Title
Development of Energy Models for Production Systems and Processes to Inform Environmentally Benign Decision-Making

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Publication Date
2013

Peer reviewed|Thesis/dissertation

Development of Energy Models for Production Systems and Processes to Inform Environmentally Benign Decision-Making

by

Nancy Diaz-Elsayed

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Engineering - Mechanical Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor David Dornfeld, Chair
Professor Arpad Horvath
Professor Alice Agogino

Spring 2013

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Abstract

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Professor David Dornfeld, Chair

Between 2008 and 2035 global energy demand is expected to grow by 53%. While most industry-level analyses of manufacturing in the United States (U.S.) have traditionally focused on high energy consumers such as the petroleum, chemical, paper, primary metal, and food sectors, the remaining sectors account for the majority of establishments in the U.S. Specifically, of the establishments participating in the Energy Information Administration's Manufacturing Energy Consumption Survey in 2006, the "non-energy intensive" sectors still consumed $4.0*10^9$ GJ of energy, i.e., one-quarter of the energy consumed by the manufacturing sectors, which is enough to power 98 million homes for a year. The increasing use of renewable energy sources and the introduction of energy-efficient technologies in manufacturing operations support the advancement towards a cleaner future, but having a good understanding of how the systems and processes function can reduce the environmental burden even further. To facilitate this, methods are developed to model the energy of manufacturing across three hierarchical levels: production equipment, factory operations, and industry; these methods are used to accurately assess the current state and provide effective recommendations to further reduce energy consumption.

First, the energy consumption of production equipment is characterized to provide machine operators and product designers with viable methods to estimate the environmental impact of the manufacturing phase of a product. The energy model of production equipment is tested and found to have an average accuracy of 97% for a product requiring machining with a variable material removal rate profile. However, changing the use of production equipment alone will not result in an optimal solution since machines are part of a larger system. Which machines to use, how to schedule production runs while accounting for idle time, the design of the factory layout to facilitate production, and even the machining parameters – these decisions affect how much energy is utilized during production. Therefore, at the facility level a methodology is presented for implementing priority queuing while accounting for a high product mix in a discrete event simulation environment. A baseline case is presented

and alternative factory designs are suggested, which lead to energy savings of approximately 9%.

At the industry level, the majority of energy consumption for manufacturing facilities is utilized for machine drive, process heating, and HVAC. Numerous studies have characterized the energy of manufacturing processes and HVAC equipment, but energy data is often limited for a facility in its entirety since manufacturing companies often lack the appropriate sensors to track it and are hesitant to release this information for confidentiality purposes. Without detailed information about the use of energy in manufacturing sites, the scope of factory studies cannot be adequately defined. Therefore, the breakdown of energy consumption of sectors with discrete production is presented, as well as a case study assessing the electrical energy consumption, greenhouse gas emissions, their associated costs, and labor costs for selected sites in the United States, Japan, Germany, China, and India.

By presenting energy models and assessments of production equipment, factory operations, and industry, this dissertation provides a comprehensive assessment of energy trends in manufacturing and recommends methods that can be used beyond these case studies and industries to reduce consumption and contribute to an energy-efficient future.

To my family.

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Acknowledgments

I am blessed to have many people to be grateful to, from my family to members of the UC Berkeley community and beyond.

I would like to first thank my family for their love and support throughout my graduate studies. I would like to thank my parents for helping shape me into the person I am today and for believing in me. My mom, Ana Maria, was always a great source of encouragement. She helped me discover who I am and provided a continuous reminder that no matter what, I should strive to be happy. With his humor, my dad, Abraham, showed me how to not take life too seriously. His career in manufacturing helped shaped my academic endeavors and his perseverance in his fight against cancer gave me strength to overcome some of my greatest struggles.

I was blessed with having my brother, Junior, at Berkeley and having the opportunity to host my family and friends in the bay area. Junior's humor brought about many fun, memorable, and insightful get-togethers and road trips home. Visits from my brothers, Victor and Carlos; nieces and nephew, Lizbeth, Maricarmen, and Jonathon; my cousins; and friends from MIT and Southern California, helped me create fond memories of the bay that I will forever cherish. I am also grateful to my friends at UC Berkeley for the lasting friendships we have built as we sought to pave our paths through our academic programs, developed professionally as research scientists, and strived to maintain a balanced life.

I would also like to thank my husband, Adel, for our enthusiastic discussions of manufacturing research; for asking me questions that helped me dig deeper; and for giving me feedback on my practice presentations and drafts of my dissertation that helped me become a better communicator. I am grateful for his patience, optimism, love, and support, traits that nourished my mind and spirit as I strived to attain my Ph.D.

I would like to express my sincerest gratitude to my adviser, Professor David Dornfeld, for creating a dynamic learning environment that fostered collaboration and excellence; for encouraging me to participate in countless opportunities that helped me advance my research and expand my network of colleagues; and for helping me navigate academia to facilitate the improvement of my teaching and research skills.

I am also very grateful to the members of the Laboratory for Manufacturing and Sustainability (LMAS), alumni, and visiting scholars for their unique perspectives and experiences that contributed to making LMAS a fun, interesting, and effective working environment. Additionally, I would like to thank the members of the LMAS editing and writing groups for providing me with feedback and encouragement throughout the dissertation writing process, Kathy for helping make the LMAS community feel like a home away from home, and the Mechanical Engineering administrative and technical staff for providing their support throughout my graduate studies.

The LMAS Sustainable Manufacturing Partnership (SMP) provided an avenue for my work to be grounded in application. The collaborative research efforts with Mori Seiki and Autodesk proved to be invaluable in the development and validation of my research. I am very grateful to the members of Mori Seiki and Autodesk for their feedback and enthusiasm, and for the opportunity to work with them in our efforts to advance sustainable manufacturing research.

Additionally, I am very grateful for the guidance of my dissertation committee members, Professor Arpad Horvath and Professor Alice Agogino, who also served as my Qualifying Exam committee members. Their expertise has improved my knowledge of sustainability and product design, and allowed my work to reach an audience beyond manufacturing. I would also like to thank Professor Sara McMains and Professor Lee Schruben for being a part of my Qualifying Exam committee, for sharing their insight about teaching, and for their guidance in the development of my research plan.

Lastly, I would like to thank the funders of my doctoral studies: the Ford Foundation, the UC Berkeley Graduate Division, the Alfred P. Sloan Foundation, the LMAS SMP members, and the HENAAC Scholars Program. Their financial support provided me with the flexibility to explore potential research topics and facilitated the advancement and completion of my doctoral studies.

Chapter 1

Introduction

Global energy demand is expected to grow by 53% between 2008 and 2035 [1]. During that time, China and India, two countries with prominent manufacturing operations, are projected to more than double their energy demand. Presently, more than 75% of their electricity is generated by fossil fuels [2; 3] and the United States is not far behind, generating over half of its electricity from fossil fuels [4]. The increasing use of renewable energy sources and the introduction of energy-efficient technologies in manufacturing operations support the advancement towards a cleaner future, but having a good understanding of how the systems and processes function can reduce the environmental burden even further.

Industrial sectors make up approximately one-third of the overall energy consumption of the United States [5]. Manufacturing alone consumed $1.65 * 10^{19}$ Joules of energy as a fuel in 2006 [6]. Figure 1.1 shows the relative consumption of the twenty-one manufacturing sectors defined by the North American Industry Classification System (NAICS) [7]. Industry-level analyses of manufacturing in the United States have historically focused on high energy consumers, namely the petroleum, chemicals, paper, primary metals, and food sectors. However, these are energy-intensive sectors because of the nature of the processes involved; they require a significant amount of energy for the transformation of raw materials and for process heating. The remaining sectors account for 82% of the establishments in the United States and still consume a significant amount of energy: $4.0 * 10^{18}$ Joules, enough to power 98 million homes in the United States for a year [6; 8].

Manufacturing systems are intricate. They exist to transform raw materials and components into products by utilizing local and distant resources, thus, working within a broader network of manufacturers also known as the supply chain. Reich-Weiser et al. [9] capture these intricacies with the presentation of the spatial and temporal perspectives of manufacturing. Spatial views of manufacturing span from the product through the machines and factory, and finally reach the manufacturing supply chain. Assessments can occur across the temporal scale, from the initial design of a unit (a product, machine, factory, or supply chain), the design of the implementation scheme (such as the manufacturing of the product), the refinement of the process, and its completion with post-processing.

This dissertation develops methods to model and assess the energy consumption of man-

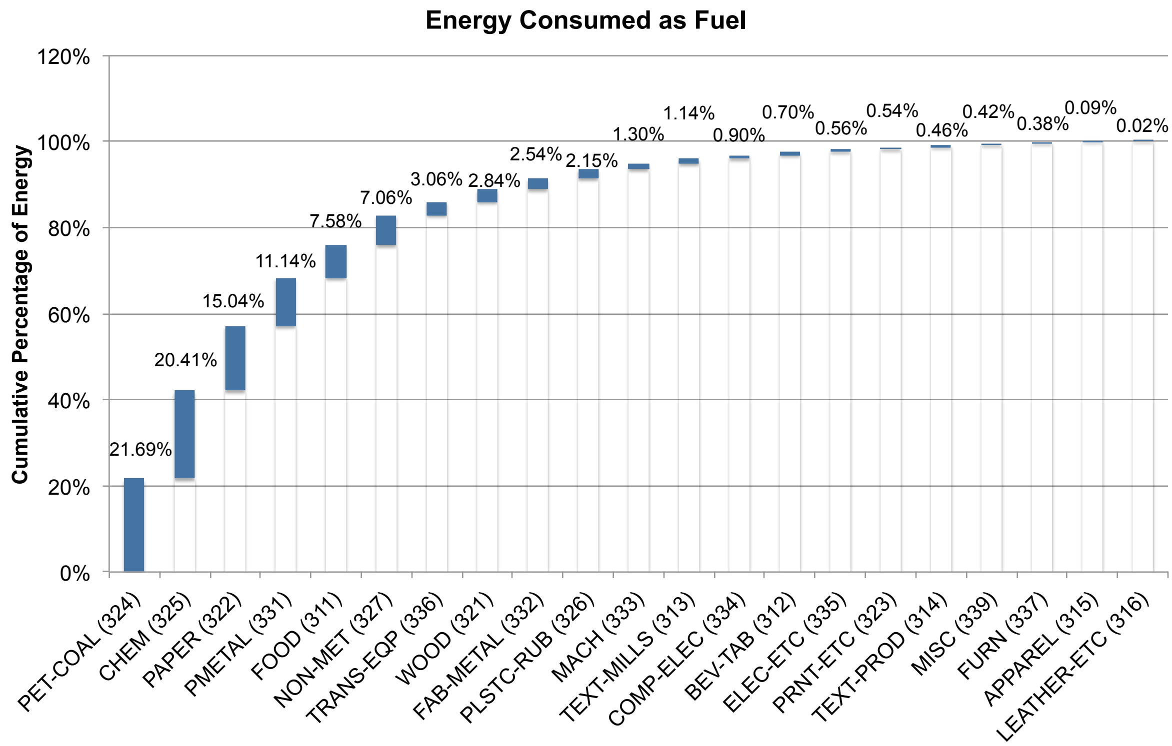


Figure 1.1: 2006 cumulative energy consumption for the U.S. manufacturing sectors (data sourced from [6]).

ufacturing across three heirarchical levels: production equipment, factory operations, and industry (see Figure 1.2). Chapter 2 presents the background and previous research that has been conducted on energy modeling of production equipment and factory operations. Chapters 3 and 4 of the dissertation focus on characterizing the energy consumption of production equipment, identifying ways in which a product designer can be mindful of the manufacturing phase impact of their product, and validating the energy model for a toolpath with a varied material removal rate profile.

However, changing the use of production equipment alone will not result in the optimal solution since machines are part of a larger system. Limiting green manufacturing strategies to production equipment could lead to inefficiencies down the line. Machine tools can sit idle for an extended period of time, for example, with increased processing speeds. The flow of products must be well-orchestrated through the factory floor in order to effectively implement green strategies on the production equipment and factory operations as a whole. Which machines to use, how to schedule production runs while accounting for idle time, the design of the factory layout to facilitate production, and even the machining parameters – these decisions affect how much energy is expended for production. These decisions can be

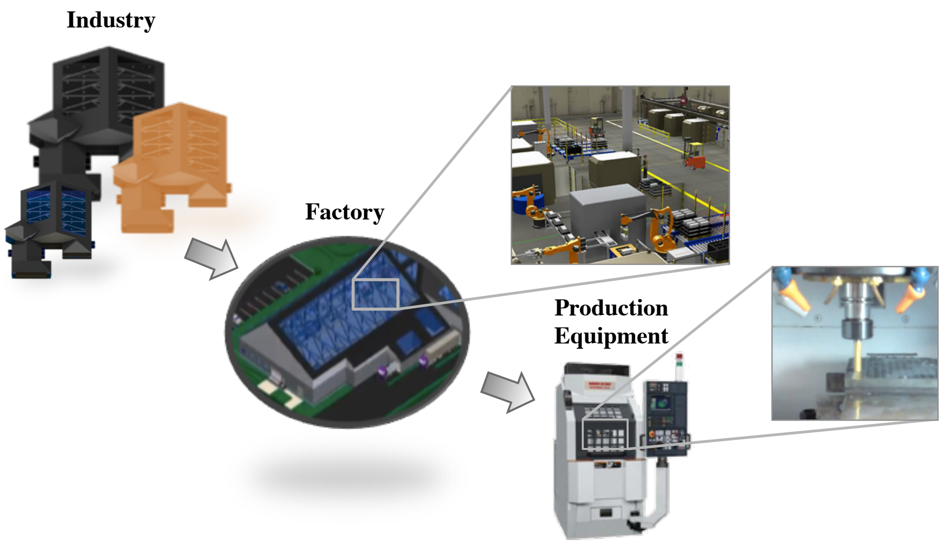


Figure 1.2: The spatial scope: from production equipment to factory and industry level energy consumption.

utilized to influence the flow of products and manufacture in an energy-efficient way.

Current environmental impact models of factory operations are limiting. They accommodate the production of a single product with a strict, pre-determined process flow. The simulations do not allow for smart or green scheduling and realistically, many manufacturers must redefine a process plan on demand as new products enter their system. Nowadays, many manufacturers produce products under flexible manufacturing operations to accommodate a high product mix and meet customer demands. The research of Sheng et al. [10; 11] emerged in the 1990s with the development of process planning tools that accounted for environmental impact, but now more information is known about the real energy consumption of manufacturing equipment. The process mechanics do not dictate the majority of the power demand of equipment. In fact, the efficiency of the production equipment dictates the energy consumption because of the increased use of sensors and peripheral equipment. By simulating the factory with greater accuracy, new, energy-efficient factory layouts can be recommended and the efficacy of process plan and design changes can be accurately assessed. Chapter 5 will therefore present the development of a green machine tool scheduling algorithm and identify optimal factory designs for reduced energy consumption.

At the industry-level, the majority of energy consumption for manufacturing facilities is utilized for machine drive, process heating, and HVAC. There have been countless studies on characterizing the energy consumption of manufacturing processes [12; 13] and the HVAC energy consumption of buildings [14]. However, a holistic and accurate representation of manufacturing systems is still not apparent. Without obtaining detailed information about the energy use of manufacturing sites, the precise location of energy consumption is unknown and the scope of factory level studies, whether a life cycle assessment or the simulation of factory operations, cannot be properly defined. Many manufacturing companies are hesitant to release this information for fear of being overcome by competitors. Furthermore, the ability to obtain refined information about the breakdown of energy usage in facilities is limited because sites are rarely equipped with the appropriate sensors to track it.

Chapter 6 therefore aims to break down the energy consumption of manufacturing facilities for sectors manufacturing discrete products – specifically concerning the production of wood, metal, and plastic raw materials and their associated products. Since it is important to account for the fact that the energy consumption and manufacturing costs vary with location, a case study will be presented which estimates the electrical energy consumption, greenhouse gas emissions, their associated costs, and labor costs for sites in the United States, Japan, Germany, China, and India.

By presenting energy assessments of production equipment, factory operations, and industry, this dissertation will provide a comprehensive overview of energy trends in manufacturing and recommend effective methods that can be used beyond these case studies and industries to reduce consumption and contribute to an energy-efficient future.

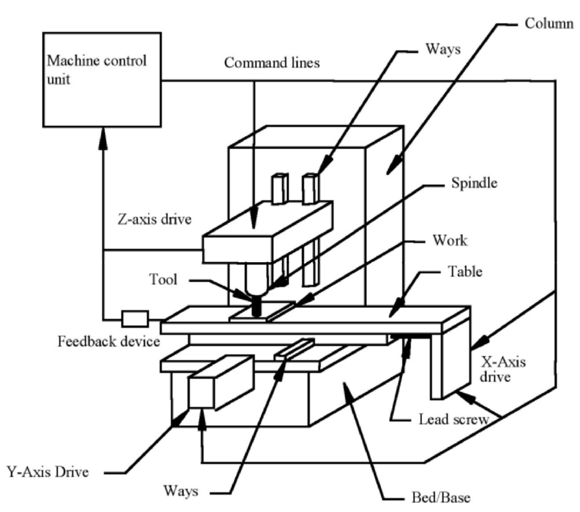
Chapter 2

Background and Literature Review

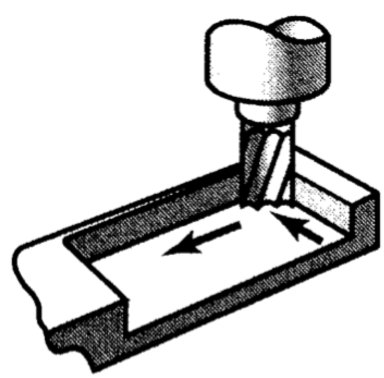
2.1 Energy Consumption of Production Equipment

2.1.1 The Machining Process

Production equipment are utilized to create precise and accurate features. Since milling will be the primary machining process used in many of the case studies discussed throughout this dissertation, the discussion of machining will revolve around a milling example. Figure 2.1a shows the basic components of a vertical machining center, which is composed of four primary components: the spindle, table, bed (or base), and column.



(a) The structural "loop" of a vertical machining center [15].



(b) The milling process (after [16]).

Figure 2.1: A vertical machining center and the milling process.

In a vertical machining center, the spindle serves to rotate and position the cutting tool along the z-axis in order to remove material from a workpiece (see Figure 2.1b for the milling process); the table moves the workpiece along the x- and y-axes by means of a guiding mechanism such as a lead screw and ways; and the bed and column stabilize the machine tool by absorbing the forces generated during the cutting process.

The amount of material that is removed during a milling operation can be described by the width of cut, w, depth of cut, d, and feed rate, f. For peripheral milling, where material is removed along the side of a workpiece, the width of cut denotes how much the cutting tool (in this case an end mill) is engaged in the workpiece in the direction that is perpendicular to the cut being made. Slot milling is a scenario where the entire diameter is used to remove material. The depth of cut describes how deep the cut is, while the feed rate denotes the speed of the table movement. Given these parameters, the material removal rate for milling can be calculated with Equation 2.1.

$$MRR = w * d * f \tag{2.1}$$

Processing conditions of a milling operation are typically described by the cutting speed, V, feed per tooth, f_t, and feed rate, f. The cutting speed denotes how quickly material is removed at the interface between the cutting tool and workpiece material. It can be calculated by Equation 2.2, and is a function of the diameter of the end mill, D, and the spindle speed, N. The feed per tooth indicates the amount of material that is removed by each tooth of the end mill (see Equation 2.3). The number of teeth on an end mill, n, is equivalent to the number of flutes. The shape of the flutes can vary depending on the type of cutting tool used for any given application. Typical recommendations for the feed per tooth fall in the range of 0.08 to 0.46 mm per tooth, and are largely dependent on the type and the diameter of the cutting tool as well as the type of material being cut [16].

