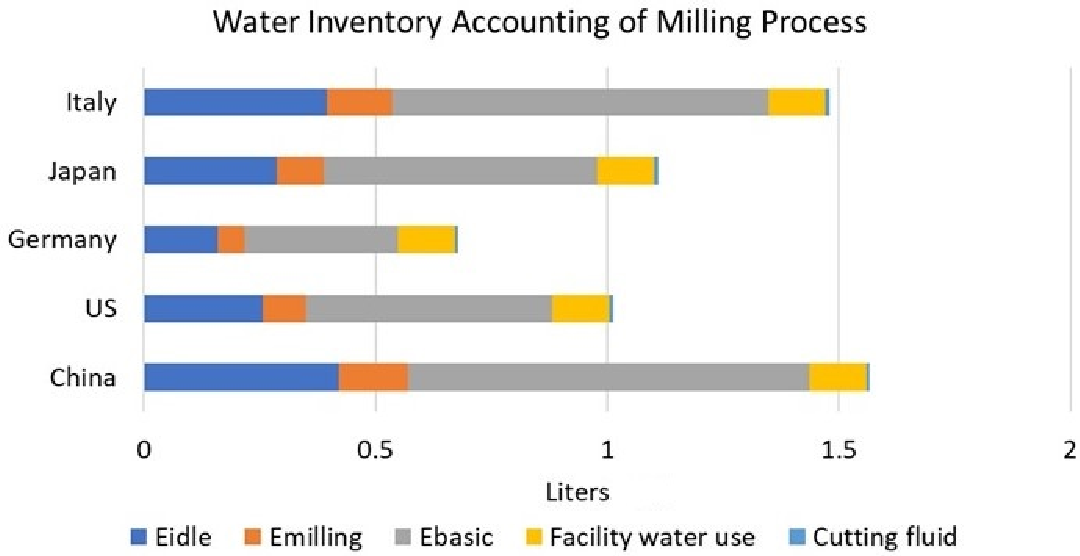
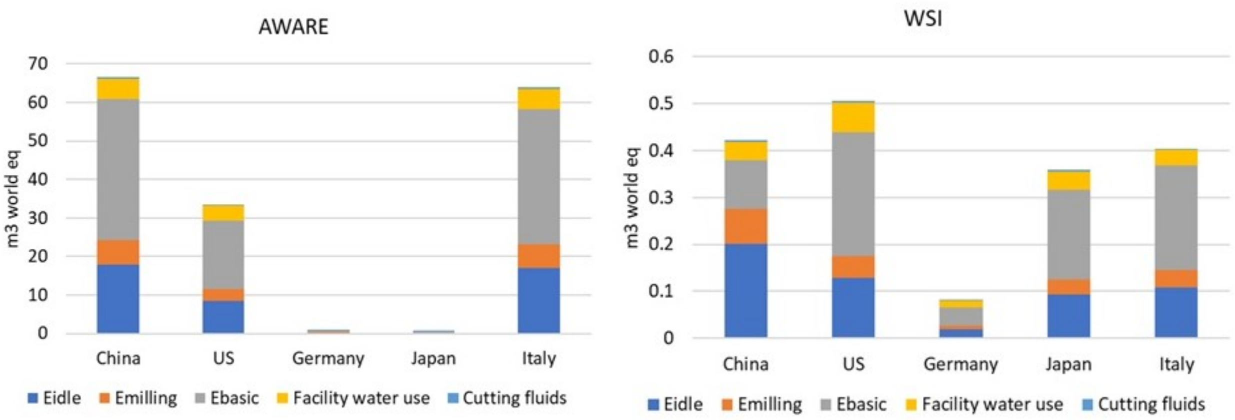


Figure 4.11: Inventory of freshwater consumed for machining, facility use, and cutting fluids

in water scarcity impacts country for milling processes. Table 4.6 shows inventory amount, CFs, as well as WSF impact results for each country respectively.



(a) AWARE

(b) WSI

Figure 4.12: Regional sensitivity analysis for water scarcity footprint using AWARE and WSI methods

4.3.2 Lessons Learned

This chapter provides insights into the water footprint assessment of manufacturing processes with a case study of a face milling process on aluminum alloys. Water inventory accounting

Table 4.6: Characterization Factors (CFs) used in the sensitivity analysis

Country	Inventory (m^3 world eq)	AWARE CFs	WSI CFs	AWARE (m^3 world eq)	WSI (m^3 world eq)
China	6.77×10^{-2}	42.47	0.48	6.66×10^{-2}	4.21×10^{-4}
Unite States	1.01×10^{-3}	33.13	0.50	3.36×10^{-2}	5.06×10^{-4}
Germany	6.80×10^{-4}	1.31	0.12	8.93×10^{-4}	8.16×10^{-5}
Japan	1.11×10^{-3}	0.59	0.32	6.54×10^{-4}	3.59×10^{-4}
Italy	1.48×10^{-3}	43.21	0.27	6.40×10^{-2}	4.04×10^{-4}

has been conducted based on published literature, and associated environmental impacts of water consumption has been calculated for 5 different countries using the WSF metric.

Of the three elements of machining process studied here, electricity consumption has the largest impact for each category. After quantifying the water inventory, improving water efficiency of a machine tool is another subject begging for more work. How we might develop or fine-tune a machine tool to improve real-time water consumption and reduce water degradation desires more research efforts. A sizable reduction in water consumption is possible through careful monitoring and analysis of energy patterns

Additionally, energy profiles can be vastly varied from one country to another. Water consumption for the same process will be different due to site locations. The results show that the choice of location with lower water scarcity to conduct milling process can be a determinant in the calculation of lower water scarcity footprints. Among the five countries selected, Germany has the lowest water scarcity impact.

It should be noted that CFs used in this study did not consider seasonal variation. For an assessment of water scarcity, it is not only crucial where the water consumption takes place, but also when. Many regions in the world are water abundant in a certain period of time and extremely water stressed in another. That is, the WSF would change for the same location in different seasons. Future study not only should consider geographic locations, but also incorporate seasonal variation to achieve more accurate results.