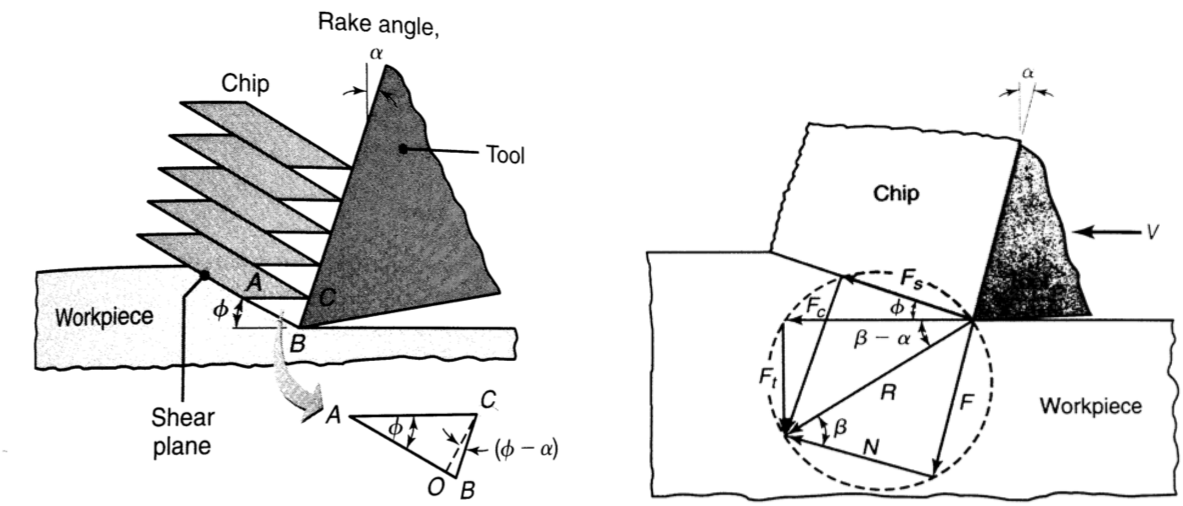
$$V = \pi * D * N \tag{2.2}$$

$$f_t = \frac{f}{N * n} \tag{2.3}$$

Machining is considered a subtractive manufacturing process where chips are produced by means of plastic deformation and shearing as shown in Figure 2.2a. Note that the figure portrays a larger chip size relative to the size of the cutting tool than what realistically occurs during machining. The depth of cut, rake angle (α), and shear angle (ϕ) affect the thickness of the chip, t_c (see Equation 2.4) [16].

$$t_c = d * \frac{\cos(\phi - \alpha)}{\sin(\phi)} \tag{2.4}$$

Figure 2.2b shows the relevant cutting forces during the machining process. The cutting force, F_c, provides the energy required for removing material. F_c acts in the direction of the cutting velocity, V. Perpendicular to the cutting force and cutting veloicty is the thrust



(a) Chip formation during machining [16]. (b) Cutting forces during machining [16].

Figure 2.2: Chip formation and the relavant cutting forces during a machining operation.

force, F_t. The cutting force and thrust force produce the resultant force, R, shown in Figure 2.2b. Consequently, these forces can be represented by Equation 2.5 and Equation 2.6 where β is the friction force and α is the rake angle.

$$F_c = R\cos(\beta - \alpha) \tag{2.5}$$

$$F_t = R\sin(\beta - \alpha) \tag{2.6}$$

The shear force, F_s, acts parallel to the shear plane and is shown in Equation 2.7 as a function of the cutting force, thrust force, and the shear angle, ϕ.

$$F_s = F_c\cos(\phi) - F_t\sin(\phi) \tag{2.7}$$

The power required to remove material is the product of the cutting force, F_c, and the cutting velocity, V, as is shown in Equation 2.8. More specifically, the power is the combination of the power required for shearing and for overcoming friction:

$$Power = F_c * V = F_s * V_s + F * V_c \tag{2.8}$$

where F represents the friction force, V_s denotes the shearing velocity, and V_c represents the velocity of the chip (see Equation 2.9, Equation 2.10, and Equation 2.11).

$$F = R\sin(\beta) \tag{2.9}$$

$$V_s = \frac{V\cos(\alpha)}{\cos(\phi - \alpha)} \tag{2.10}$$

$$V_c = \frac{V \sin(\phi)}{\cos(\phi - \alpha)} \tag{2.11}$$

The specific energy consumed for cutting a unit of material, e_c, can thereafter be calculated as shown in Equation 2.12. An accurate prediction of cutting forces is difficult to obtain since there are so many factors involved, leaving it largely dependent on experimental data. A list of the range of the minimum energy requirements of cutting operations is listed in Table 2.1 for many different types of workpiece material. The steady state value of the experimentally obtained energy models will be shown to lie within the range of these minimum specific energy requirements in chapter 4.

$$e_c = \frac{F_s * V_s}{w * d * V} + \frac{F * V_c}{w * d * V} \tag{2.12}$$

Table 2.1: Specific energy requirements for cutting operations [16].

Material	Specific Energy $[\frac{W-s}{mm^3}]$
Aluminum	0.4–1
Cast irons	1.1–5.4
Copper alloys	1.4–3.2
High-temperature alloys	3.2–8
Magnesium alloys	0.3–0.6
Nickel alloys	4.8–6.7
Refractory alloys	3–9
Stainless steels	2–5
Steels	2–9
Titanium alloys	2–5

2.1.2 The History of Energy Models for Machining

The modeling of the energy consumption of machine tools begins with the development of the process mechanics models by Ernst and Merchant [17] and Boston [18] summarized in subsection 2.1.1. In the 1940s, they developed the force models associated with orthogonal and oblique cutting, and deduced the associated power requirements (see Figure 2.3). Since then, many others have contributed to the research of process mechanics such as Boothroyd and Knight [19], Niebel et al. [20], and DeVries [21].

Following the development of process mechanics models, in 1952 the Massachusetts Institute of Technology (MIT) showcased the first Numerical Control (NC) machine tool [22]. NC

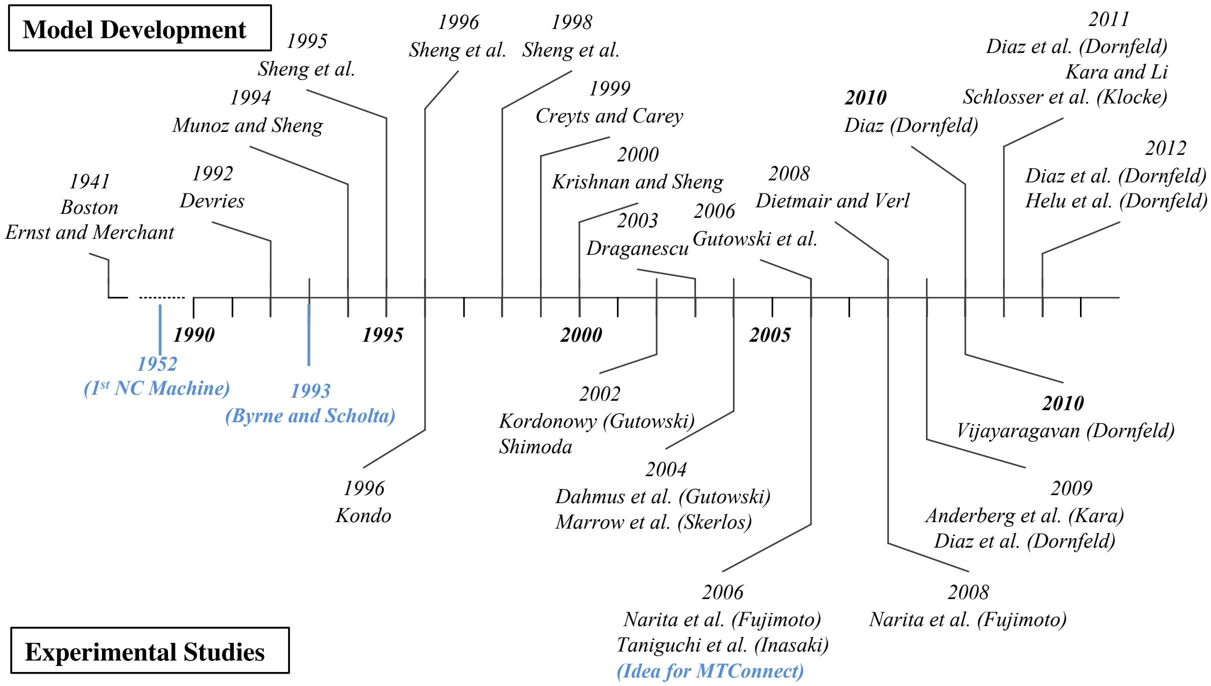


Figure 2.3: Research concerning the energy consumption of milling and turning.

machines essentially accept input commands, which are read by a controller and fulfilled by peripheral equipment (such as servos). Common functions include turning off/on components such as the coolant pump, positioning the table axes or cutting tool, and modifying speeds such as the feed rate or spindle speed. NC machines improved the precision of machine tools by utilizing feedback mechanisms to reduce error, and dramatically increased the capabilities of machine tools to produce precise parts at faster rates, with greater repeatability.

In 1993, Byrne and Scholta discussed the need to expand our research efforts in the field of manufacturing to incorporate the development of "clean" processes and systems [23]. In order to successfully develop clean machining processes, "Increasing importance will have to be placed on methods for improving our understanding of the exact mechanisms arising within the processes".

The emergence of studies concerning the environmental impact of machining commenced in the 1990s with Munoz and Sheng who modeled the energy consumption and waste streams associated with machining [10]. Munoz's energy models utilized prior research on process mechanics to model the material processing stage and calculate the theoretical minimum energy consumption required for processing. Munoz found that the part geometry, material selection and cutting fluid selection had the greatest influence on the processing energy consumption. The further development of micro and macro process planning tools[1] to optimize

[1]Micro process plans concern setting up the conditions surrounding the workpiece and cutting tool

energy, waste, and cost followed [11; 24; 25; 26], as did the development of a detailed exergy analysis of machining by Creyts et al. [27].

The first power measurements of machine tools were published in 1996. Kondo [28] found that the coolant supply pump consumes 60% of the total power (three times as much as the spindle motor). From this study, the following recommendations were made for implementing eco-machining: reduce cutting time, reduce non-cutting time, reduce cutting fluid used, and improve the performance of peripheral devices [29].

In 2002, Kordonowy [30] conducted experimental studies concerning the energy consumption of milling, turning, and injection molding machines and developed the power versus load profile of production equipment shown in Figure 2.4. Kordonowy measured the power demand of an injection molding machine, as well as manual and automated milling and turning centers. For machining, Kordonowy compared the theoretical energy consumption needed to process material, which was comparable to the manual milling machines (Bridgeport F-5-09-355 and 6-X005) and the newer automated milling machine (Bridgeport Torq-Cut TC3 built in 1998), but approximately half of the older automated milling machine (Cincinnati Milacron VC-750 built in 1989).

Additionally, Shimoda [31] conducted a life cycle assessment of turning, Dahmus et al. [32] studied the energy consumption of milling machine tools, and Morrow et al. [33] conducted a case study comparing the difference in energy consumption for utilizing Direct Metal Deposition (DMD) versus conventional milling techniques for tool and die manufacturing. Narita et al. [34; 35] developed an environmental burden analyzer for machining, which included the estimation of energy consumption, cutting fluid consumption, and estimated greenhouse gas emissions. The effects of downsizing a CNC milling machine tool on energy consumption was researched by Taniguchi et al. [36] who found that the smaller machine tool consumed less power, although use of the smaller machine tool was limited with respect to machine performance during heavy cuts. Diaz et al. [37] found that up to 75% of the machining energy can be saved by utilizing the same machine tool and increasing the process rate with the use of coated cutting tools. The results of experimental studies of milling machine tools will be presented in greater detail in section 3.1.

Draganescu et al. [38] modeled the energy efficiency of a vertical machining center and studied the effect of cutting parameters on the cutting forces, energy efficiency, and the specific energy consumption of the machine. Gutowski et al. [12] combined the electrical energy values of a wide array of manufacturing processes including machining in 2006. They found that the specific energy of manufacturing processes was largely dependent on the process rate. Specifically, that manufacturing processes with very low process rates such as oxidation required much more energy than those with high process rates such as machining and injection molding. From this work, Diaz et al. [39] [40] and Kara et al. [41] developed an energy model for machine tools per unit of material processed. This model was proven to have an accuracy greater than 90% for constant material removal rate profiles [41] and

interface such as toolpath planning and processing conditions. Macro process plans concern planning at a higher level such as defining the sequence of manufacturing processes for production.

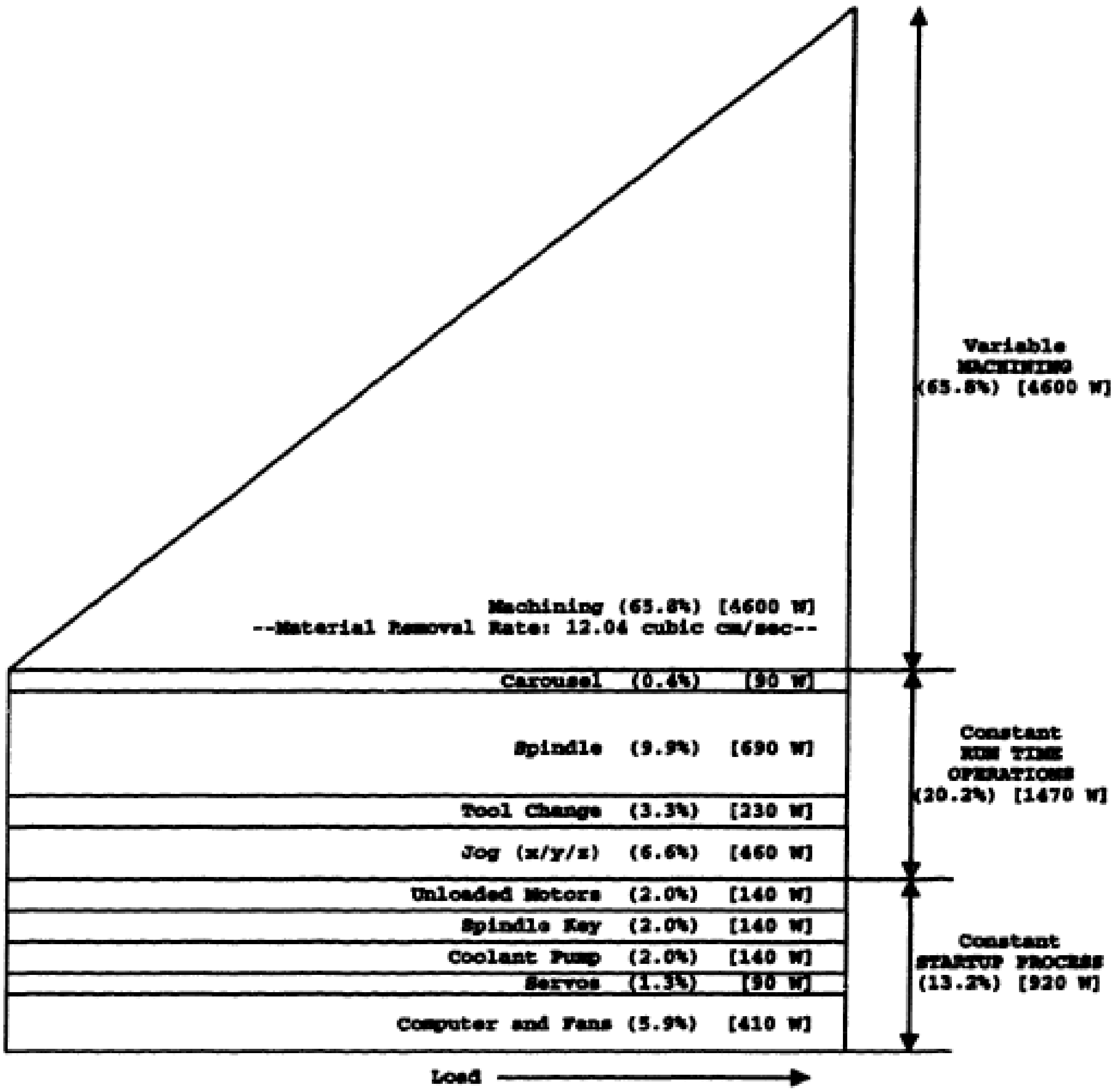


Figure 2.4: Power versus load profile for the Bridgeport Torq-Cut TC3 [30].

97% for a variable material removal rate profile [42]. The variable material removal rate (MRR) case study will be presented in chapter 4. Additionally, the model was validated for turning by Helu et al. [43] who researched the cost and energy consumption associated with roughing and finishing a titanium part.

Dietmair developed a model of the power demand of a machine tool with respect to the machine's usage profile (i.e., accounting for the different operating states of a machine and part machining) by utilizing the energy consumption models of individual, machine components [44; 45; 46; 47]. The detailed model had an exceptionally high accuracy that nearly replicated the measured power precisely and even the coarse (less refined) model had only a 5% error associated with it [44].

The Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) grew from the desire to develop a methodology that captures the intricacies of manufacturing processes with a screening and in-depth approach [48; 49]. The screening approach utilizes public data and engineering calculations to deduce the energy, material flows, and variables for improvement, while the in-depth approach is composed of time, power, consumables, and emissions studies. These approaches provide improved information about the life-cycle inventories of manufacturing processes.

Behrendt et al. [50; 51] developed a methodology for assessing the energy consumption of milling machine tools and suggested the realization of energy efficiency labeling for production equipment. Within this methodology, Behrendt developed standardized tests to evaluate the power demand of common machine tool functions and designed a standard part to measure the energy consumption. Nine machine tools were tested in this study, and these tests would allow a consumer to compare the energy consumption of different machine tools.

Additional experimental studies on the energy consumption of machining have been conducted for milling [52; 53; 54; 55; 56], turning [56; 57], and drilling [53; 58]. A comprehensive summary of studies related to the energy consumption of discrete manufacturing processes has been provided by Duflou et al. [13].

The increased frequency of studies has indeed been facilitated by technological developments occuring within the past decade for correlating power measurements with the machine tool state. Standalone power meters are useful for measuring the power demand of a piece of production equipment, but obtaining information about the corresponding states of the machine tool allows for a much more comprehensive analysis of toolpath efficiency and part design, for example. In 2006 the idea to develop an open standard to facilitate interoperability between a machine tool's controls, devices, and software applications was conceived, which became known as MTConnect [59]. MTConnect can not only be used to identify machine tool states such as spindle speed, position, and feed rates under a common time stamp, but additional sensor technologies as well, such as power meters. Vijayaraghavan et al. [60] show the flexibility that utilizing such a standard provides in conducting a range of energy studies at multiple levels of a manufacturing system and time-scales.