Chapter 5

Production Flow Analysis through Environmental-Value Stream Mapping

5.1 Introduction to Environmental Value Stream Mapping

There is no single common definition of sustainable manufacturing, but the U.S. Environmental Protection Agency (EPA) sums it up as: the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources [31]. Much evidence suggests that lean is beneficial for sustainable manufacturing, dominantly from environmental and economic aspects. This chapter presents the implementation of lean thinking principles by utilizing value stream mapping (VSM), and provides practical process improvement strategies.

A major challenge is to identify manufacturers' embedded energy costs. Managers at each stage of a manufacturing process may overlook energy waste because "energy is only two, three or five percent" of production costs [94]. Any waste of energy in the intermediate stages, or disguised in the cost of inputs, eats up profit margins at every step. Current sustainable management approaches often deal with environmental and production issues separately. In this section, a lean production tool called environmental-value stream mapping (E-VSM) will be introduced to simultaneously assess environmental and production waste.

5.1.1 The History of Lean

In the beginning of the twentieth century, Henry Ford installed the first assembly line for the mass production of an entire car [49]. After the end of World War II, manufacturers experienced drastic materials shortages which forced businesses to grow in a different trajectory. At Toyota Motor Company, Taichii Ohno and Shigeo Shingo began to incorporate

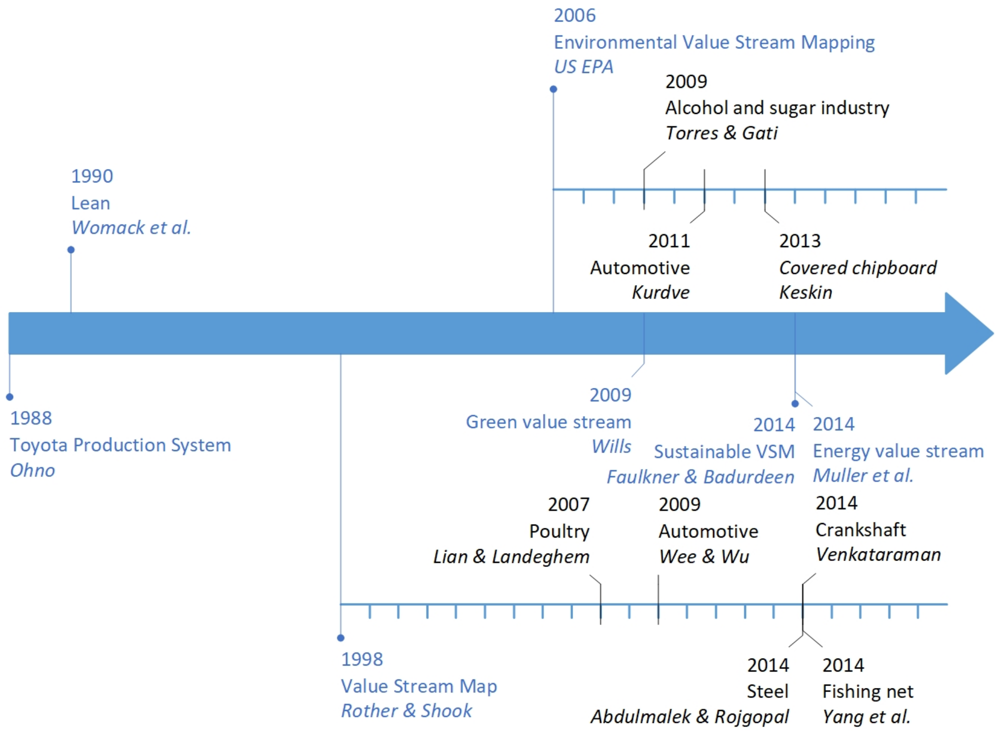


Figure 5.1: Research concerning value stream mapping

Ford production and other techniques into an approach called Toyota Production System (TPS) [82], which is seen as the forebearer of lean production. The main purpose of the TPS is to eliminate various types of waste lying within the production line [75]. The concept of lean became widely popular after the publication of Womack et al. book [109]. The book ”The machine that changed the world” demystified the Japanese manufacturing method and provided a comprehensive description of the entire lean system. Lean production focuses on cost reduction which is achieved by eliminating activities that do not add value [1]. The concept of lean continues to spread beyond manufacturing, to retail, healthcare, and even government.

Value steam mapping (VSM) was invented as a lean production tool to visualize and analyze the production flows by Rother and Shook [93] in 1998. Conventional VSMs are used extensively in industries to assess the value-added and non-value-added activities in production lines, and identify opportunities to reduce costs, save time, and reduce inventory. Applications of VSM have spanned across different sectors, including the steel industry [1], automotive industry [107] [103] [90], and fishing net production [114]. However, covering only economic aspects, conventional VSM is no longer sufficient as awareness of climate change rises. The US environmental protection agency (EPA) encourages industry to integrate environmental waste into the VSM. EPA has developed a lean and environment toolkit aiming to help industry reduce pollution and energy consumption while increasing profits

[31]. Figure 5.1 shows the brief history of value stream mapping.

5.1.2 Lean Production

The goal of mass production is to produce large quantities at low-cost. Mass production processes are often a ”push” typea of process in which products are ”made-to-stock”. Mass production is not based on actual demand. On the contrary, lean production is a ”pull” process in which products are ”made-to-order”, as shown in Figure 5.2. Lean production refers to a manufacturing process in which items are produced on current demand, and focuses on eliminating waste in processes.

(a) Mass Production

(b) Lean Production

Figure 5.2: Push system vs. pull system in lean manufacturing

Form	**Description**
Over Production	Producing more than is needed.
Waiting	Time delays for materials, information or people.
Transportation	Moving tools/materials to the point of use.
Over-processing	Additional work above the requirements.
Inventory	Stacks of parts waiting to be completed or finished products waiting to be shipped.
Movement	Unnecessary movement of people (walking, riding) as well as smaller movements.
Defect	This requires additional rework.