2.1.3 The Power Demand of Production Equipment

Although manufacturing processes differ tremendously, from injection molding to milling and electrical discharge machining, the power demand of any piece of production equipment may be classified into three categories: constant, variable, and processing (see Figure 2.5). The constant power is made up of the power demanded by the peripheral equipment, which remains unaffected by machine load; variable power is dictated by the input settings of production equipment; and the processing power increases as the machine experiences a greater load. The constant and variable power components constitute the tare power demand.

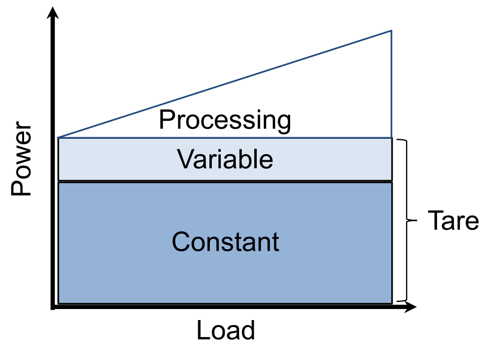


Figure 2.5: Power breakdown of a machine tool versus processing load (after [30; 32]).

Constant Power

Once powered on, a piece of production equipment requires electricity even if it is not processing material or engaged in production operations. This demand for constant power may be attributed to auxiliary equipment that consumes power at a constant rate, independent of the process inputs. For example, a milling machine tool requires electricity when idle to power the controller, computer panel, light fixture, coolant pump, etc. These components draw a constant amount of power regardless of what the machine tool is programmed to do.

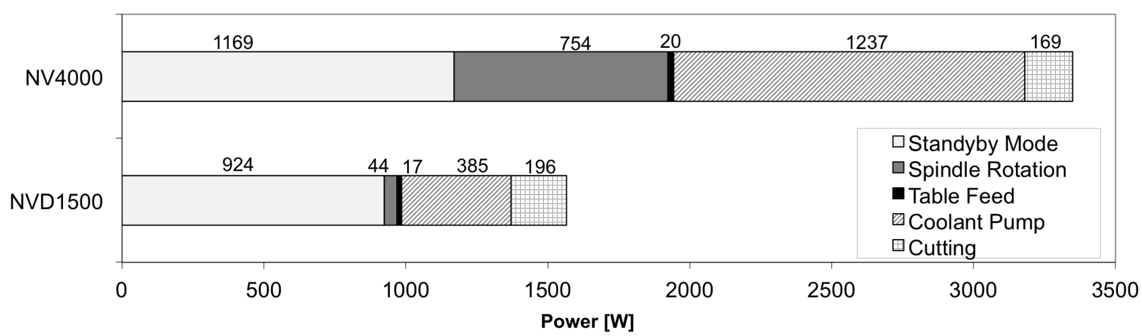


Figure 2.6: Power breakdown of a Mori Seiki NV4000 and NVD1500 with a spindle rotation of 3,500 rpm and feed rate of 300 mm per minute (after [36]).

Out of all of the machine tool's components, the coolant pump draws a relatively large amount of power. As Figure 2.6 shows, the coolant pump of the Mori Seiki NV4000 consumes approximately the same amount of power as the standby power, and for the Mori Seiki NVD1500 about a third of the standby power. This high constant power demand is one reason why machining faster can reduce energy consumption on a per part basis, which will be shown in section 2.1.4.

Variable Power

The magnitude of power demand for some components varies based on operating conditions; this is termed the variable power demand. The power necessary for the motors to traverse and position the axes of a machine tool, for example, is a function of the feed rate. Similarly, the power demanded by the spindle motor of a machine tool varies with spindle speed (see Figure 2.7). The spindle power increases with an increase in spindle speed, and the rate of increase depends on the size of the machine tool as shown by Behrendt et al. [50]. The power was measured without material removal, therefore, the constant and variable power demand are independent of the material processing operation. The power demand for moving the machine tools axes can be characterized in a similar fashion, though the magnitude of the power demand is typically much smaller than that needed for the spindle motor [39].

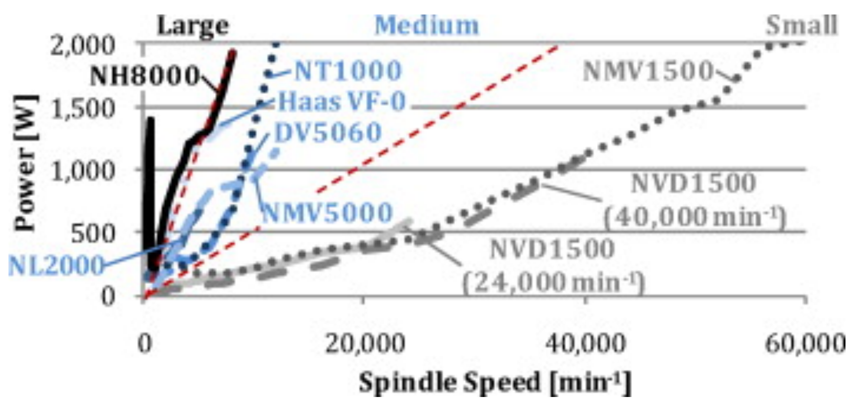


Figure 2.7: Spindle power versus spindle speed of small. mid-size, and large machine tools [50].

Processing Power

Regardless of the type of manufacturing, the act of processing material requires more energy than that provided by the tare power in order to drive the physical phenomena that occur. The power that provides this energy is called the processing power. For a machining center, it is also known as the machining or cutting power. The magnitude of the processing power is comprised of many factors including workpiece material, material removal rate conditions, and cutting tool type. As the load on the production equipment increases, more electricity is required to run the machine. A toolpath without material removal would be considered air cutting and consumes only tare power. If sub-metering was not a viable option, the energy required for material processing could be deduced by subtracting the air cutting power demand from the total power demand, and integrating over time.

2.1.4 Strategies to Reduce the Energy of Production Equipment

Since energy consumption is the integration of power over time, the overall energy consumption of a machine tool may be reduced by reducing the machine power and machining time. The following sections describe strategies for energy consumption reduction that have been developed in both of these areas.

Lower the Power Demand of a Machine Tool

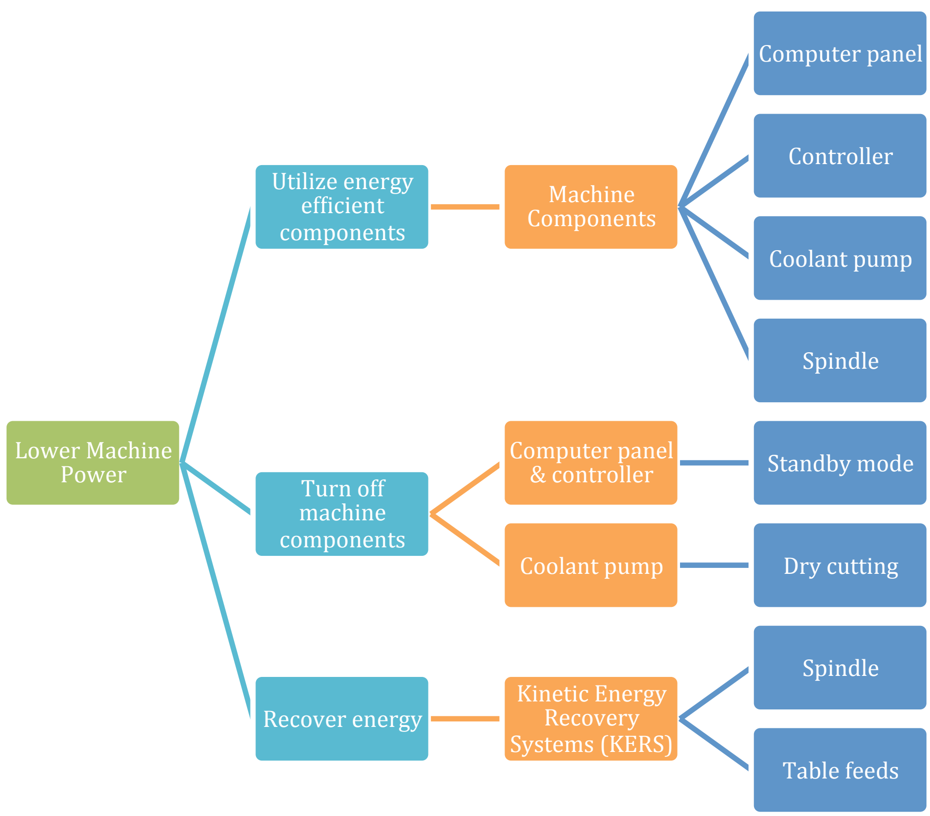


Figure 2.8: Summary of strategies to lower the machining tool's power demand.

The power demand of a machine tool can be lowered by means of the following strategies: utilize energy efficient components, turn off machine tool components, and recover energy dynamically (see Figure 2.8). These strategies summarize methods to lower the machine tool's power demand based on the design and operation of the machine tool.

Utilize Energy-Efficient Components

The breakdown of the power demand of a milling machine tool is shown in Figure 2.9. More than 85% of the machine tool's power demand is used to power the equipment required for standby mode and the coolant pump. Since this is the case, utilizing energy-efficient components can lower the total energy consumption dramatically. Improving the servomotors for the table axes, for example, would not have a significant impact on the overall power demand of the machine tool. Therefore, focus should be placed on utilizing energy-efficient components and improving the energy consumption of the computer panel and controller (components which contribute to the standby mode), and the coolant pump.

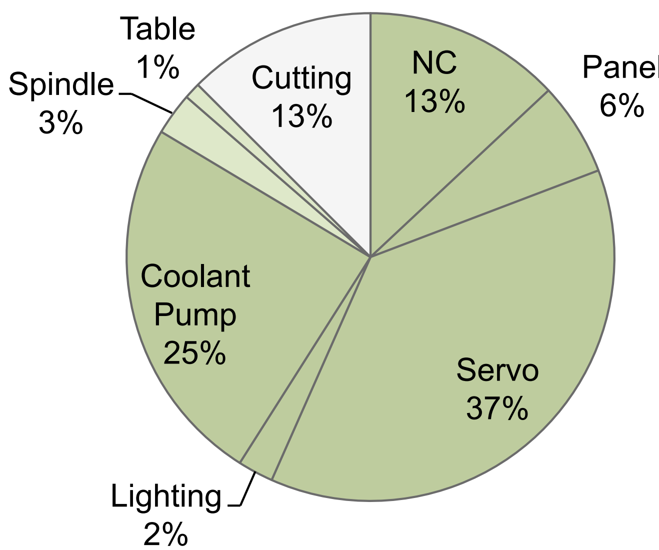


Figure 2.9: Power breakdown of a Mori Seiki NVD1500 with a spindle rotation of 3,500 rpm and feed rate of 300 mm per min (after [36]).

Realistically, the controller is rarely upgraded even though the technological advancements to the machine tool typically occur for this component most often. This is because the controller is one of the most expensive components of the machine tool and requires detailed integration with the other components of the machine. Manufacturers, therefore, often opt to wait to purchase a new piece of production equipment altogether instead of only upgrading the controller.

Turn Off Machine Components

Additionally, power demand of a piece of production equipment can be lowered by turning off some of the machine tool components. Some machine tool manufacturers already incorporate a standby mode, which powers off the computer panel in order to save energy. This component makes up 6% of the overall power demand of the NVD1500 and even more when the machine tool is idling [36].

Aside from targeting the computer panel, the coolant pump, which accounts for 25% of the overall power demand, can be turned off. Thus, if the power demand of the coolant pump can be reduced, one can significantly reduce the power demand of the machine tool as a whole. Dry cutting is one option for eliminating the power demand of the coolant pump altogether. However, there are limitations as to when dry cutting can be implemented. These limitations are related to the manufacturing process, the workpiece material, and design requirements. Klocke et al. have researched the impact of utilizing dry cutting on part quality and tool wear [61]. If the strategy to reduce the power demand of the coolant pump by shutting off this component was chosen, then a change in processing parameters would need to be exercised in order to accommodate the desired tolerances of the part design.

Recover Energy

Energy recovery is another feasible option for lowering the machine tool power requirements and consists of utilizing the power that can be saved from the change in kinetic energy. Energy recovery systems can be integrated into the moving components, i.e., the spindle motor and table feed drives. This power can be stored or utilized immediately. Diaz et al. researched the potential energy savings and economic feasibility of utilizing Kinetic Energy Recovery Systems (KERS) on machine tools and found that it is currently best to target the spindle motors since little energy can be recovered from the table axes [37]. They highlighted that capacitive storage units were too expensive to implement, but using the power immediately, e.g., for another machine tool in the same production line or stored in a shared capacitor for other machines, would be more economically feasible.

Reduce the Processing Time

The reduction of machining time for energy consumption reduction focuses on three areas: utilizing process integration, optimizing the toolpath design, and increasing the process rate (see Figure 2.10).

Process Integration

Process integration requires that there be a significant amount discussion between the designer and the manufacturer in order to maximize the possible energy savings in the manufacturing phase. Often times, a limited amount of discussion occurs between a product designer and the manufacturer regarding manufacturability and best practices. Unfortunately, a product designer may not be aware of the feasibility of manufacturing the part

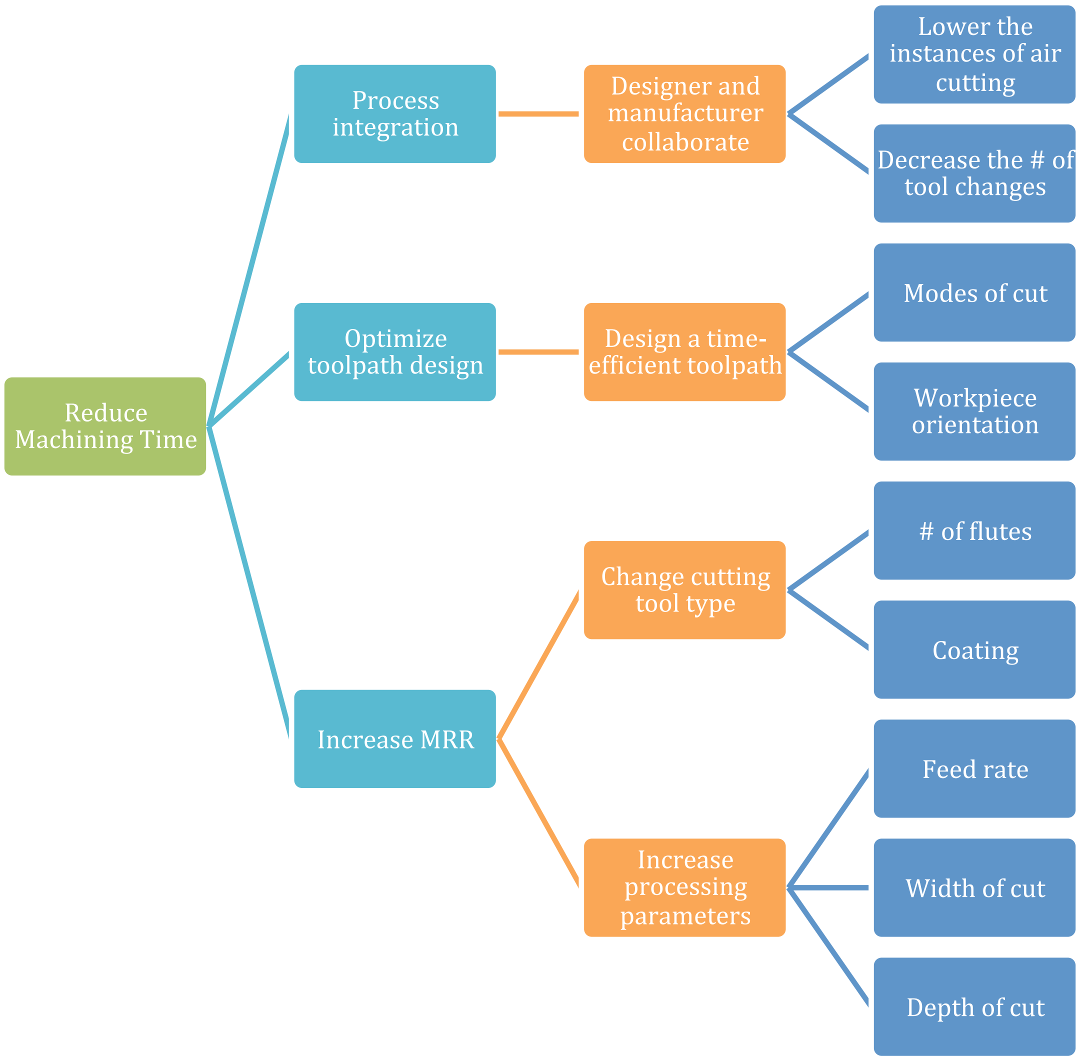


Figure 2.10: Summary of strategies to reduce the machining time.

and its features, and the subsequent environmental impact because of the recent emergence of sustainable manufacturing research. Consequently, designers may not be aware of the impact of their design decisions. Some strategies for designers for the energy reduction of machining will therefore be presented in section 3.2.

With process integration the instances of tool changes and the amount of time spent air cutting can be lowered tremendously as was observed at the Mori Seiki machine tool factory in Iga, Japan as part of this research. Minor design changes of the casting that holds the spindle motor, for example, resulted in the reduction of the number of setups and machining time. Mori Seiki was interested in the reduction of production costs, but the direct advantage of energy consumption reduction also results from these improvements.

Optimize Toolpath Design

The design of the toolpath offers an alternative way of reducing the energy consumption of a machine tool for the production of a particular product without having to select a different piece of production equipment or modify the machine tool design. As was shown previously, lowering the time that a machine tool is used for can effectively lower the energy consumed by the machine tool. Toolpaths offer a tremendous amount of flexibility when it comes to designing how the machine will actually be used to cut a part. Kong et al. [62; 63] developed a methodology for estimating the energy consumption of a part's production based on the toolpath design. They showed that for the same feature, the energy consumption ranged from 1 to nearly 2.5 kWh (see Figure 2.11). Similarly, Rangarajan et al. [64] studied how the orientation of a workpiece affects the toolpath designs and consequently the processing time. As such, a reduction in processing time results in the reduction of energy consumption, so workpiece orientation is another means of altering the possible toolpath designs and subsequently lowering the energy consumption of part production.

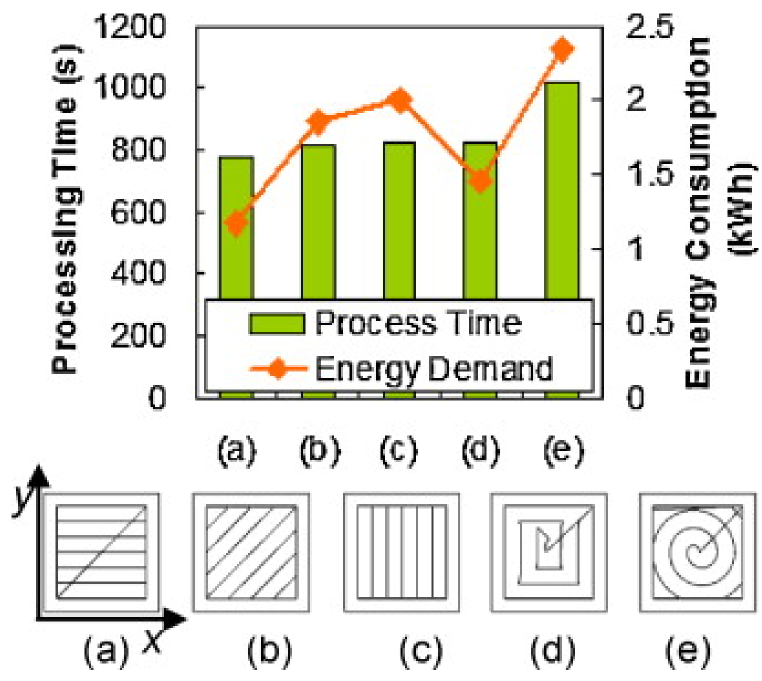


Figure 2.11: Processing time and energy consumption of various toolpaths [63].

Increase the Process Rate

The process rate can be increased by upgrading the type of cutting tool that is utilized and/or increasing the process parameters (see Figure 2.10). Diaz et al. [37] conducted experiments concerning energy consumption reduction and studied the influence on energy from changing the feed rate, feed per tooth, and spindle speed. Initial experiments showed that significantly increasing the feed per tooth, spindle speed, or feed rate while machining with the same cutting tool resulted in a poor surface quality or a dramatic increase in tool wear as the energy consumption decreased with lower processing times. High speed cutting was then analyzed such that the cutting tool was changed from a 2-flute uncoated carbide end mill to a 4-flute TiN coated end mill so that faster processing times could be achieved while staying within the recommended spindle speeds and feeds for a particular cutter (see Figure 2.12). This tool change resulted in a significant reduction in energy consumption with minimal wear on the tool and good surface quality.

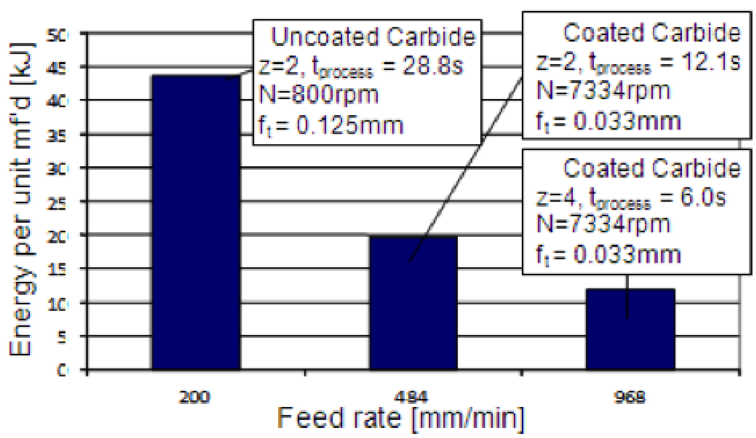


Figure 2.12: Specific energies for part manufacture while varying the cutting tool [37].

Aside from tool wear and the effect of surface quality, another item to keep in mind when increasing the process parameters for energy usage is the impact of these changes on the reliability of the sub-components. Increasing the spindle speeds and feed rates change the load profile of the machine tool. These changes affect the rate of failures of the machine, which in turn increases the life-cycle cost of the machine. The overall effectiveness of this optimization scheme for turning was evaluated by Helu et al. [43] who conducted a trade-off analysis incorporating different processing conditions. They found that higher material removal rates led to lower service costs because of the larger volume of parts produced over the course of a year.

2.2 Energy Reduction in Facility Operations

The following sections describe research related to the energy consumption of facility operations. First, introductory material on process planning is presented in order to describe the inherent flexibility in decision-making that can be utilized for achieving energy-efficient factory operations. Within the decisions that must be made for the development of the process plan, machine tool selection can be leveraged to reduce the energy consumption of facilities, which will be discussed in subsection 2.2.2. Lastly, the research related to the simulation of the energy consumption of factory operations will be presented.

2.2.1 Process Planning

Simple part features requiring milling can typically be produced by a wide array of CNC machine tools. A job shop produces a high mix of specialty parts that can, generally speaking, be processed by a variety of machine tools. These types of facilities require a high worker skill level in order to accommodate the high mixture of products being manufactured within the facility. The facility is set up to accommodate a high product mix, so a layout organized by manufacturing process is commonly utilized [65]. The role of a process planner is to define the optimal route for production, which is especially important in when routing flexibility exists within a facility. Process planning can be broken down into the steps outlined in Figure 2.13 adapted from Scallan [66].

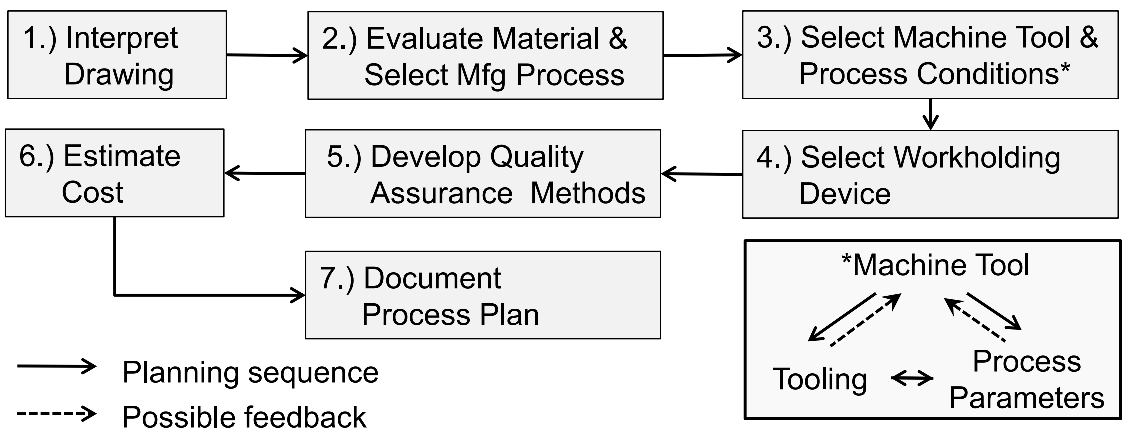


Figure 2.13: The process planning steps (adapted from [66]).

The customer provides an engineering drawing, which is interpreted by the process planner in order to recommend the appropriate type of workpiece material, size, and shape to use and manufacturing process(es) to produce the part. These factors are typically dictated by part characteristics including the types of features and tolerance specifications. Once the manufacturing process(es) are selected, the optimal machine tool is selected. The variables taken into consideration for this step include machine tool availability and work volume, the precision necessary to meet the part tolerance, and the power of the spindle motor.

The process planner or a separate toolpath planner designs the toolpath and selects the tooling and optimal processing conditions. If the planners are optimizing for say, process time, they may first design the toolpath, recommend process parameters, then select the machine tool to manufacture the part (thus taking a bottom-up approach). Alternatively, they may take a top-down approach and first select a machine tool, then determine the optimal toolpath and process parameters if, for example, the spindle motor or work volume is a critical factor. As such, this particular step of process planning can have interdependencies (see *Machine Tool in Figure 2.13).

Once the machine tool is selected and the toolpath and processing conditions are defined, the workholding devices are selected. Thereafter, quality assurance methods are developed. Finally, the cost of production can be estimated and the final process plan is documented.

2.2.2 Machine Tool Selection

The greatest flexibility affecting the energy consumption of factory operations lies in step 3 of the process plan: selecting the machine tool, toolpath, and process conditions. Machine tools have remarkably different rates of energy consumption. Behrendt et al. [50] developed a methodology for evaluating the energy consumption of machine tools, which takes into account the wide array of possibilities of the machine tools functions. The size of the workpiece that was machined for six machine tools is presented in Table 2.2, along with the respective cycle time T_{cycle} that was required to manufacture the part. The energy, E, required to machine the small to large parts varied from 0.1845 to 9.2907 kWh. The energy required for the material processing part alone is shown as a percentage, q_{cut}, of the total energy, E. q_{cut} is relatively small, varying from 1.85 to 20.53%, which is standard for the cutting component of machine tools. Additionally, q_{cut} for precision machines with an extensive amount of peripheral equipment (e.g., NVD1500, NMV1500, NMV5000, and NH8000) is even lower, between 2 and 8%. The peak power, P_{peak}, is also shown and is a function of machine tool size and complexity, reaching as high as 55,600 W.

Table 2.2: Power and energy characteristics of the machining process (adapted from [50]).

Value	Unit	NVD1500	NMV1500	Haas VF-0	DV5060	NMV5000	NH8000
Size	[-]	Small	Small	Medium	Medium	Large	Large
T_{cycle}	[h]	0:10:45	0:10:45	0:15:00	0:15:00	1:16:15	1:16:15
E	[kWh]	0.1845	0.7142	0.3638	0.5557	1.9323	9.2907
q_{cut}	[%]	3.65	1.85	20.53	14.7	4.25	7.57
P_{peak}	[W]	3320	20,130	15,610	16,440	36,900	55,600

Sheng et al. developed micro and macro process planning tools to identify the optimal process plan with respect to waste streams, cost, and environmental impact [10; 11; 24; 25; 26]. These models were based on the thereotical energy consumption of the machining process. Alternatively, a machine tool may be selected based on its specific energy models developed from the research of Diaz et al. [40] and Kara et al. [41]. With knowledge about the recommended process parameters for a particular part, a machine tool may be selected based on the machine tool's energy model in order to lower the overall energy consumption of part production. It is important, however, to take into account the scheduling of and production by all machines operating in the facility, and the simulation of factory operations is one method of identifying the most energy-efficient strategy.

2.2.3 Simulating the Energy of Factory Operations

Previous work in sustainable manufacturing at the facility level is limited, as the majority of facility-level optimization is focused on costing. There are only a handful of contributors that have developed simulations at the factory level, and even fewer researchers who have looked at manufacturing a product with multiple types of manufacturing processes.

Herrmann et al. developed a simulation to analyze lean and green manufacturing strategies [67]. They evaluated the effect of implementing lean manufacturing strategies on energy consumption and cost.

Heilala et al. [68] and Lind et al. [69] furhtered the research accounting for the environmental impact at the facility-level with the development of the SIMTER tool as a means of conducting an environmental impact analysis of a production facility while accounting for part processing metrics. Additionally, Fang et al. [70] studied the energy consumption and peak power demanded by a two machine job shop and Johannson et al. [71] showed how discrete-event simulation (DES) and life-cycle assessment can be combined to evaluate the performance of a manufacturing system with the exemplary case study of a paint shop.

These studies though either focused on the manufacture of one type of product, manufacturing with preset processing conditions and equipment, or both. Since products evolve over time and some facilities manufacture a high mix of products over a range of processing conditions, chapter 5 discusses the development of a methodology for assessing and optimizing the energy consumption of a facility with stochastic operations in order to more accurately characterize factory operations [72].

Chapter 3

Electricity Requirements of Production Equipment

3.1 The Power Demand of Milling Machines

This section is concerned with the impact of changing the material removal rate on the power demand and subsequent energy consumption of a machining center. The material removal rate for a three-axis machining center can be varied by changing the feed rate, width of cut, or depth of cut. Since increasing the feed rate has dire consequences on the cutting tool life [37], the experiments conducted herein varied material removal rate through width of cut and depth of cut experiments [40].

Although increasing the material removal rate translates to faster machining times, the loads on the spindle motor and axis drives increase as well, resulting in a higher power demand. Since the primary goal is to lower the energy consumed for the manufacturing a product, the trade-off between power demand and machining time was also analyzed to confirm that the increased loads due to faster material removal rates did not increase the total energy consumed.

3.1.1 The Effects of Varying Width of Cut and Depth of Cut

Machine tool programmers and operators have an array of options to choose from when outlining the machining strategy for part production. This analysis strives to reduce energy consumption by process parameter selection. Specifically, the parameters of part production concerning material removal rate (MRR) were varied on a Mori Seiki NVD1500 while selecting appropriate tooling. The Mori Seiki NVD1500, is a micromachining center with a relatively low standby power demand when compared to large machining centers. There are quite a few variations of this machine tool model; this particular NVD1500 model had the capability of reaching a spindle speed of up to 25,000 rpm.

In previous work, experiments were conducted in which spindle speed, feed rate, feed per tooth, and cutter type were varied to analyze the change in energy consumption while milling a low carbon steel (AISI 1018) work piece [37]. Additionally, Inamasu et al. [52] conducted experiments on face milling, end milling, and drilling operations in which the energy consumption, machining cost, and tool wear were compared for increased cutting speeds. Tool wear and, consequently, cutting tool cost increased significantly when the process parameters veered away from the recommended cutting conditions. Therefore, in the following experiments the cutting tool type was changed to maintain the recommended process parameters, but nonetheless reduce energy consumption while machining.

Width of Cut Experiments

In this section, the effect of modifying the width of cut on the power demand of the machine tool for machining operations will be assessed. In order to further vary the material removal rate, three types of cutting tools were utilized in this analysis. The width of cut was increased while machining with the following cutting tools:

1. 2-flute uncoated carbide end mills,
2. 2-flute TiN coated carbide end mills, and
3. 4-flute TiN coated carbide end mills.

Peripheral cuts were made along the y-axis of the machine tool at a depth of cut of 2 mm over a length of 101 mm in an AISI 1018 steel work piece with an 8 mm diameter end mill. The width of cut was varied by 1 mm increments between 1 and 7 mm, in addition to a 7.5 mm width of cut. The power demand was measured with a Wattnode MODBUS wattmeter. Table 3.1 summarizes the cutting conditions used. The chip load was maintained at approximately 0.03 mm per tooth to avoid excessive tool wear and breakage.

Table 3.1: Process parameters for width of cut experiments.

Cutter	Spindle Speed $[\frac{rev}{min}]$	Feed Rate $[\frac{mm}{min}]$	Chip Load $[\frac{mm}{tooth}]$	MRR $[\frac{mm^3}{sec}]$
(1)	5426	330	0.033	11–83
(2)	7060	430	0.030	14–108
(3)	7060	860	0.030	28–215

Once the power was measured for each width of cut experiment, the power demand was measured for the machine tool while air cutting, that is, while running the toolpath without material removal. This way the power associated with the material removal process could be extracted, known hereafter as the cutting power demand. The average air cutting power demand was found to be 1510 W for the cutter (2) process parameters, so this value was subtracted from the average total power demand to determine the cutting power demand. Figure 3.1 shows the cutting power demand as a function of the MRR for cutter (2).

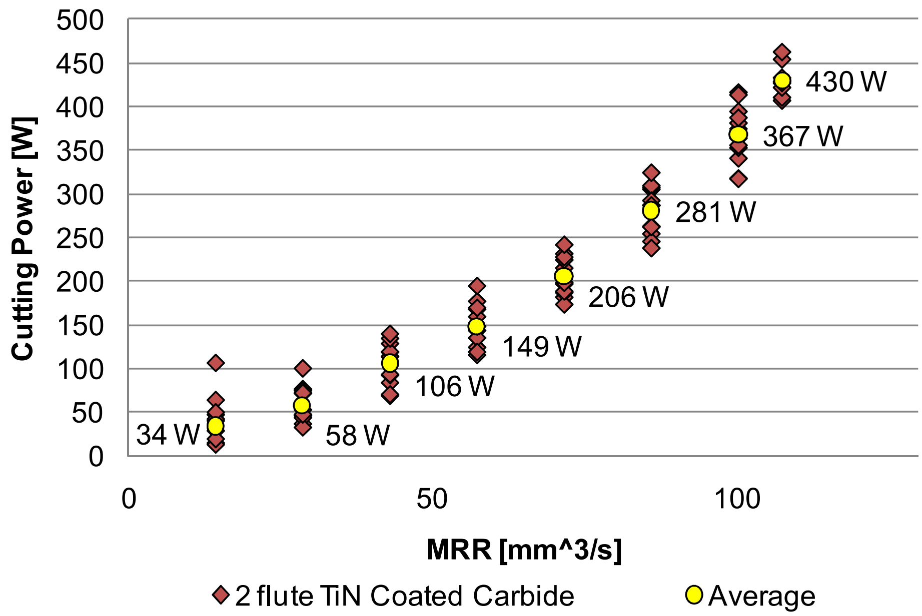


Figure 3.1: Cutting power demand using cutter (2) while cutting AISI 1018 steel [40].

The cutting power demand increases with an increase in MRR. In fact, the cutting power demand for the 7.5 mm width of cut was almost nine times greater than the 1 mm width of cut. However, since the total air cutting power demand was 1510 W, the resulting increase in total power demand of the machine tool was only 28%.

Figure 3.2 shows the average power demand of the NVD1500 for cutters (1)–(3). The relationship between power and MRR shifts from parabolic to linear in moving from the conditions imposed on cutter (1) to cutter (3). The increase in power demand is the greatest for cutter (3), but this is due to the higher load exerted on the machine tool because higher a feed rate is used relative to the other cutting tools.

The magnitude of the cutting power demand with respect to the total power demand of the machine tool increases with load as was highlighted in subsection 2.1.3. Using the width of cut as a means of representing the load on the machine tool, Figure 3.3 shows the relative breakdown of the cutting power demand over the total power demand with respect to the width of cut. For this particular micromachining center, the proportion of cutting power demand varies between 0% and 23% of the total power. Machines that process materials at a much higher load may experience a higher percentage of cutting power demand, but the range shown in Figure 3.3 is fairly typical of machine tools. Most of the power is drawn for the peripheral equipment and to drive the spindle motor.

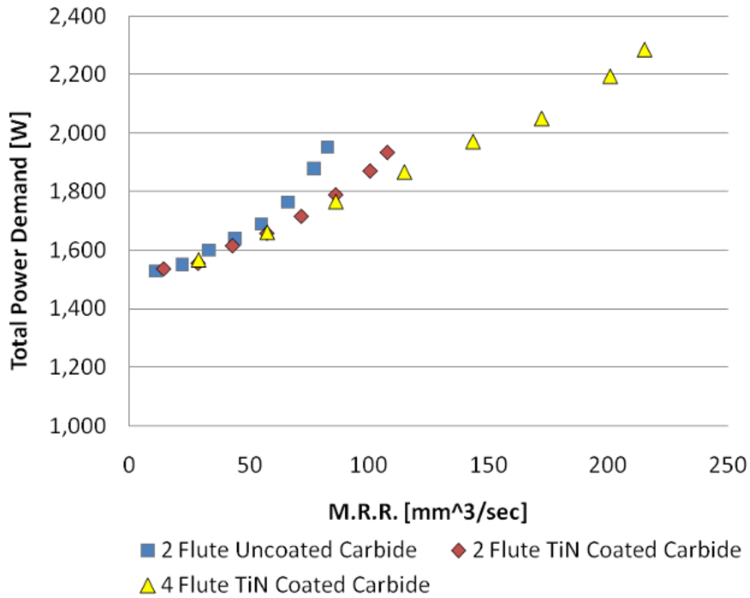


Figure 3.2: Average, total power demand as a function of MRR [40].

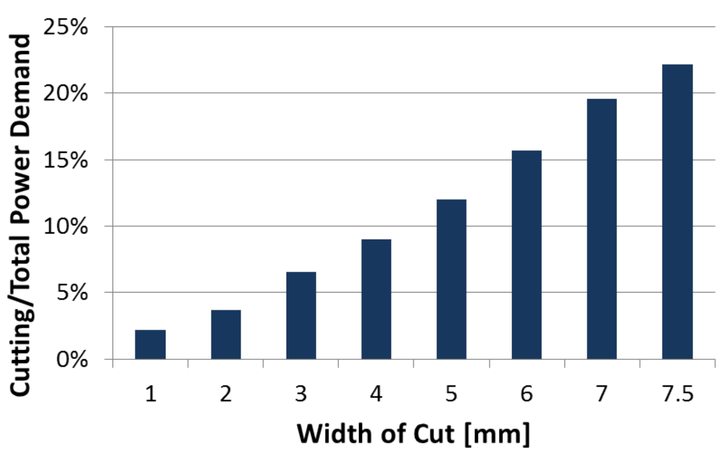


Figure 3.3: Relative proportion of cutting power demand versus width of cut.