Table 5.1: Type of lean wastes (modified from [71])

Taiichi Ohno [82] identified a list of wastes that would impede the efficient use of resources within an organization, as shown in Table 5.1. Overproduction occurs when operations continue after they should have ceased, which results in an excess of products. Waiting refers to queuing and occurs when there are periods of inactivity in a downstream process. Transportation wastes mean unnecessary motion or movement of materials, such as work in progress. Over-processing refers to extra operations, such as rework and handling. Inventory wastes are all the inventory that is not directly required to fulfill current customer orders. Movement refers to the extra steps taken by employees and production equipment. Finally, defects are the finished goods or services that do not fulfill the specifications or customers' expectation.

5.1.3 The Differences between VSM and E-VSM

VSM is a lean management method for analyzing the current state and designing a future state for the series of events that take a product or service from its beginning through to the customer with reduced lean waste. To further enhance the tool, the US EPA developed environmental VSM (E-VSM) incorporating environmental considerations into VSM.

Data collected	Conventional VSM	E-VSM
Cycle time	yes	yes
Availability	yes	yes
Operator numbers	yes	no
Defect rate	yes	yes
Transport time/type	yes	yes
Shifts and working time	yes	yes
Power demand of machine tools	no	yes

Table 5.2: Comparison of key performance metrics [51]

The differences between VSM and E-VSM are listed in Table 5.2. Conventional VSM can overlook environmental wastes, such as:

- Energy, water, or raw material consumption
- Pollutants and material waste released into the environment

Since environmental VSM was proposed, there have been a few case studies addressing the applicability of E-VSM. The existing literature includes alcohol and sugar industry [102], automotive industry [64], covered chipboard [61], and robotics plant [98]. However, no research has been done on glass manufacturing facilities. There is a need to apply E-VSM method to different manufacturing facilities to assess its usability as well as to evaluate any difficulties in data collection or analysis. The presented application of E-VSM can add value to the existing literature, and provide insights on improving environmental impacts while reducing production costs.

5.2 Case Study: E-VSM Development for a Cover Glass Manufacturing Facility

This section concerns a production flow analysis of a facility producing cover glasses for electronics. Due to the high demand of smartphones and tablets, the cover glass market has been growing at a strong pace. The analysts forecast the global cover glass market to grow at a rate of 11.11% during the period 2016-2020 [39]. Such remarkable growth comes along with substantial energy consumption and waste generation. Therefore, a cover glass manufacturing facility has been chosen as case study subject. The study aims to provide decision makers at cover glass manufacturing companies a holistic view of their operations that considers both economic and environmental aspects.

Table 5.3 shows the research methodology for constructing an E-VSM study. This research study was carried out based on the methods created by Rother and Shook [93], while adding environmental metrics [31]. The scope of the study was cover glass manufacturing on a factory level. The production data, such as cycle time and availability, was collected while walking around the shop floor and interviewing key individuals in each station. The environmental data, like energy consumption, was collected from machine tool specifications and operators using the machine tools. Once a current E-VSM is completed, candidates for improvement can be identified and prioritized. Finally, researchers and facility designers can come up with improvement plans based on the assessment.

Steps	Goal
Define scope	Select processes to be mapped
Collect data	Collect process times, material, and inventory information
Construct current state	Map out the flow
Identify areas for improvement	Look for areas of waste
Design future State	Develop improvement strategies and compile a future state map

Table 5.3: Research methodology

5.2.1 Data Collection

In order to construct the current state map, the first step is to observe the production line and collect required information. Data collection took place in December 2015 at Lens Technology, a cover glass fabrication facility in China. Lens Technology accounts for about one-fifth of the global market for cellphones and tablet computers. In this study, conventional VSM data along with environmental data were collected, as shown in Table 5.2. Conventional VSM data, such as cycle time, are useful for calculating energy consumption in E-VSM study. Since the information on the E-VSM must be on a per glass piece basis, the energy consumption was calculated on a per glass piece basis as well.

Table 5.4 summarizes the manufacturing processes and equipment in the facility.

Operation	Process	Machine
1	Cutting	Glass cutting machine
2	Lapping	Lapping machine
3	Drilling	CNC machine
4	Edge Polishing	Polishing machine
5	Polishing	Polishing machine
6	Defective products polishing	Polishing machine
7	Cleaning	Horizontal glass cleaning machine
8	Inspection	Manual
9	Adding pressure	Automatic adding pressure stove
10	Testing	Stress testing machine
11	Polishing	Lapping machine
12	Cleaning	Horizontal glass cleaning machine
13	Inspection	Manual
14	Applying protective layer	Manual
15	Printing	Printing machine
16	Cleaning	Horizontal glass cleaning machine
17	Finished product inspection	Manual
18	Coating	Spraying machine
19	Packaging inspection	Manual
20	Warehousing	Manual

Table 5.4: Summary of manufacturing processes and equipment

5.2.2 Cover Glass Manufacturing Process

To successfully construct an E-VSM, a thorough understanding of the production line is required. In this section, cover glass manufacturing processes will be introduced step by step, as shown in Figure 5.3. The production line starts with scribing. A large panel of glass will be processed into small pieces of glasses using automatic glass cutter. The machine will mark lines on top of the glass panel, and workers will break them into small pieces. This machine produces 2934 pieces per hour. After scribing, grinding machines will be used to reduce the thickness of the glass to a desired level. Next, workers will operate CNC machines to shape the rectangle to rounded rectangle and drill a hole. A special drill was developed to finish all the shaping processes without the change of tool. The drill will be replaced after processing 120 pieces of glasses. After the drilling process, workers will stack glass pieces and slightly tilt them to perform edge polishing. The glass piece will be polished again to improve surface quality, and then the workpiece will go through manual inspection.