Depth of Cut Experiments

Depth of cut experiments were also conducted on an AISI 1018 steel work piece. Cuts were made along the y-axis using 8 mm diameter 2-flute uncoated and TiN coated carbide end mills under near slotting conditions (a width of cut of 7.5 mm) over a length of 101 mm.

The power demand was measured at depths of cut of 1, 2, 4, and 8 mm. The chip load was maintained constant across the various cutters at 0.051 mm per tooth. The spindle speed and feed rate were varied, though, to account for higher loads on the machine tool during the depth of cut experiments (see Table 3.2 for a summary of the processing conditions).

Table 3.2: Process parameter ranges for depth of cut experiments.

Cutter	Spindle Speed $[\frac{rev}{min}]$	Feed Rate $[\frac{mm}{min}]$	Chip Load $[\frac{mm}{tooth}]$	MRR $[\frac{mm^3}{sec}]$
(1)	2500–3200	254–325	0.051	40–250
(2)	3250–4160	330–425	0.051	50–330

Figure 3.4 summarizes the power demanded by the NVD1500 for the 2-flute TiN coated end mill (cutter (2)) and the energy consumed as a function of material removal rate. Although the power demand increases with load, the energy consumption still decreases significantly with the increase in material removal rate. The machine tool increases its power demand by approximately two-thirds of its original value, whereas the energy consumption reduces to less than one-third of its original value. This shows that the decrease in process time effectively dominates the increase in power demand due to increased loads.

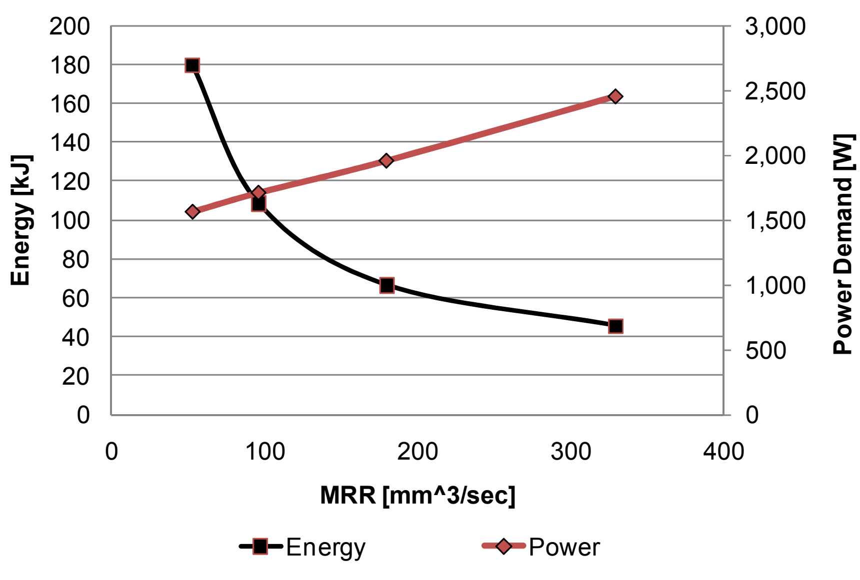


Figure 3.4: Energy and power demand as a function of MRR for depth of cut experiments with cutter (2) [40].

3.1.2 The Effect of Workpiece Material on Power

The aforementioned experiments were conducted with a low carbon steel workpiece. As has been previously mentioned, the type of workpiece material being machined also affects the magnitude of the cutting power demand of the machine tool. For example, a plastic part is expected to exert a smaller load on the spindle motor than a metal part. Therefore, a lower cutting power demand for plastic relative to metal should be observed.

Since the cutting load is expected to vary with the workpiece material, the following experiments measured the power demand of the Mori Seiki NVD1500 while machining peripheral cuts on AISI 1018 steel, AISI 6061 aluminum, and polycarbonate. A depth of cut and width of cut of 2 and 4 mm, respectively, were used. A chip load of 0.0254 mm per tooth was maintained constant across the experiments to allow for the comparison of the results. The process parameters used in the experiment are summarized in Table 3.3.

Table 3.3: Process parameters for power demand experiments with varied workpiece materials.

Material	Spindle Speed $[\frac{rev}{min}]$	Feed Rate $[\frac{mm}{min}]$	Chip Load $[\frac{mm}{tooth}]$	MRR $[\frac{mm^3}{sec}]$
1018 Steel	4889	248	0.0254	44
6061 Aluminum	12223	621	0.0254	82.8
Polycarbonate	6112	310	0.0254	41.3

The recommended cutting speed varied with the workpiece material. Aluminum was cut at the highest speed, followed by polycarbonate, then steel. The cutting tool manufacturer recommended using coolant while machining aluminum due to the material's ductility and its tendency to build-up on the cutting tool edge. Coolant was also recommended for polycarbonate to prevent it from melting because of the high temperature at the cutting tool and workpiece interface. Cutting fluid also aids with chip exit and the coolant pump has been shown to consume a significant amount of power. Steel can be cut without coolant, which would significantly reduce the total power demand of the machine tool. However, since this study is primarily concerned with comparing the power demand necessary to process different materials, coolant was used when cutting all material types.

The power demand of the NVD1500 is shown in Figure 3.5, and is broken down into cutting and air cutting power demand for each type of workpiece material. The air cutting power demand is approximately the same across the three processing conditions. The difference is due primarily to the change in spindle speed, the highest of which was used while cutting aluminum. The difference in the power demanded by the axis drives was found to be negligible even though the feed rate for aluminum is more than two times that of steel.

The cutting power demand shows greater variability for the three workpiece materials. The cutting power was the greatest while machining the steel workpiece. In fact, it was

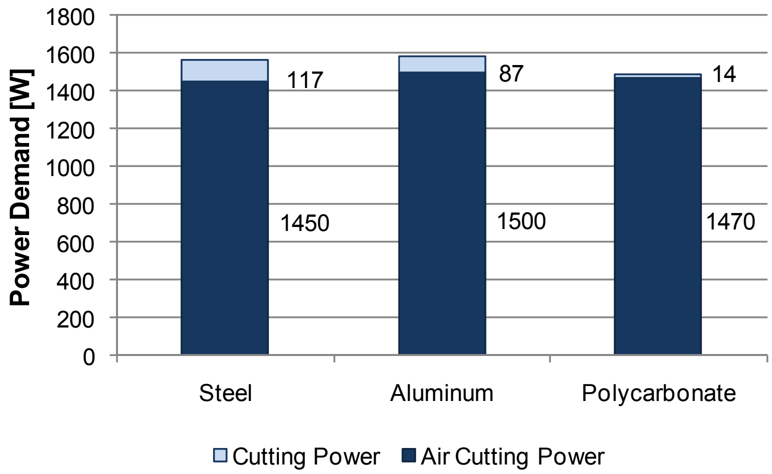


Figure 3.5: Power demand of NVD1500 for steel, aluminum, and polycarbonate workpieces from [40].

approximately 7% of the total power demand. The cutting power while machining the polycarbonate workpiece was the smallest and almost negligible, only 1% of the total power demand. This may be due to the fact that steel has the highest yield strength, followed by aluminum, then polycarbonate, as the magnitude of the yield strength follows the changes in the cutting power demand fairly closely (see Figure 3.6). The power demand of the spindle motor and the axis drives should be measured directly in future experiments to improve the accuracy of the power measurements since presently the cutting power demand is obtained by subtracting the air cutting power from the total power of the machine tool.

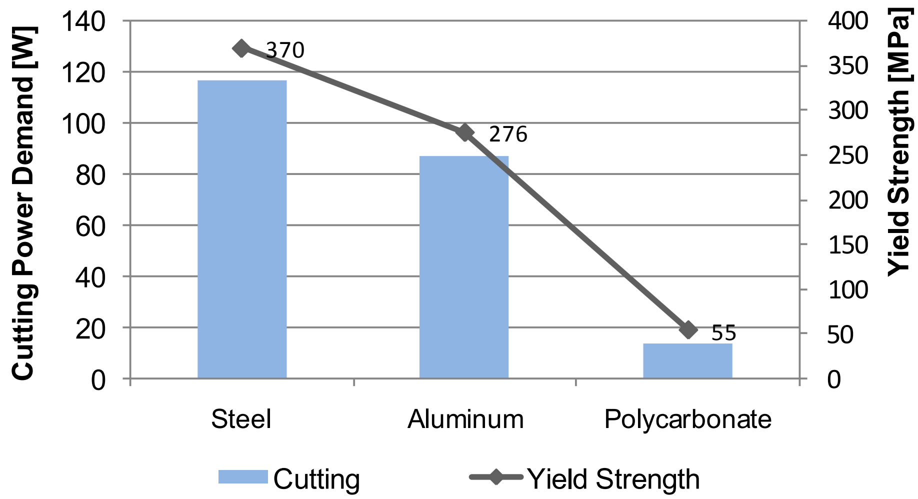


Figure 3.6: Cutting power demand and material yield strength (data sourced from [73]).

3.2 Product Design Considerations for Green Machining

Collaboration between product designers and manufacturers offers many opportunities for lowering the manufacturing phase impact of a product. Just as Design for Manufacturing (DFM) requires the utilization of cross-functional teams [74], reducing the impact of the manufacturing phase of a product also requires integrative practices. Manufacturers can reduce the setup and machining time by working directly with the product designer as was done at the Mori Seiki machine tool factory for the spindle motor's casting.

Product design makes a significant impact on the manufacturing phase energy consumption. Part geometry can improve the energy consumption of manufacturing by accommodating faster processing speeds. Additionally, standardizing part features lowers energy consumption by reducing the number of tool changes and consequently the setup time as well. These changes in the product design phase can lead to significant improvements when a product designer understands the environmental impact that is accrued during the manufacturing phase.

Ulrich and Eppinger [74] identified key elements of the manufacturing cost of a product as shown in Figure 3.7, noting that the cost of custom components is the "most significant element of the manufacturing cost" for most engineered, discrete products. The manufacturing energy consumption of a product follows a similar breakdown, especially for the production of custom components, which require raw materials, processing, and tooling.

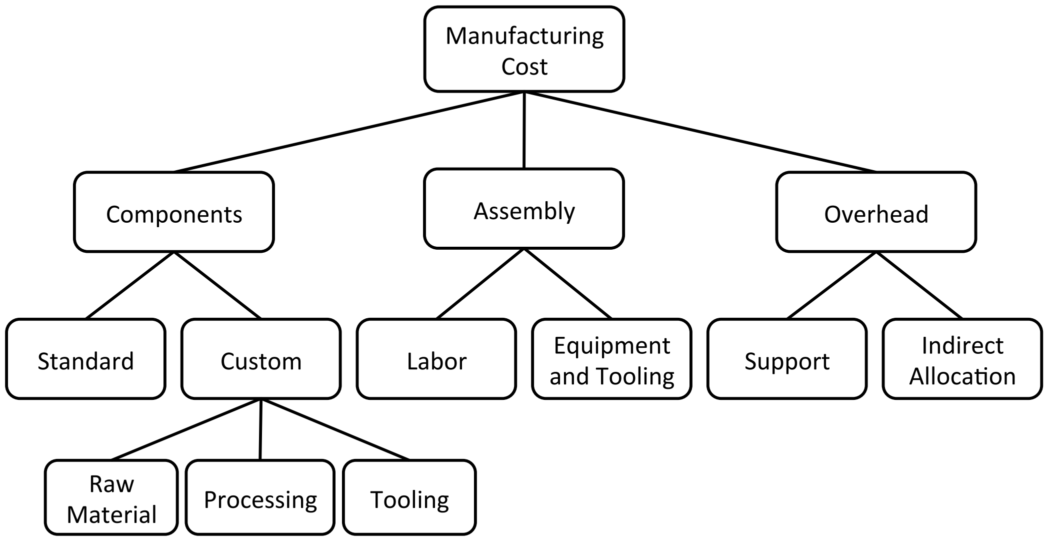
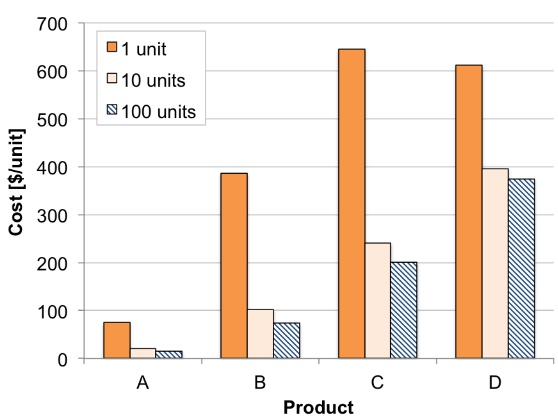
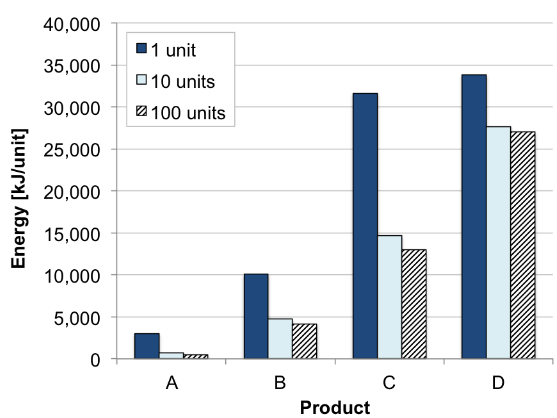


Figure 3.7: Elements of the manufacturing cost of a product [74].

Figure 3.8a shows the unit cost of manufacturing four types of products at production volumes of 1, 10, and 100 units. The cost assumes a labor rate of $60 per hour for setup and machining time, individually. Assuming that the standby power demand during the setup was 950 W and the average processing power was 1250 W for machining the products, the unit energy consumption of each product was estimated.



(a) Unit cost (after [74]).



(b) Unit energy consumption.

Figure 3.8: Unit cost and energy consumption of four product types.

The energy consumption of part processing highly resembles the processing costs because of the dependency on setup and processing time (see Figure 3.8b). However, the energy consumption decreases at a slower rate than the unit cost of processing because of the difference in setup and processing power demand. Regardless though, an increase in the production volume results in the reduction of the influence of the setup time. This is so, because setup time is amortized over the number of parts produced, therefore, resulting in a greater reduction of the unit energy consumption during manufacturing.

Although the volume of production may not be dictated by the product designer, the designer still has a significant influence on many parameters that affect the manufacturing phase energy consumption.This section focuses on the processing of custom components and highlights some design areas that lead to reductions in energy consumption, specifically concerning the feature design, material selection, and surface roughness specification.

3.2.1 Design of the Features

Part Geometry

When manufacturing a part, stock material is first chosen, which is transformed into a product by means of a sequence of manufacturing processes. The stock material for machining typically takes the form of a bar, rod, pipe, or near-net shaped component. The energy that is required to process material is largely dependent on the process rate. Figure 3.9 shows the specific energies of a wide array of manufacturing processes from oxidation to the manufacturing of parts by means of injection molding. Since the process rate is much lower for micro scale manufacturing, the subsequent time to manufacture a unit volume would be much higher than that required at the macro scale. The size of the features and knowledge about the potential processes used during the manufacturing phase can therefore provide a product designer with a rough estimate of the energy required to manufacture a part.

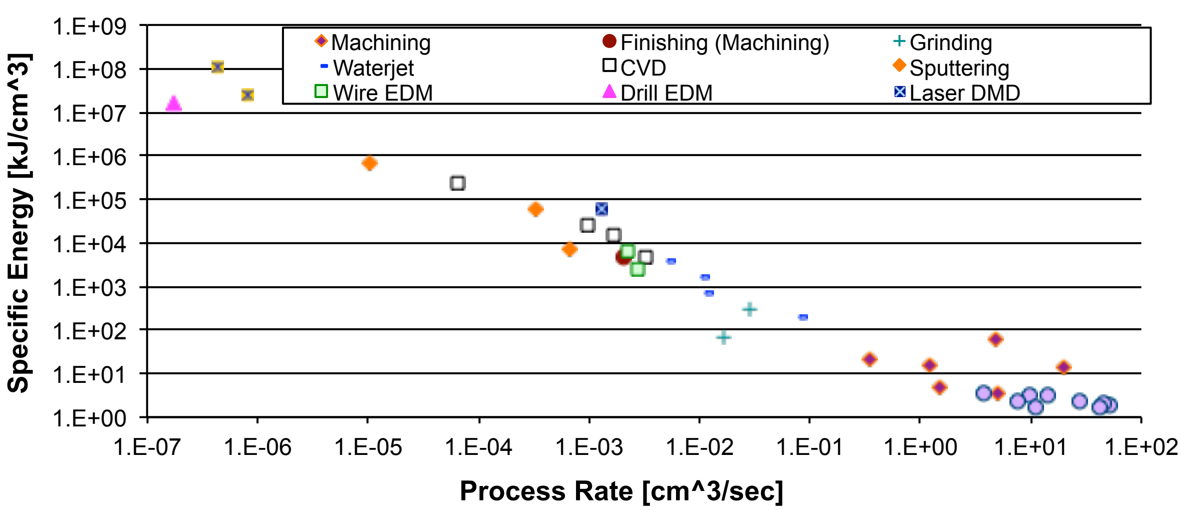
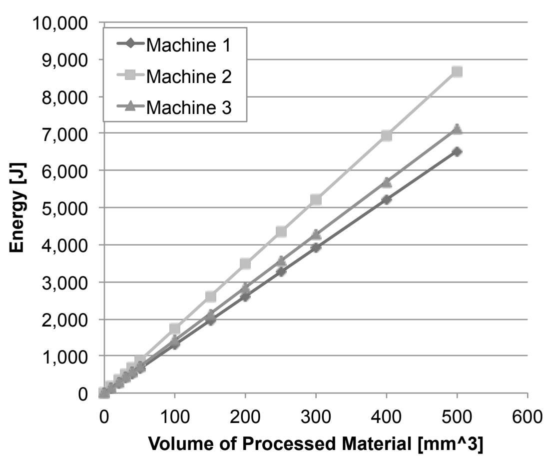


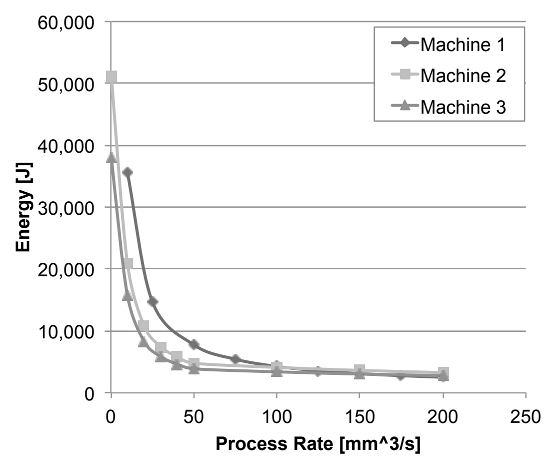
Figure 3.9: Specific energies of manufacturing processes (after [12]).