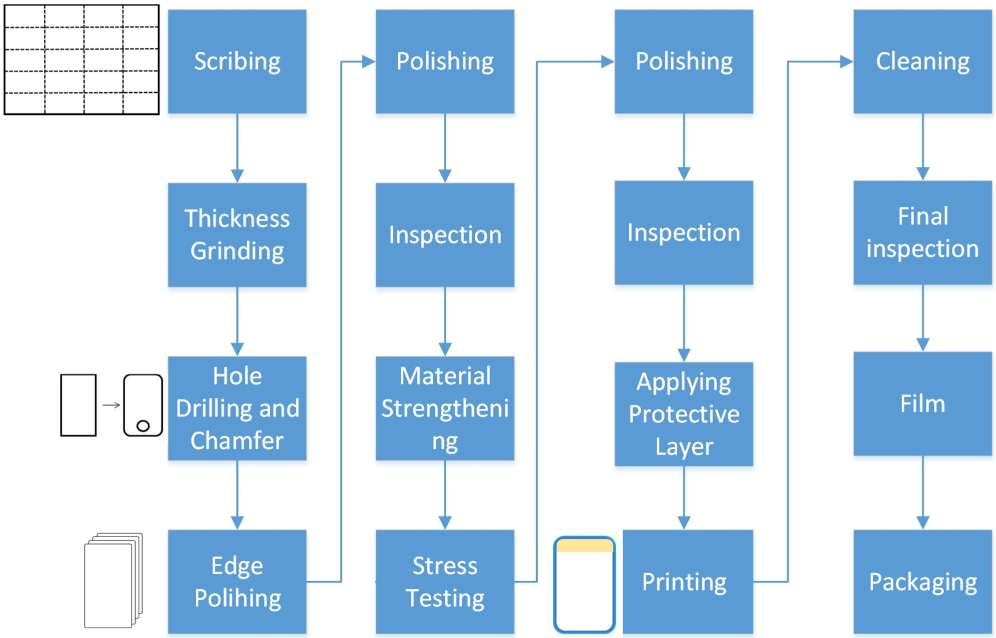


Figure 5.3: Cover glass manufacturing process [51]

5.2.3 Development of E-VSM

Figure 5.4 demonstrates how E-VSM facilitates identification of manufacturing and environmental metrics using symbols designed to represent production information. Each data box represents a process and the numbers inside the box provide information about the corresponding process. To make E-VSM legible, some abbreviations were used in the figure, including cycle time (CT), availability (AV), and defect rate (D). The timeline section of the E-VSM shows cycle time and wait time. The process energy consumption is captured inside the oval, while energy consumed during transportation is listed on a line between ovals. The triangle icon shows the inventory between two processes.

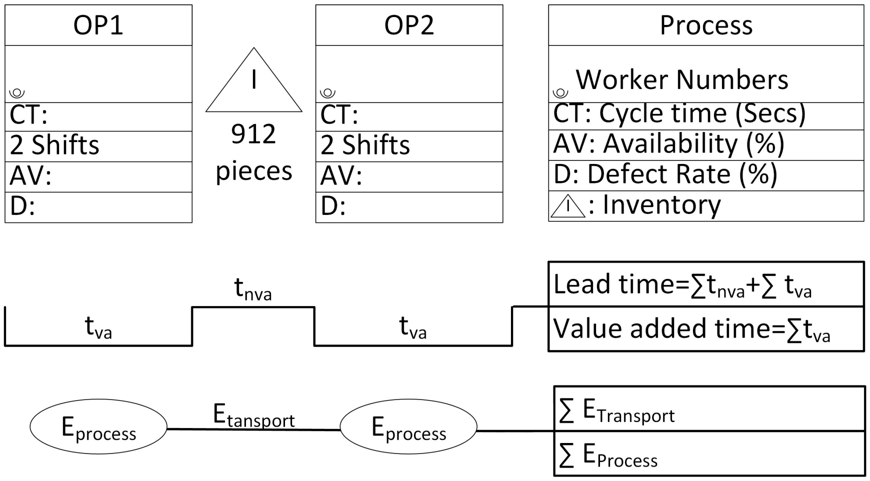


Figure 5.4: Visual representation of metrics in E-VSM

The scope of assessment is factory level which includes all different kinds of machine tools need to make up a production line. Figure 5.5 represents the current state map of the facility which was completed after the plant floor visit. The value-added time is approximately 2 minutes, whereas the total lead time is over 19 hours. The total material travel distance is 628 meters from first station to shipping dock. Every glass piece that was produced in this line consumed 14.7kWh of energy. Since manual material handling was used to transport parts between stations, there is no between-process energy consumption. Overall, the company finds E-VSM to be extremely beneficial to visualize the performance of the production line. The data presented in E-VSM provides the glass manufacturer with a good overview of current performance and helped the company to identify areas that require further improvement.

5.3 Discussion of the Results

5.3.1 Improvement Strategies

The construction of E-VSM has provided a chance to identify production problems and waste in the system. Upon completion of the current state map, improvement strategies will be proposed based on the diagnosis provided by E-VSM.

Implement a modified facility layout

Operators frequently need to walk a long distance to load and pick up the work-in-process. Figure 5.7 shows the current layout of the cover-glass manufacturing facility. A process-based straight production line is used from the beginning to the end of the production line. Materials are moved over long distances, which means a waste of time and energy, resulting

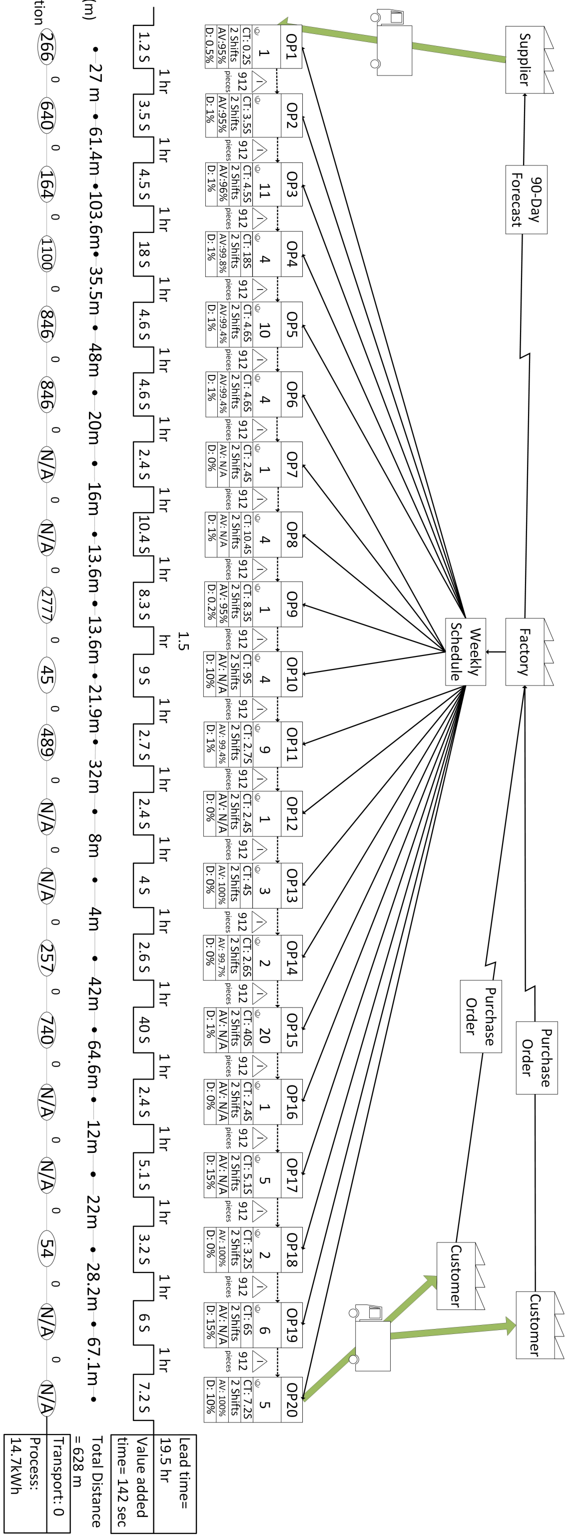
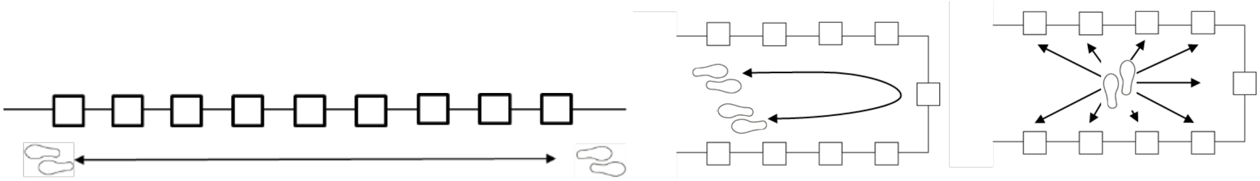


Figure 5.5: E-VSM of a cover glass manufacturing facility [51]

in high cost. Implementing U-shaped production line within certain stations can successfully reduce cycle time. By adopting a U-shape production line, the longest walking distance for 10-meter-long I-shape production line can be reduced to 6 meters, as shown in Figure 5.6a and Figure 5.6b Assuming that operators walk at an average speed of 1.5 m/s, the new layout can reduce 33% of original walking time.



(a) I-shape Production Line (b) U-shape Production Line

Figure 5.6: Production line layout planning

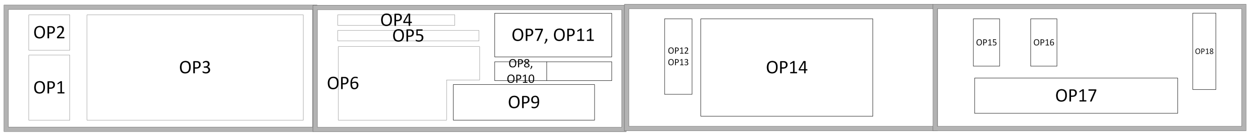


Figure 5.7: Schematic layout of the cover glass manufacturing facility [51]

Identify the bottlenecks

Takt is a German word for a musical beat or rhythm. Takt time is the rate that the company should produce, based on the rate of sales, to meet the customers demand. It is calculated by dividing the customer demand for the identified time period, into the net available working time for the same time frame. Using the collected customer data, it is now possible to understand the demand and its effects on the current value stream. In the cover-glass manufacturing facility, there are two shifts per day and 10 hours per shift. Operators have meal periods and breaks, which amount to 2 hours; thus the net available time is 8 hours per shift. The customer demand is 10000 pieces per day. The calculation for takt time is as follows:

$$\begin{aligned} Takt\ Time &= \frac{Net\ available\ time\ for\ identified\ time\ period}{Customer\ demand\ for\ the\ same\ period} \\ &= \frac{16\ hours}{10000\ pieces} = 5.76\ seconds \end{aligned} \tag{5.1}$$

Based on the above Takt time, the production system must complete one piece and have it ready to ship on the average of every 5.76 sec. When the cycle time of a process step