Taking milling as an example, there is a high degree of flexibility that can be achieved with large dimensions that can lead to reductions in energy consumption. When milling very small features, the type of cutting tools that can be used for roughing is limited. Typically, the largest cutting tool that can possibly machine the part is chosen in order to manufacture the feature quickly. For example, an 8 mm wide slot can be milled with a 7 to 8 mm diameter end mill, whereas a 1 mm wide slot would have to be milled with a smaller end mill and at a much slower rate in order to accommodate chip exit.

Figures 3.10a and 3.10b exhibit the relationship between energy consumption, the volume of processed material, and the process rate for three types of machine tools. The energy models were taken from [40] and [41], and although the machine tools are different with respect to the work volume and energy models, the total energy consumption for one set of processing conditions is fairly similar at low volumes of material removed (see Figure 3.10a). The energy consumption for each machine tool varies significantly at low process rates (see Figure 3.10b). Low process rates are utilized for manufacturing micro features, which typically are less than 10^{-4} cm^3 per second. From Figure 3.9 and Figure 3.10 it can be concluded that the energy consumption increases as the volume of material processed increases since production equipment must run for a longer period of time. Additionally, energy increases as the feature's dimensions decrease because of the limits dimensions impose on the process rate.



(a) Energy versus volume of material processed at a constant process rate of 140 mm^3 per second.



(b) Energy versus process rate for a volume of 250 mm^3 of material.

Figure 3.10: Energy consumption versus volume and process rate.

Standardization of Features

The recommendation to standardize part features follows the design for assembly principle of part standardization to reduce complexity [74], except here the primary concern is with the design of a part's features. The standardization of a part's features allows us to reduce the setup and machining time. A simple example is the design of holes, which serve as a reference point for mating two or more parts. If the holes have different diameters, then not only will the complexity of the product assembly increase, but more tool changes and a higher processing time would be required than if the holes were a standard size.

For example, the part shown in Figure 3.11 would require at least five types of cutting tools in order to produce holes of three different diameters, mill the perimeter of the part, and face mill the surface. Each cutting tool requires an additional setup and therefore extends the total processing time of the part. For a high volume of parts, the setup time can be amortized over the number of parts produced and therefore becomes negligible, but for a small volume of parts the setup time can be significant. Aside from increasing the setup time, the use of various types of tools also increases the tool changeover and air cutting time. For machine tools with automatic tool changers, this increase in time would not be as pronounced and can take a matter of seconds, but for manual tool changes the increase in processing time is much more significant.

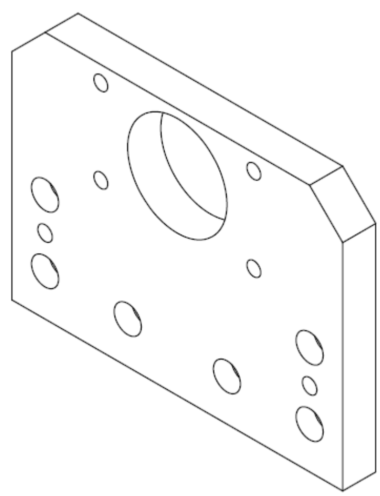


Figure 3.11: A sample part that lacks the standardization of part features [75].

The example presented here highlights the standardization of hole size, but the same principle can be applied for the specification of the radius of recessed corners and the width of features, to name a few examples. Standardizing part features reduces energy consumption by lowering the setup time and tool changeovers, which are non-value added procedures.

3.2.2 Selection of the Material

Achievable Process Rate

It was previously shown in subsection 3.1.2 that the processing energy consumption varies based on the type of workpiece material. Although the process energy consumption is relatively low (between 1.85 and 20.53% [50]), the process rates do vary by a significant amount. Many manufacturing restrictions result from the type of workpiece material that is used during the machining process. As such, the processing time and energy consumption will vary accordingly.

For example, Table 3.4 exhibits the recommended feed rate for milling various types of workpiece materials. The speeds of other types of workpiece materials can be compared to a baseline case, low carbon steel. From Table 3.4, it is observed that titanium is machined at 19% to 29% of the speed of soft steel, while stainless steel is machined at 37% to 45% and grey cast iron 91% to 133% the speed of soft steel. The feed rate while machining with a 2-flute, 6.35 mm diameter end mill for plastics, aluminum, and copper is approximately 2, 5, and 8 times as fast as that of a low alloy steel, respectively, when using conservative estimates for cutting speeds obtained from [76]. Since the energy consumption is inversely proportional to the material removal rate and therefore the feed rate, the rankings of workpiece materials from lowest to highest expected energy consumption[1] can be listed as: copper, aluminum, plastic, low alloy steel/grey cast iron, stainless steel, and titanium.

Table 3.4: Recommended feed rate for slotting with 4-flute end mills at a depth of cut equal to the diameter for various workpiece materials and cutting tool diameters (after [77]).

	Feed rate $[\frac{mm}{min}]$								
Cutting tool diameter [mm]	3.2	6.4	7.9	9.5	11.1	12.7	15.9	19.1	25.4
Gray Cast Iron	1242	930	930	879	975	970	932	904	777
Low Carbon Steels (> 25 Rc)	932	932	968	932	958	978	1006	993	932
Alloy Steels (4140)	434	544	653	653	622	653	609	615	544
Tool Steels (A2, D2)	249	249	297	330	355	343	323	310	279
Die Steels (H13, P20)	279	384	419	465	460	437	391	396	351
Stainless Steel (303)	343	343	409	455	465	470	445	455	406
Difficult Stainless Steel	279	244	307	351	340	351	351	351	305
High Temperature Alloys	137	119	150	160	157	163	150	160	142
Titanium	198	175	239	264	269	286	269	264	249

[1]This assumes that the same cooling and/or lubricating conditions are used for all materials. The following section will show how additional energy savings can be realized with dry cutting.

The Use of Metalworking Fluid

Metalworking fluid (MWF) serves the following primary purposes: the cooling and/or lubrication of the cutting tool and workpiece interface, and the removal of chips. Figure 3.12 highlights the factors that affect the effectiveness of cooling and lubricating methodologies. The part quality is often times a critical specification of the product designer and the workpiece, coolant, cutting tool, and process speeds will dictate the effectiveness of the cooling and lubricating techniques. Additionally, the conditions of the cutting tool is important to the manufacturer since costs can rise very rapidly if a tool wears rapidly because of the short life span and frequent tool changes. The MWF therefore plays a critical role in achieving the product designer's specifications and maintaining low costs for the manufacturer.

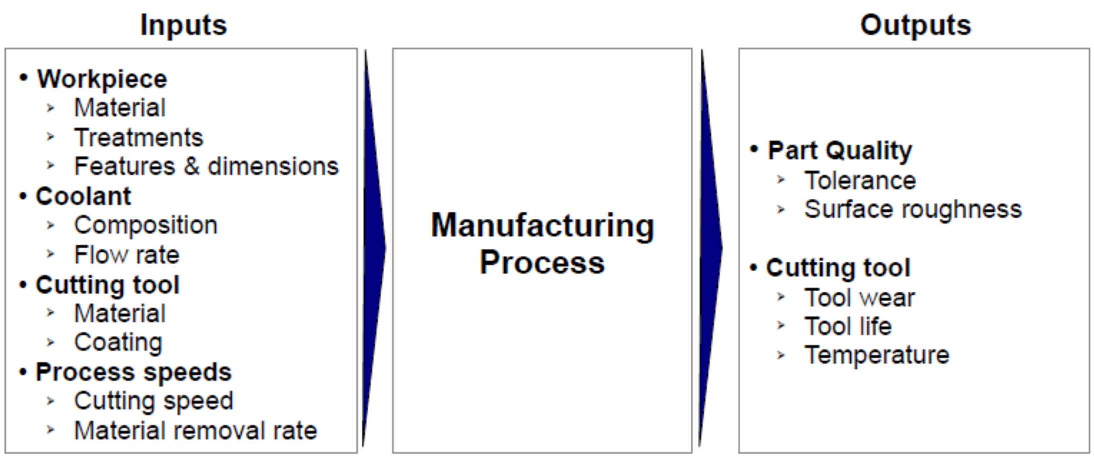


Figure 3.12: Factors affecting the effectiveness of coolants and lubricants (after [61]).

The coolant pump has been shown to consume a significant amount of power (see subsection 2.1.4), on the order of 25% of the total power demand in fact [36]. One method of reducing the use of MWF is by implementing dry cutting techniques. Weinert et al. [78] and Klocke et al. [61] have done a comprehensive examination of the applicability of MQL and dry cutting techniques on different material types. Aside from the cost savings associated with the use of less metalworking fluid, implementing dry cutting also results in a significant reduction of energy consumption.

The energy consumption associated with MQL highly depends on the sensor technology used in the application. A study by Rotella et al. [79] found that the power demand while using MQL was significantly greater than while utilizing dry or wet cutting conditions. Future technological developments in MQL applications will hopefully achieve reduced consumption of energy aside from savings already associated with fluid consumption and the improved impact on human health.

The type of workpiece material largely dictates whether or not MWF is necessary for the manufacturing process at hand. Aluminum, for example, requires lubrication because of the ductility of the material, which increases the cutting forces. For the drilling of aluminum, it is especially important to provide the proper environment for chip exit so that the operation is not disrupted with a broken tool. Conversely, steel may be machined without MWF and consequently has a higher machinability rating than aluminum.

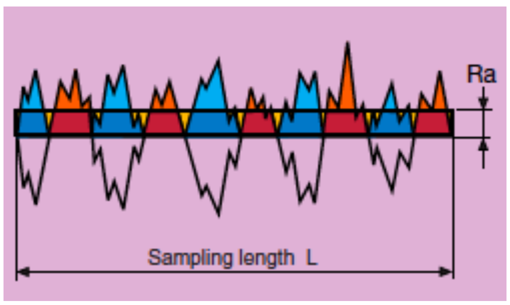
Figure 3.13 shows whether or not MWF is needed while machining various grades of aluminum, cast iron, and steel. Material and process combinations that are listed as "Dry" do not require coolant or lubrication when the correct processing conditions and tools are utilized. Dry machining is common for milling and turning cast iron and steel, and in some cases the broaching and drilling of cast iron and some steel as well. Aluminum does require some sort of lubrication, as was previously mentioned, which is why MQL or wet cutting conditions are necessary for the majority of the processes listed in Figure 3.13.

Process	**Aluminum**		**Cast Iron**	**Steel**	
	Cast alloys	Wrought alloys	GG20 to GGG70	High-alloyed bearing steel	Free cutting, quenched, and tempered steel
Broaching			Dry	MQL	Dry
Deep hole drilling	MQL	MQL	MQL		MQL
Drilling	MQL	MQL	MQL Dry	MQL	MQL Dry
Gear milling			Dry	Dry	Dry
Milling	MQL Dry	MQL	Dry	Dry	Dry
Reaming	MQL	MQL	MQL	MQL	MQL
Sawing	MQL	MQL	MQL	MQL	MQL
Tapping	MQL	MQL	MQL	MQL	MQL
Thread forming	MQL	MQL	MQL	MQL	MQL
Turning	MQL Dry	MQL Dry	Dry	Dry	Dry

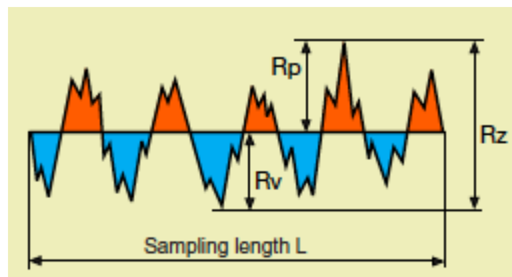
Figure 3.13: Material and manufacturing process combinations for the use of MWF (after [61; 78]).

3.2.3 Specification of the Surface Roughness

The surface roughness of a part is a common specification of a part drawing. Molds for injection molded parts, for example, require a fine surface finish in order to generate a product with a smooth surface. The Society of Plastics Industries (SPI) provide guidelines for mold-making, specifically how they can be achieved with different grit specifications [80]. A common measure of surface roughness is the arithmetic average, R_a, which is calculated by integrating the absolute value of the surface profile, $Z(x)$, over a sample length, L as shown in Figure 3.14a and Equation 3.1 [15].



(a) Surface roughness, R_a [81].



(b) Surface roughness, R_z [81].

Figure 3.14: Surface roughness measurements.

$$R_a = \frac{1}{L}\int_0^L |Z(x)|\, dx \tag{3.1}$$

Additionally, the maximum height profile is denoted by R_z. R_z represents the summation of the maximum height, R_p, and valley, R_v, of the surface (see Equation 3.2 and Equation 3.3). A visual representation of the maximum height profile can be found in Figure 3.14b.

$$R_z = R_p + R_v \tag{3.2}$$

$$R_z = max(Z(x)) + |min(Z(x))| \tag{3.3}$$

The factors that affect the surface roughness are the manufacturing process, material type, process speeds, and use of coolant. Manufacturing processes have different capabilities with respect to surface roughness. Figure 3.15 shows the average of the maximum height profile, R_z, with respect to the manufacturing process. Forming processes, i.e., primary shaping, die forming, and extrusion, result in a much higher surface roughness than machining processes such as turning, drilling, reaming, milling, and grinding. Grinding is a common finishing process, although the other machining processes can be utilized as finishing processes as well depending on the process speeds.

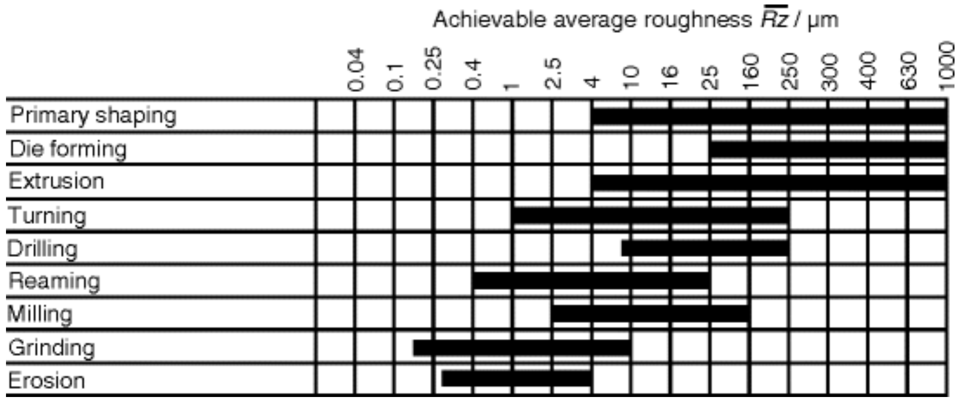
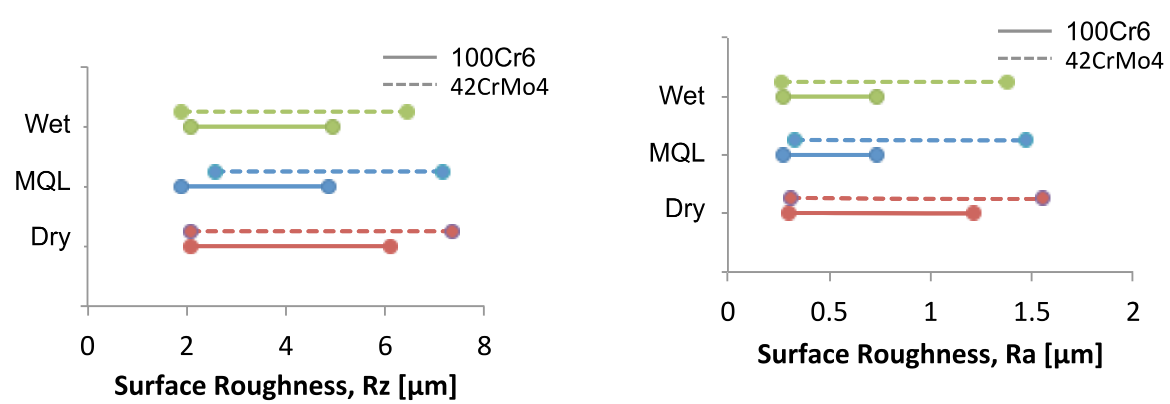


Figure 3.15: Achievable average roughness for a range of common manufacturing processes [82].

Combining the information from Figure 3.9 and Figure 3.15, the process rate for forming processes is observed to be greater than that of machining and grinding. Therefore, higher surface roughness specifications (offering greater flexibility in manufacturing) can result in a significant reduction in specific energy with the utilization of faster manufacturing processes.

The surface roughness has also been studied with respect to the type of MWF conditions used for the grinding of 100Cr6 hardened steel and 42CrMo4 soft steel by Tawakoli et al. [83] (see Figures 3.16a and 3.16b). The results presented here are for those measurements taken across the grinding direction and within the specific material removal rates of 0.21 and 4.17 mm^3 per mm-s. Surface roughness measurements were also provided by Tawakoli et al. [83] along the grinding direction. Here the measurements across the grinding direction are presented since they are more common measurements for grinding.



(a) MWF versus surface roughness, R_a

(b) MWF versus surface roughness, R_z

Figure 3.16: MWF condition versus surface roughness for grinding (data sourced from [83]).

The surface roughness of the 100Cr6 workpiece material when dry grinding was generally higher than that under wet or MQL grinding conditions, especially at high specific material rates. The surface roughness under MQL grinding conditions was typically the lowest at low specific material rates and some times comparable to the wet grinding conditions, especially at very low speeds.

The surface roughness results for the grinding of 42CrMo4 were lowest for grinding under wet conditions, followed by MQL, and highest for the dry grinding conditions overall. However, choosing the correct grinding speeds and parameters will allow us to obtain the proper surface roughness under the preferred cooling conditions.

Dhar et al. [84] studied the effect of turning AISI 4340 steel under different MWF conditions. The growth in the surface roughness, R_a, over the machining time of 50 minutes is exhibited in Figure 3.17. MQL resulted in the least growth while wet cutting conditions resulted in the greatest growth in surface roughness. Dry and wet turning resulted in roughly the same surface roughness over time, however, dry turning would result in a significant reduction in power demand of the turning center.

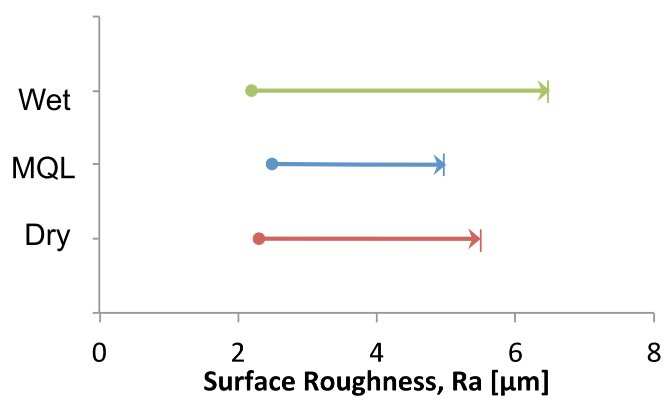


Figure 3.17: MWF condition versus surface roughness for turning AISI 4340 steel (data sourced from [84]).