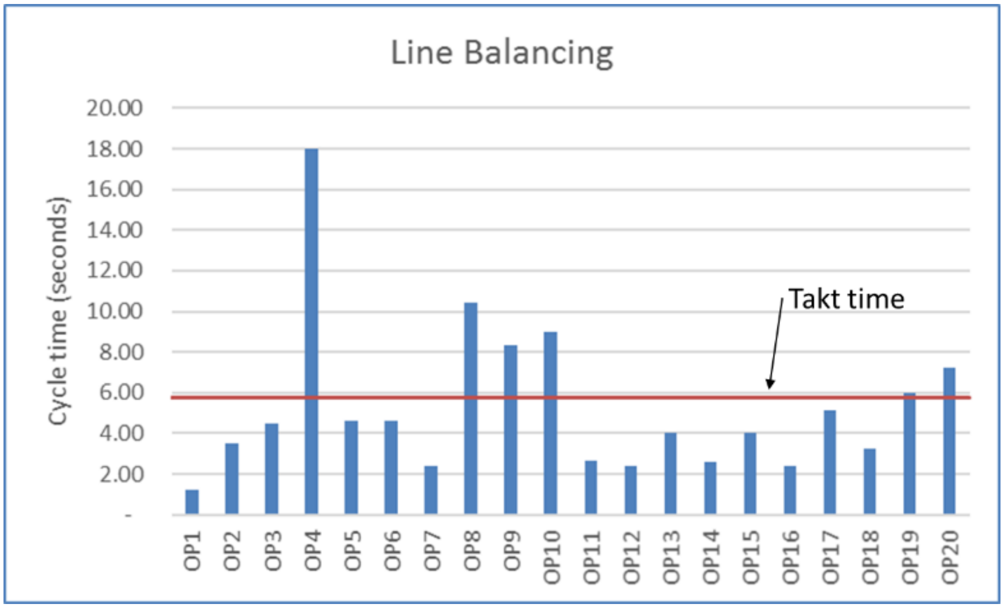


Figure 5.8: Cycle time and takt time

is longer than takt time of the production line, the process is identified to be a potential bottleneck. Using value stream concepts, the current state of manufacturing processes is analyzed and potential areas of improvement can be identified. In Figure 5.8, operations 4, 8, 9, 10, 19 and 20 will not be able to keep pace with the system which means that they are process bottlenecks.

There are many possible causes of process-related problems [17]. Each station has different production rates and cycle times. There are processes that use automated machines with high productivity, processes that require manual operations with low productivity. Then there are processes that need constant maintenance. All the differences result in unbalanced processes and production bottlenecks. The production bottlenecks can be eliminated with careful planning, such as adding resources to bottlenecks, or minimizing machine downtime.

Reduce emissions by installing off-grid power

According to Figure 5.5, the material treatment process (OP8) consumed the highest energy (2.78 kWh). Currently electric ovens are used to harden the material through extreme heating. Considering CO_2 emissions, generally electric ovens are better than gas ovens. However, it might not be true in this manufacturing line. The grid power sources decide whether the process is green or dirty. According to statistical data from the China National Energy Administration, most of the electricity comes from coal, generating 70% of domestic power production. China's second largest energy generating technology is hydropower, representing 19% of its capacity in 2012 [61]. Due to lack of emission data related to electricity generation in China, US EPA eGRID emission factors were used to calculate CO_2 emissions, as a proxy [58]. The amount of CO_2 emitted from electricity generation depends on the quantity and type of energy source consumed. Using both the electricity generation mix in china and EPA eGRID emission factors, the average CO_2 emissions factor for electricity generated in China can be calculated. Generating 1 kilowatthour (kWh) electricity will produce 0.53 $kgCO_2eq$ emissions. One piece of finished glass corresponds to 8.5 $kgCO_2eq$. If the facility can stop using dirty grid power and switch to renewable energy like solar power, the CO_2 emissions can be reduced greatly. For example, if the facility has on-site solar panels which can produce 50% of their energy needs, the CO_2 emissions can be reduced to 4.6 $kgCO_2eq$ per piece, which is about a 46% reduction.

5.3.2 Uncertainty Analysis

Electricity usage and its associated emissions are important contributors to the environmental impacts of many processes in this study. However, it is important to know that these estimates are uncertain and dynamic, since electricity generation involves either an explicit or implicit assumption about the mix of methods used to generate purchased electricity at the given location and time. Changes to this critical assumption can raise or lower the CO_2 emissions associated with a product or service by a factor of 100 or more [106]. Due to lack of information on the electricity generation emissions in China, generation grid mix data have been derived from the literature [52]. Therefore, the uncertainty in the CO_2 emissions factor at various geographic levels in China will be investigated.

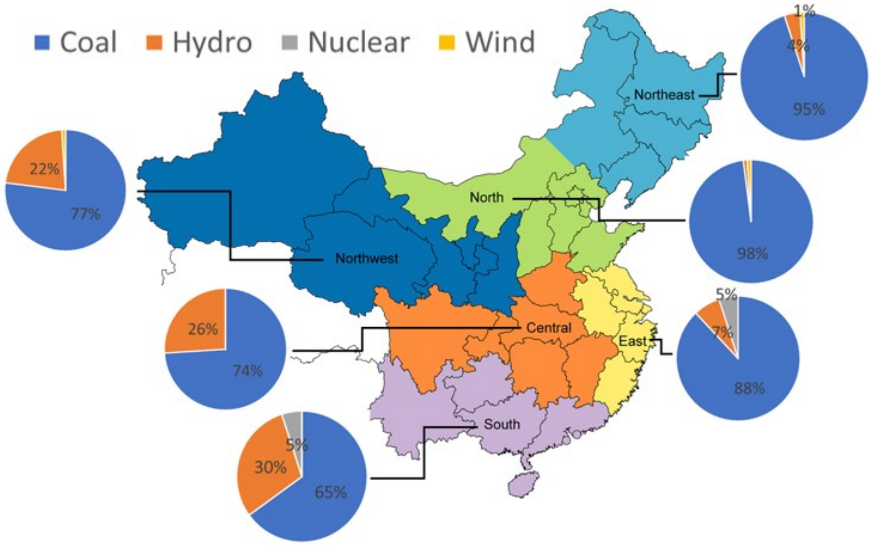
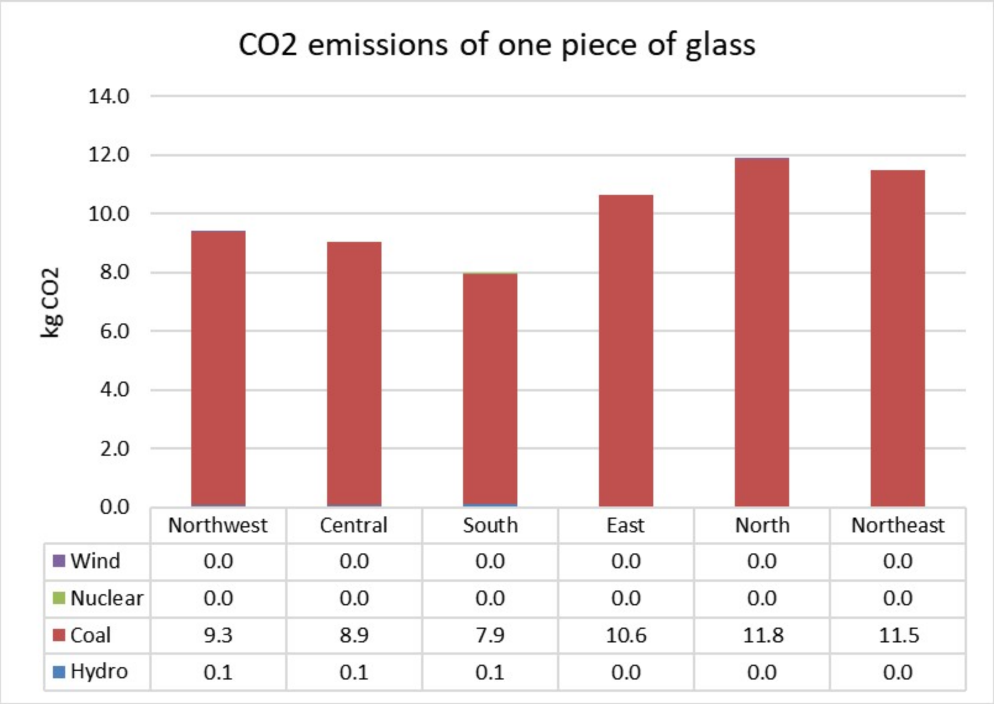