Chapter 4

Energy Model Development and Validation for Production Equipment

A product undergoes four life-cycle stages: material extraction, manufacturing, use, and end-of-life. Consumer products whose environmental impact is dominated by the use phase include light fixtures, computers, refrigerators, and vehicles. In general, these are products that are used extensively during their functional life. All the while these products consume resources, in particular energy in the form of electricity or fuel. The machine tool is one such product. The use phase of milling machine tools has been found to comprise between 60% and 90% of CO2-equivalent emissions during its life cycle [85]. This chapter presents a method for predicting the electrical energy consumed in manufacturing a product for the purpose of reducing its environmental impact [40] and validates the model for a complex toolpath [42].

4.1 Development of the Specific Energy Model of a Machine Tool

The specific energy of a wide range of manufacturing processes was previously summarized by Gutowski et al. [12]. But for any given manufacturing process, the data was limited to only a sample of process rates. This section, will characterize the specific energy of milling machine tools working within the operable range of the piece of production equipment.

So, what is in fact the specific energy of a machine tool? The answer depends on the processing conditions, better known as the material removal rate in the case of a milling machine tool. The specific energy of a machine tool, e_{sp}, represents the energy required to process a volume or mass of material and is, therefore, provided in units of Joules per mm^3, Joules per kg, or the like. As the MRR increases and approaches infinity, the specific energy is expected to reach a steady-state of zero because energy is inversely proportional to the process rate. However, operating at a rate close to infinity is infeasible. Given the work volume, spindle speed, and table feed constraints of a machine as well as the maximum loads that can be applied without deforming the main body frame or breaking the spindle motor, the operator cannot reach an MRR anywhere close to infinity. Additionally, energy is neither created nor destroyed so some energy is required to physically remove the material. Therefore, under the constraints of the MRR and the requirement to have a minimum energy consumption for material removal, a curve of the following form:

$$e_{sp} = k * \frac{1}{MRR} + b \tag{4.1}$$

was fit to the data based on the width of cut and depth of cut experiments from subsection 3.1.1. Note that the constant k essentially has units of power and b represents the steady-state specific energy.

The specific energy, which accounts for cutting and air cutting power demand, was indeed found to have an inverse relationship with the MRR as shown in Figure 4.1 because the air cutting power demand dominates the energy consumption. The impact of the cutting power demand on the specific energy was minimal since at high loads (i.e., at high MRR's) the machining time decreased significantly.

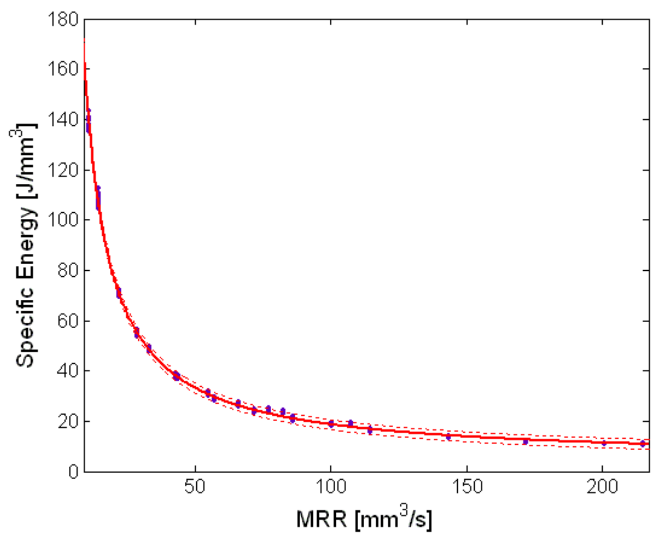


Figure 4.1: Specific energy as a function of MRR of the Mori Seiki NVD1500 with a max spindle speed of 25,000 rpm [40].

In the case of the Mori Seiki NVD1500, the specific energy decreases rapidly until an MRR of approximately 75 mm^3 per second is reached. For MRR's lower than 75 mm^3 per second, a slight increase in the material removal rate causes a sharp drop in the specific energy because machining time decreases dramatically. At MRR's greater than 100 mm^3 per second, the gain from increasing the process rate is minimal since the specific energy begins approaching a steady-state value. This gain could be significant for a workpiece requiring a substantial amount of material removal, but since the machine tool used in this study is a micromachining center, anything greater is unlikely for the manufacturing of parts with micro-sized features.

The best fit model was found to be:

$$e_{sp} = 1481 * \frac{1}{MRR} + 3.678 \tag{4.2}$$

where the first constant, k, is similar to the average air cutting power demand and the second constant, b, falls within the range of the specific energy consumption for material removal based on the process mechanics (see subsection 2.1.1). As was expected, the specific energies at low MRR's had such large variations that they surpassed the bounds of the model, but at high MRR's the specific energies were well within the bounds. The lower and upper bounds, respectively, for the specific energy model with a 95% confidence level are provided below:

$$e_{sp} = 1478 * \frac{1}{MRR} + 3.541 \tag{4.3}$$

$$e_{sp} = 1488 * \frac{1}{MRR} + 3.853 \tag{4.4}$$

This specific energy model can be used to estimate the total energy consumed while cutting. The part features and tolerances would dictate the size and type of machine tool required to manufacture a particular part. The optimal MRR can be determined using standard process parameters based on the workpiece material and appropriate cutting tool for the creation of the feature. Therefore, the total energy consumption while cutting can be calculated by multiplying the estimate of the specific energy by the volume of material removed as is exhibited by Equation 4.5,

$$E = (k * \frac{1}{MRR} + b) * V \tag{4.5}$$

where E is the total electrical energy consumed by the machine tool for material processing and V is the volume of material removed.

At low material removal rates the specific energy model has a relatively high rate of change, whereas the model approximates a constant value as the MRR increases. As such, an increase in the MRR will not exhibit a significant reduction in electrical energy at high MRR's except when undergoing long processing times. The specific energy model maintains its inverse relationship with material removal rate, even if data for other types of workpiece materials were included and the same holds true for the inclusion of conventional and climb milling data. As was found in subsection 3.1.2, the workpiece material affected the processing power demand of the machine tool while cutting, but the cutting power demand relative to the air cutting power demand was small. As such, introducing the energy data for additional types of workpiece materials did not have a significant impact on the specific energy model and approximated the same curve as that generated with data from one type of workpiece material, i.e., low carbon steel.

The width of cut, depth of cut, and workpiece material experiments were conducted under fairly simple cutting conditions, specifically, straight-edged peripheral cuts. However, the capabilities of a three-axis machining center are quite vast. In order to study the accuracy of the specific energy model for a more complex toolpath, experiments were conducted for a toolpath that utilizes a combination of two- and three-axis movements while machining a part [42]. The methodology and results will be discussed in the following section.

The specific energy model was found to hold true regardless of the type of material being cut, the type and size of the cutting tool used for processing material, and the direction of cut because of the high tare power demand; a trait that is common of precision machine tools because of the peripheral equipment needed to maintain accuracy. Therefore, higher process rates result in the consumption of less energy. At this point, though, the toolpath planner or machine tool operator will have to determine the optimal operating conditions to maintain a reasonable cutting tool life and meet the part designers specifications with respect to part quality.

4.2 Case Study: Energy Prediction and Model Validation for a Variable Material Removal Rate Profile

The following case study presents a methodology for predicting the energy consumption of part production involving a variable MRR profile. Additionally, the accuracy of the energy prediction is assessed and factors that influence the accuracy of the energy prediction are discussed.

4.2.1 Methodology for Predicting the Energy of a Machined Part

Energy Model Parameters for the Machining Center

This study also utilized the Mori Seiki NVD1500 machine tool, but a model with a maximum spindle speed of 40,000 rpm (versus a maximum spindle speed of 25,000 rpm as used for the studies in section 3.1 and section 4.1). It should be noted that although the specific energy model's parameters can be used for any type of workpiece material, they vary from machine tool to machine tool.

In order to develop the machine tool's energy model, the electrical energy consumed while machining AISI 1018 steel was measured. Energy data was obtained for a broad range of MRR's by machining peripheral cuts with three types of cutting tools: 2-flute uncoated, 2-flute TiN coated, and 4-flute TiN coated 8 mm diameter carbide end mills. The feed rate, f, and spindle speed, n, were varied with cutting tool type as recommended by the cutting tool manufacturer for a constant chip load, f_t, of 0.0254 mm per tooth [86]. The machining parameters are summarized in Table 4.1. The depth of cut, d, was maintained at 2 mm, while the width of cut, w, was varied between 1 mm and 7.5 mm.

Table 4.1: Cutting tool parameters for energy validation experiments with varied MRR.

Cutting tool	f $[\frac{mm}{min}]$	N [rpm]
2-flute uncoated	170	3361
2-flute TiN coated	217	4278
4-flute TiN coated	860	7060

The specific energy parameters, k and b, were found to be 1556 W and 1.475 W-s per mm^3, respectively, given a material removal rate in units of mm^3 per second and volume in units of mm^3. Figure 4.2 shows the curve fit for the specific energy model and the experimental data. The specific energy approaches a value close to zero as the MRR increases, reducing significantly until approximately 50 mm^3 per second. Therefore, energy reductions by means of increasing the process rate for MRR's higher than 50 mm^3 per second would only be worthwhile for long processing times.

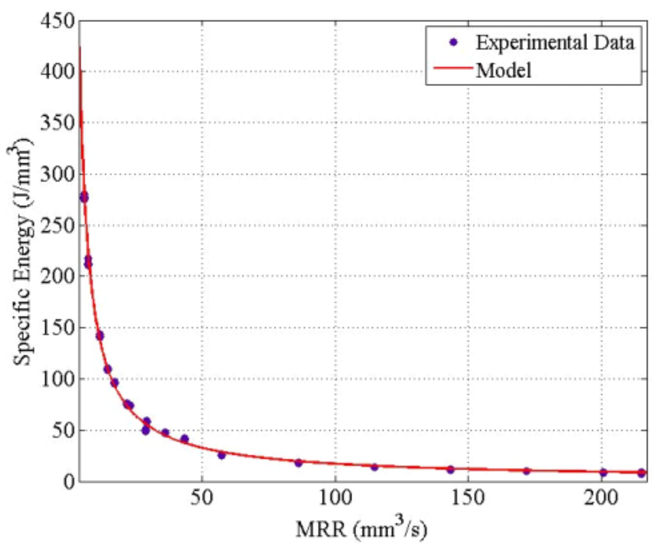


Figure 4.2: Specific energy model and experimental data for Mori Seiki NVD1500 with max spindle speed of 40,000 rpm [42].

Part Design and Material Removal Rate Profile

The electrical energy required for milling was estimated for an inclined spiral design on an AISI 1018 steel work piece with flood cooling. Machining occurred over 87% of the total cycle time of 259 seconds. The part design was broken down into 9 features as shown in Figure 4.3, where each feature indicates a change in the MRR profile.

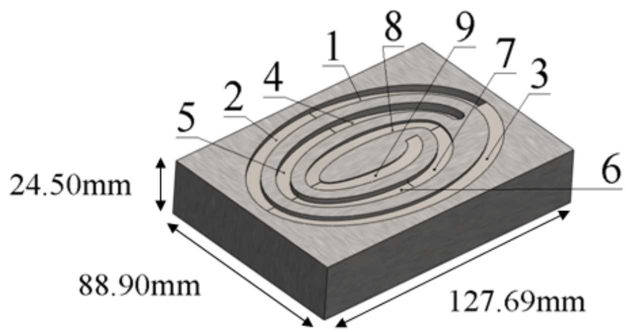
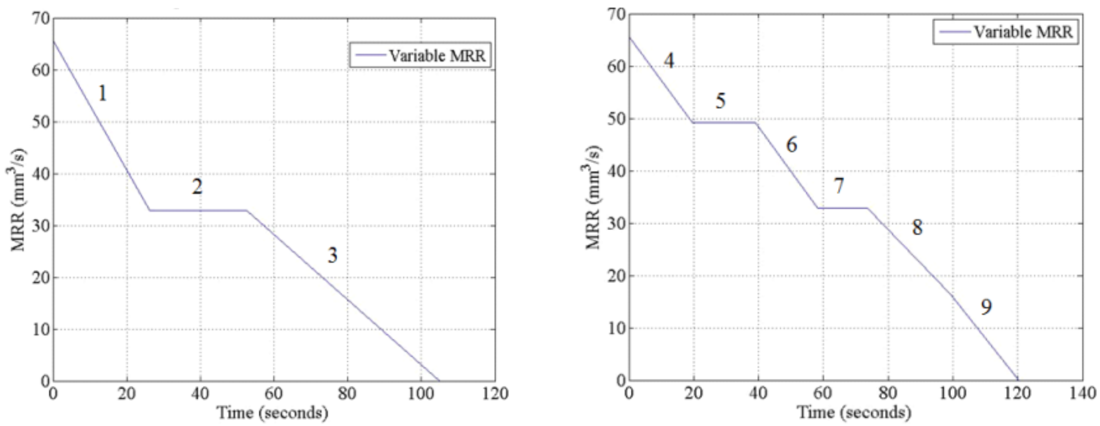


Figure 4.3: Spiral part design and feature labels for energy validation experiments [42].

The test cuts used to obtain the specific energy models were completed at a constant depth of cut and a constant MRR with movement along only the x- or y-axis at any given time. Machining the part in Figure 4.3 requires movement along the x-, y-, and z-axes simultaneously. The part was designed such that the MRR profile could be easily constructed since current Computer Aided Manufacturing (CAM) software does not output MRR as a function of time for a generated toolpath.

The MRR was calculated based on the depth of cut, d, width of cut, w, and feed rate, f. The recommended feed rate for slotting conditions with an uncoated 6 mm carbide end mill of 164 mm per minute was used with a spindle speed of 3558 rpm [86]. The MRR as a function of elapsed time was then used to estimate the energy consumption.

The width of cut throughout the experiment was maintained at a constant 6 mm. Features 2, 5, and 7, were milled while maintaining a constant depth of cut; the depth of cut varied for the remaining features. The MRR was varied as shown in Figures 4.4a and 4.4b, which also show the corresponding part features.

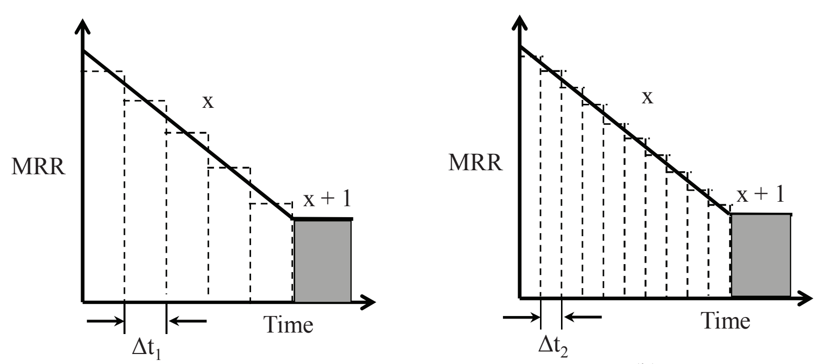


(a) MRR profile for features 1–3. (b) MRR profile for features 4–9.

Figure 4.4: MRR versus elapsed time for part features 1–9 [42].

Energy Prediction for a Machined Part

Complex toolpaths result in an MRR profile that cannot necessarily be represented by a simple function. Therefore, the energy consumption was calculated with a generalized approach. The MRR profile was first divided into sections of constant and variable MRR. For areas of constant MRR (feature $x+1$ in Figure 4.5), the energy consumption, E_{const}, was calculated based off of Equation 4.6 where t_j represents the length of machining time for feature j. However, areas with variable MRR were broken down into N subintervals as shown in Figure 4.5 for feature x.



(a) MRR breakdown of feature x with N=5 subintervals. (b) MRR breakdown of feature x with N=10 subintervals.

Figure 4.5: MRR profile for machining the part [42].

$$E_{const} = (\frac{k}{MRR} + b) * MRR * t_j \quad (4.6)$$

The number of subintervals, N, was varied from 1 to 10,000 for every feature to determine the smallest number of subintervals necessary for the energy estimate to converge. For each scenario, the average MRR of each subinterval was used to calculate the energy consumed per feature, E_{var} (see Equation 4.7). The total energy consumed to machine the part was thereafter found by summing E_{var} and E_{const} for all features as shown in Equation 4.8.

$$E_{var} = N * \Delta t_j \sum_{i=1}^{N} (k + b * MRR_{avg,i}) \quad (4.7)$$

$$E_{part} = \sum_{j=1}^{9} (E_{var} + E_{const}) \quad (4.8)$$

The number of subintervals necessary for the energy estimate to converge for a particular feature varied given the difference in process time, but all estimates converged within 1,000 subintervals or less. The corresponding subintervals were between 0.02 and 0.11 seconds. The point of convergence would be expected to vary by machine tool and toolpath. Since the optimal approach in proceeding with the energy estimate would utilize the smallest number of subintervals necessary for convergence, N of 1,000 was used in the following results.

4.2.2 Assessing the Accuracy of the Energy Model

The specific energy model provided an accurate estimate of the energy consumed to machine a part with varied MRR. Figure 4.6 shows the predicted energy and the actual energy consumed during the machining of the sample part, which was conducted six times for repeatability. The values presented above the energy bars denote the average percent error (the first value is highlighted with an asterisk, $*$).

Table 4.2: Estimate of energy consumed to create each feature and the experimentally derived values.

Energy		Feature 1	2	3	4	5	6	7	8	9	Part
Predicted	[kJ]	42.7	42.1	85.5	32.0	31.7	32.0	24.7	42.6	35.7	369
Average	[kJ]	46.6	38.9	82.1	32.3	31.7	33.7	23.1	38.9	31.7	360

The predicted energy and the average of the measured energy from the six experiments are shown in Table 4.2 with respect to each feature and the part as a whole. The accuracy

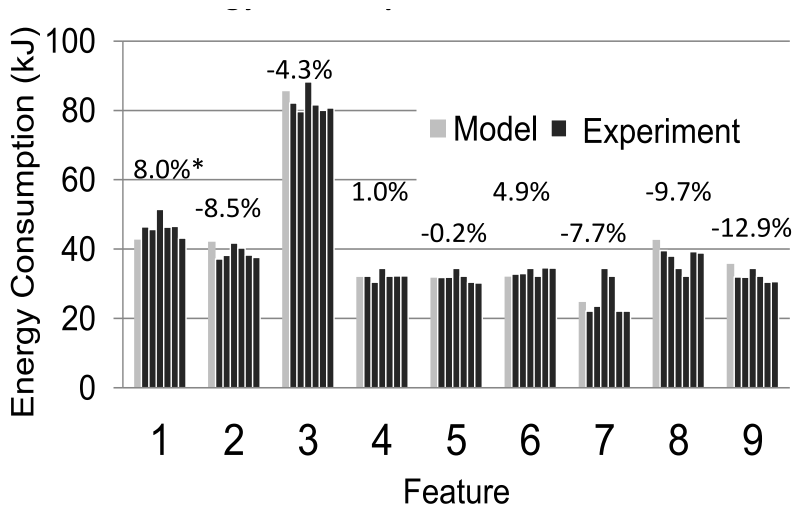


Figure 4.6: Estimate of energy consumed to create each feature and the experimentally-derived values (after [42]).

of the predicted energy was evaluated based on the average, minimum, and maximum error, as well as the standard deviation of the error (Std Dev) as can be seen in Table 4.3. The largest error occurred with feature 9. As was shown in Figure 4.2, the specific energy model showed the greatest variation in MRR's less than 50 mm^3 per second, and feature 9 was in fact fabricated at a relatively low MRR over a short period of time. Had the MRR during the feature construction been on the order of 75 mm^3 per second or greater, the variance in the model error is hypothesized to be even lower.