Figure 5.9: Electricity generation mix of six inter-provincial power grids in China in 2008 (modified from [52])

Although China is often seen as a homogeneous entity, it is a vast country with substantial regional variation in economic development as well as electricity generation. China has six large inter-provincial power grids, which are named for the regions they serve: Northeast China, North China, Central China, East China, Northwest China, and South China. In each geographic region, the electricity generation portfolio consists of a different set of fossil fuels(coal, natural gas, and petroleum), nuclear energy, and renewable energy sources (hydro power, wind energy, solar energy). Figure 5.9 presents the generation mix of these six power grids in 2008 [52]. Considering such a wide range of differences, uncertainty analysis can play a significant role in informing environmentally benign decision. The previous calculation based on the assumption that the production takes place in Hunan, China. However, Lens Technology owns factories in different locations. Incorporating the generation and emission differences between various regions is important.

Since the power mix vary significantly with different geographical locations, the CO_2 emissions results lie between 8 and 11.8 $kgCO_2$ for producing each piece of cover glass, as shown in Figure 5.10. Currently, the cover glass products are being manufactured in Hunan, a province located in Central China. If the location switches between the best and worst performer, the variation of emissions goes from -11% to 31%, compared to the original calculation. The quantified CO_2 emission results contain site-specific information that are generic and can be used for any manufacturer when deciding factory locations and products being made at certain locations. For example, Lens Technology not only produces cover glasses, but also ceramic products. The company can evaluate all the products and assign them to different factory locations to achieve a lower overall carbon footprint.



	Northwest	Central	South	East	North	Northeast
Wind	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0
Coal	9.3	8.9	7.9	10.6	11.8	11.5
Hydro	0.1	0.1	0.1	0.0	0.0	0.0

Figure 5.10: CO_2 emissions of producing one piece of cover glass

5.3.3 Lessons Learned

From constructing E-VSM, it allows manufacturers to observe the material flow, and to visualize waste in the processes. There are many benefits to using E-VSM [99]:

- Allows a broad view of the entire flow
- Helps to identify wastes
- Expands the application of conventional VSM to natural resource flows by including additional information on the use of energy, water and/or materials [31]
- Provides a simple and standardized way to treat processes

While utilizing E-VSM to improve production does have many benefits, it's not without costs and challenges. First, the complexity of the manufacturing system associated with the production of the cover glasses increases the difficulty in obtaining data for constructing E-VSM. A theoretical takt time plan can be fulfilled under a situation of a simple manufacturing flow. A more diverse products and such systems ultimately require a combination of simulation and takt time analysis for throughput improvement.

Another issue with E-VSM is that it assumes process stability. Processes that are not stable are almost impossible to map and improve. Before constructing the current state map, it is necessary to ensure that the production system will operate consistently over a given period of time.

Potential future work on this topic will include the evaluation of the interaction between various future state E-VSMs with discrete simulation tools, such as Arena by Rockwell. Lean techniques combined with simulation models can be a very effective tool. The potential of using simulation technologies in implementing lean practices needs to be explored, and only a few case studies have been investigated [69] [1]. E-VSM method enables manufacturers to identify the bottlenecks of the production system, and discrete event simulation models can be used to verify and validate the findings.

Chapter 6

Conclusions and Outlook on Future Work

6.1 Summary of Contributions

This dissertation presents a detailed systematic study of manufacturing systems at three different levels: process, machine, and factory, and contributes to improving resource consumption efficiency in manufacturing. The contributions of the research presented are highlighted below:

- Process-Level
    - Investigated micro-burr formation mechanism
    - Employed Taguchi method to select optimal drilling parameters
    - Developed a micro-drilling burr control chart for PCBs
- Machine-Level
    - Calculated water inventory consumption of the face milling process
    - Calculated water scarcity footprint of milling process in different plant locations
    - Conducted uncertainty analysis to evaluate the water scarcity footprint results using two different methods: AWARE and WSI
- Factory-Level
    - Developed an environmental value stream map of a cover glass manufacturing facility
    - Proposed strategies to improve productivity and reduce environmental impacts of a cover glass manufacturing facility

The following subsections provide additional details concerning the contributions of this dissertation.

6.1.1 Development of Micro-drilling Burr Control Chart

The first part of this work investigated process parameter design. Drilling process was chosen as a case study topic. Since the drilling burr is strongly related to process conditions, drilling burr minimization can be achieved by applying proper drilling conditions. Taguchi method was performed to select the optimal machining parameters from varying combinations of cutting conditions for drilling PCBs. Important factors of the drilling process are studied. That is, drill diameters, spindle speed, and feed rate. The classification of burrs and burr formation mechanisms were characterized into two groups: uniform burr and transient burr. Finally, a DBCC was developed as a tool to assist prediction and control of drilling burr under given drilling conditions. The uniform burr region, transient burr region, preferred burr region, drill-bit breakage region, and critical burr-height region were plotted in the DBCC according to various classifications of PCB drilling burrs. The proposed DBCC can be used to predict and control burrs for a large range of cutting parameters.

6.1.2 Water Footprint Assessment of Milling Process

The second part of this study tackled the water use of machine tools. A water footprint assessment of a milling process was conducted following ISO 14046 standards. The data were obtained from various sources, including UPLCA data base, statistics from EPA, and literature. Three input areas were studied: milling energy consumption, facility usage, and cutting fluid consumption. Parts cleaning and milling cutter replacement are studies, but left outside the scope. Water footprint accounting was carried out on a milling machine. The electricity consumption of a milling tool turned out to be the greatest consumer of water. It accounts for 88 % of freshwater consumption.

A midpoint impact assessment was carried out. Since freshwater availability and demand are highly dependent on the geographic location, five locations are selected to calculate regionalised impacts: China, the United States, Germany, Japan, Italy. The water scarcity profile calculated varies from 0.63 to 46.27 m^3 world eq following the AWARE method. The effects of water scarcity footprint on different plant locations are demonstrated. Finally, an uncertainty analysis was carried out to evaluate WSF results using two different midpoint impact assessment methods: AWARE and WSI.

6.1.3 Implementation of E-VSM

Part three of this work has been extended to the facility level. This study integrates environmental metrics into conventional VSM, and examines the implementation of E-VSM through a case study of a cover-glass manufacturing factory in China. Production bottlenecks have been identified through the construction of E-VSM. A theoretical takt time was calculated for throughput improvement. Key areas of improvement were highlighted for factory managers to consider that affect cost and energy, namely: factory layout, process cycle time, and grid power. Applicability of E-VSM was explored, and uncertainty of grid power was discussed.

Since the energy profiles and its associated emissions vary from states, the uncertainty and the associated environmental impacts are evaluated for different plant locations.

6.2 Future Work

Future research efforts should concentrate on advancing energy and resource use of manufacturing systems. Potential future works on this topic are described below:

The availability and reliability of data has been a major bottleneck in conducting environmental impact assessments. Most of the studies reported were conducted based on incomplete data from experiments, or even assumptions. This makes results hard to apply in practice. Manufacturers must implement a new data acquisition system, which continuously gather and tracks production data, such as machine and process data, energy data, QA-relevant data. With easy assess to all the data, operators and engineers can address high-value issues and increase plant productivity. Accessing real-time results and data will also propel the industry into new levels of lean achievements. It is urgent to develop a decision-making tool that supports manufacturers to access real-time production data, and deliver insights from tool choice to system configuration.

The factory is responsible for processing raw materials and semi-finished products to produce finished products. Within the boundary of a factory, various physical or informational subsystems are involved during production and management. These subsystems are present at different hierarchical levels, for example, the actuator and sensor, control, production management, manufacturing and execution, and corporate planning levels. The real challenge lies in the integration of different models. At present, the information flow is often blocked between subsystems and the continuity and consistency are generally difficult to be guaranteed; and the material flow is along the fixed production lines that lack flexibility. It's important to communicate among different levels of a manufacturing system, and provide insights to improve the system throughout all levels of the manufacturing hierarchy. Through vertical integration of the hierarchical subsystems, the traditional factory can be transformed into the highly flexible and reconfigurable manufacturing system.

Water is involved at many points of manufacturing processes, such as electricity generation, raw materials extraction and in-product water usage. Manufacturers need a better decision support tools for sustainable manufacturing, which not only consider energy consumption but incorporate water and other resources. The newly establish ISO 14046 standards provide a good framework for researchers to follow, and enable the results to be compatible to life cycle assessment. More industrial case studies would be beneficial to be added to this research field, which examines the implementation of water footprint assessment on industrial products.

Appendix A

Glossary

1. **Manufacturing Energy Consumption Survey (MECS)**: The Manufacturing Energy Consumption Survey (MECS) is a national sample survey that collects information on the stock of the U.S. manufacturing establishment, its energy-related building characteristics, and energy consumption and expenditures.

2. **Sustainable manufacturing**: Sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources [31].

3. **Takt Time**: The available production time divided by the rate of customer demand. Takt time sets the pace of production to match the rate of customer demand and becomes the beat of a lean system [28].

4. **Water Crisis**: A significant decline in the available quality and quantity of fresh water, resulting in harmful effects on human health and/or economic activity [14].

5. **Water Footprint**: Metric(s) that quantifies the potential environmental impacts related to water [55].

6. **International Organization for Standardization (ISO) Standards**: ISO standards are developed by an international body in order to establish requirements, specifications, guidelines, or characteristics that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose. Two examples of ISO standards are ISO 14046 for water footprint assessment and ISO 50001 for energy management systems [29].

Appendix B

Water Inventory Calculation

Table B.1 below summarized the data sources and assumptions for the water inventory calculation.

Types	Description	Sources
Electricity consumption of machine tool	Water used for electricity generation of the machining process	UPLCA[83]
Facility water use	13 gallons/worker/day	EPA[32]
Facility electricity consumption	Water used to maintain temperature and clean equipment	EPA [32]
Cutting fluid production	Soluble oil(96% water + 4% oil)	Peachey [85], Wu [111], Hoffman [47]
Cutting fluid loss	5% of the tank volume	Zimmerman [119]
		Iowa Waster Reduction Center [12]
Cutting fluid replacement	55 gallons of cutting fluids/two weeks	Clarens [13]
Worker working hours	8.56 hours per day	Bureau of Labor Statistics

Table B.1: Water use inventory accounting data sources

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