Table 4.3: Measured errors of each feature and the parts, collectively.

Error		Feature									Part
		1	2	3	4	5	6	7	8	9	
Average	[%]	8.0	-8.5	-4.3	1.0	-0.2	4.9	-7.7	-9.7	-12.9	-2.6
Min	[%]	0.9	-13.4	-7.4	-4.7	-4.9	2.2	-12.7	-12.2	-17.3	-5.4
Max	[%]	16.9	-0.9	3.0	7.3	6.2	7.5	6.6	-7.8	-7.1	4.9
Std Dev	[%]	5.1	4.8	3.8	3.8	4.0	2.7	7.6	1.8	3.7	3.8

The range of the error for the nine features shows a significant fluctuation. The measured energy is always greater than the predicted energy for some features (i.e., features 1 and 6). While for other features, the measured energy is always less than the expected energy (i.e., features 2, 8, and 9). The remaining features, though, are not skewed in any one direction.

This fluctuation may be attributed to the inherent variability of the power demand of a machine tool over time; a trend observable even while in standby mode. This trend is more pronounced in machine tools with a small work volume that have a relatively small standby power demand [51], so the accuracy of the specific energy model is also expected to improve for larger machine tools.

Although the predicted energy showed a significant deviation from the measured energy when evaluated on a per-feature-basis, the average error of the energy estimate for the part in its entirety was only -2.6% with a standard deviation of 3.8%. Therefore, estimating the energy consumption for complex parts proves to be promising as the toolpath for this part had a variable MRR profile.

4.2.3 The Factors Affecting the Energy Model's Accuracy

A variety of factors affect the accuracy of the energy model including the toolpath design, size of the machine tool, MRR, and prior processing conditions. First, the power demand of a machine tool varies significantly even for the same processing conditions. Figure 4.7 shows the range and average power demand of the Mori Seiki NVD1500 for slotting under the same processing condition. The power demand varies between approximately 1425 and 1650 W. Therefore, higher accuracy can be obtained for toolpaths under a constant MRR for a long period of time. When the machine tool is cutting over a short time span, the power demand will inherently experience some variability. This variability becomes even more pronounced as the power is integrated over time to calculate the energy consumption. However, toolpaths that maintain a constant MRR over an extended period of time are expected to result in a higher accuracy since the power can stabilize when integrated over time.

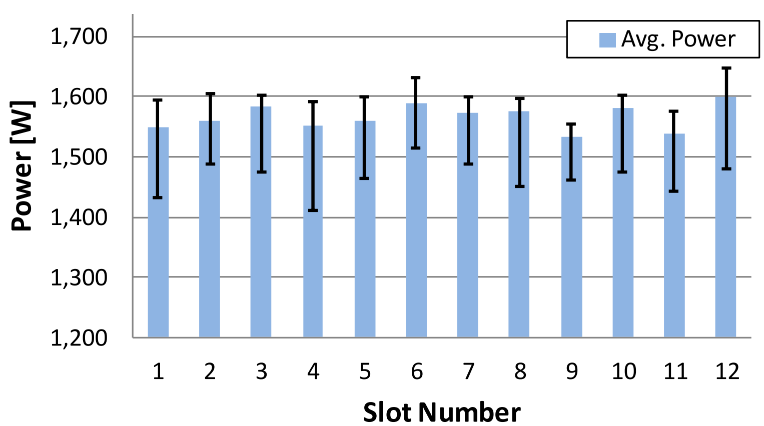


Figure 4.7: Variability in the power demand of a machine tool.

Additionally, the specification of the MRR in the toolpath design affects the accuracy of the energy model because of the inverse relationship between the specific energy and MRR.

There is a high degree of variability in the specifc energy at low MRR's versus at high MRR's when a more stable value is reached. Therefore, the energy prediction for toolpaths with high MRR's are expected to have a higher accuracy than those with low MRR's.

The size of the machine tool also plays a role in defining the range of variability in power and thus determining the accuracy of the energy prediction. Small machine tools tend to demand less power than their larger counterparts [36; 50]. These smaller machine tools with lower power demand typically experience a greater variability in the power that is drawn. As such, the energy model should prove to be more accurate for machines with a high constant power demand versus a low constant power demand because of the difference in the impact of the power variability.

Power is also dependent on the prior processing conditions since the machine tool experiences a peak in the power drawn during the initial engagement of the cutting tool with the workpiece. Feature 1, for example, was milled at a high MRR, yet still had a higher than average error for the energy prediction. Since the production of this first feature included the intial engagement between the cutting tool and workpiece, the power spiked once the cutting tool began cutting the workpiece material. The power did not stabilize during the production of the first feature, therefore resulting in a high prediction error. Features that are machined one after another under similar processing conditions are expected to have a more accurate energy prediction. Additionally, if a toolpath has a multitude of cutting tool changes or multiple instances of air cutting, the machine tool will typically consume more electrical energy than predicted because of the accumulation of peaks in power demand. The detailed modeling of the power demand of machine tools has been conducted by Dietmair et al. [44], but the methodology requires greater time in data acquisition to develop the model resulting in higher development costs.

Though the energy estimation with the specific energy model proved to be accurate, there are some limitations to the approach regarding the inclusion of air cutting time and the effects of cutting tool engagement. This approach only accounts for the electrical energy consumed during the removal of material, i.e., it does not include air cutting time as defined in section 2.1.3. Though machine tool users can account for air cutting power demand by including estimates for components contributing to the constant and variable power demand.

In summary, the energy model predicted the energy to produce each feature with an accuracy of 83.1% to 99.1%. The error was mostly due to the short processing times, low process rates, and the inherent variability in the power drawn by machine tools, which is especially prominent for smaller, precision machines. Furthermore, the energy model had an average accuracy of 97.4% for the production of the six test parts, which confirms that the energy necessary to machine complex parts can be accurately predicted.

Chapter 5

Machine Scheduling for Energy Reduction of Factory Operations

5.1 Introduction

Now, the energy consumption of production equipment has been presented and the energy model has been validated for a complex toolpath. However, 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, the idle energy consumption as well. In order to be most effective in suggesting green manufacturing strategies, the scope of assessments must be widened to the factory level.

The decisions concerning the process flow of a product lie in the hands of the process planner. They are tasked with the responsibility of defining the optimal process while accommodating consumer demand, the desired lead time, and the variability in the arrival and preparation of sub-components. Additionally, process planners typically take into consideration customer satisfaction, worker safety, profit maximization, and machine tool availability when determining the optimal process plan for manufacturing a product. It is becoming increasingly important, though, for manufacturing facilities to account for the environmental impact of part production as concern for resource availability grows.

The research presented in this chapter outlines a methodology for optimizing for cost and environmental impact of a job shop – a facility equipped to handle a high mix of products. Previous work in sustainable manufacturing at the facility level is limited, as the majority of facility-level optimization is focused on costing. Simulations concerning the environmental impact of factory operations include Fang et al. [70] who studied the energy consumption and peak power demanded by a two machine job shop, Heilala et al. [68] who developed a simulation tool for optimizing between production efficiency and environmental impact, using a toy manufacturing plant as a case study, and Johansson et al. [71] who showed how discrete-event simulation (DES) and life-cycle assessment can be combined to evaluate the performance of a manufacturing system with the exemplary case study of a paint shop.

These studies though focused on the manufacture of one type of product or manufacturing with preset processing conditions and equipment. Since products evolve over time and some facilities manufacture a high mix of products at a range of processing conditions, methods must be developed to assess the environmental impact of a facility to more accurately characterize operations by moving away from a deterministic approach to environmental impact assessments. In a flexible manufacturing environment the greatest flexibility in the process plan lies in the selection of the machine tool, toolpath, and process conditions. The following case study utilizes machine selection to optimize for the cost and energy consumption of part production in a high mix production facility.

5.2 Methodology

DES provides a convenient environment for modeling stochastic processes, defining flows and relationships within a manufacturing system, and providing the flexibility necessary to calculate metrics for life-cycle inventory analyses. Sigma was used in this case study, specifically to calculate the cost and environmental metrics of the system, and developing the machine tool prioritization algorithm. The following sections describe how the costs and energy consumption were defined, and identify how the part processing, manufacturing facility, and machine tool scheduling algorithm were implemented.

5.2.1 The Cost of Machine Operation

The components that comprise the life-cycle cost of machining were identified by Enparantza et al. in [87] and summarized in Figure 5.1. They consist primarily of three categories: acquisition, ownership, and end-of-life costs. This section describes the associated machine tool costs utilized in this model, specifically the acquisitional costs, $C_{acquisition}$, labor costs, C_{labor}, and electricity costs, C_{elec}.

The machine tool acquisition consists primarily of the purchasing transaction and the installation of the machine. The cost to purchase and install a machine tool, $c_{acquisition}$, must be amortized over the functional life of the machine tool, t_{life}. The part processing time, $t_{process}$ (a parameter dictated by the toolpath), was assumed to be independent of the type of machine tool used to manufacture the part.

$$C_{acquisition} = c_{acquisition} * \frac{t_{process}}{t_{life}} \tag{5.1}$$

Throughout the functional life of a machine tool, there are standard operational costs such as the cost of direct labor to operate the machine, electricity and other utilities to drive the machine, consumables such as raw material and lubricating oil, as well as fixtures for part setup and the waste from normal operation. The cost of shared consumables such as

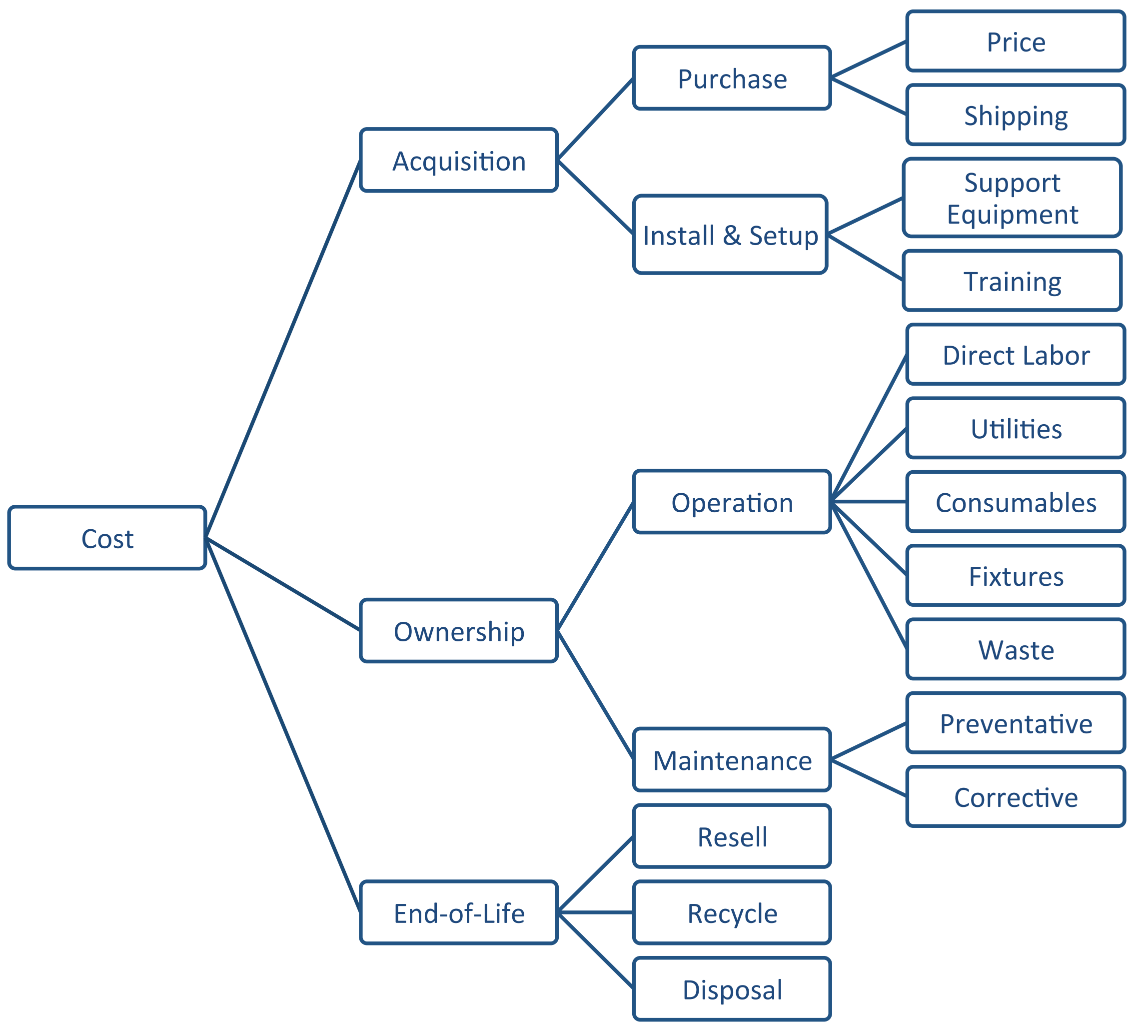


Figure 5.1: Machine tool costing factors (adapted from [87]).

cutting tools, maintenance oil, coolant, and water were neglected since these resources would be amortized over the parts produced by the facility. Facility overhead and holding costs were also neglected since they are independent of the type of machine tool being used.

The primary factors taken into consideration in this study were direct labor and electricity costs. Labor costs are directly proportional to the processing time and the labor rate, c_{labor}, as seen below in Equation 5.2.

$$C_{labor} = c_{labor} * t_{process} \tag{5.2}$$

The cost of the electricity to power the machine tool is a function of the electricity rate, c_{elec}, idle power, P_{idle}, idle time of the machine tool, t_{idle}, process power, $P_{process}$, and the process time, $t_{process}$.

$$C_{elec} = c_{elec} * (P_{idle} * t_{idle} + P_{process} * t_{process}) \tag{5.3}$$

Maintenance is important in obtaining a long useful life and comes in the form of preventative and corrective maintenance. Maintenance costs depend on the type of machine tool and how it is used throughout its life-time. A comprehensive life-cycle cost analysis of machining that includes maintenance cost is presented in [88], but the ownership cost presented here focuses solely on labor and electricity since historical data is not available for the machine tools under study.

Pertaining to a machine's end-of-life, machine tools are typically resold when a site opts to acquire another machine [85]. Upgrading or retrofitting a machine tool is generally not a cost-effective solution because of the integrative nature of a new component to the entire unit. Machine tool technologies typically achieve significant advances over the useful life of a machine, particularly the controller [89]. Since the end-of-life costs and/or profits are amortized over the functional life of the machine tool, the end-of-life impact remains negligible and the total cost will be represented by Equation 5.4.

$$C_{total} = C_{acquisition} + C_{labor} + C_{elec} \tag{5.4}$$

The cost of acquiring the machine tools was assumed to range between $100,000 and $200,000, each with a functional life of 15 years. A labor rate of $40 per hour and an electricity rate of $0.12 per kWh was used. Although the acquisitional cost of the machine tool is sizable, it had a negligible impact since it was amortized over the functional life of the machine. Even when a low utilization of the machine tool is assumed, i.e., if the machine tool was only utilized for part processing 30% of the time throughout its functional life, the acquisitional cost would still be negligible relative to the cost of ownership. Reducing the functional life from 15 to 10 years also showed a negligible impact on the cost of machining.

During the use phase, the cost of electricity relative to the cost of labor was extremely low, so the labor rate naturally overshadowed electrical energy costs. The overall cost was therefore dominated by processing time and the labor rate. In strategizing for cost reduction, since labor rate is fixed one should target a reduction in processing time, which can be achieved with proper tooling so as to maintain optimal cutting conditions. Without implementing proper cutting conditions, high process rates can quickly lead to significant tool wear and a high frequency of tool changes. In such a scenario, the cutting tool price and the amount of time taken to change cutting tools should be accounted for. However, in this analysis the proper specification of processing conditions is assumed.

5.2.2 The Energy Consumption of Machine Operation

The use phase of a machine tool has been shown to have the greatest environmental impact, even in facilities with a low utilization of machines [85]. The principal resources consumed during machine tool operation include electrical energy, water, cutting fluid, cutting tools, and workpiece material [32]. This case study focuses on the use of electrical energy to power machine tools.

The energy associated with manufacturing cutting fluids was found to be negligible by [90], therefore it will not be included as part of this analysis. Additionally, the energy associated with raw material extraction is typically sizable, but since the material type is often dictated by the product designer, it is outside of the scope of decisions that can be made by the manufacturer and will not be varied in this case study.

It was previously shown in section 4.1 that the energy consumed by a machine tool could be characterized with the following model:

$$E_{part} = (k * \frac{1}{MRR} + b) * V \tag{5.5}$$

where k and b are the specific energy constants, MRR is the material removal rate, and V the volume of material removed. As such, the electrical energy consumption for any given machine tool is dominated by the time required to process the part when optimal cutting conditions are used. This study will utilize this energy model to calculate the energy consumption during factory operations.

5.2.3 Characterization of Part Processing

DES was used to model the processing of three types of parts. These parts were generically labeled types A, B, and C and produced in proportions of 45%, 30%, and 25%, respectively. Three important considerations in defining the part processing environment are the interarrival time, queuing discipline, and process time. The interarrival time denotes the amount of time between the arrival of one part and the next part at a particular work station. Manufacturing processes are often characterized as being Poison processes since events occur on a continuous time scale (versus discrete), independent of one another at a constant, average rate. The interarrival time has quite often been found to be exponentially distributed for poison processes [91]. The parts for this simulation were, therefore, modeled as having exponentially distributed interarrival times with a mean interarrival time of 10 minutes. One of the many benefits of utilizing DES is that such input parameters can be easily modified to describe another manufacturing system.

The queuing discipline identifies the order that parts are processed in. For example, banks typically serve customers in the order that they arrive, which would be an example of the first-in-first-out (FIFO) model. Alternative schemes include last-in-first-out (LIFO) and priority queues. The parts were processed using a first-in-first-out (FIFO) queuing discipline [92] in a multi-server queuing model as shown below in Figure 5.2.

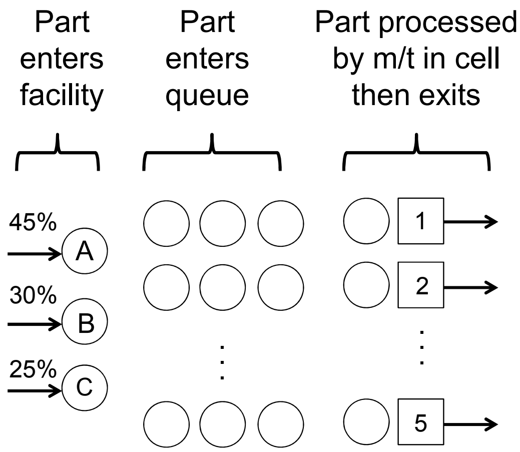


Figure 5.2: Part queuing in model of facility operations [72].

The manufacturing floor was laid out such that it consisted of five cells, M1–M5, of milling machine tools. The number of machines per cell is depicted in Figure 5.3. Cells M1 and M2 consisted of three and two Fadal VMC 400 machines, respectively; cells M3 and M4 consisted of one Mori Seiki DV5500 each; and cell M5 consisted of four micromachining centers, the Mori Seiki NVD1500. Cells M1 and M3 were run under dry cutting conditions, while cells M2, M4, and M5 were run under wet cutting conditions.

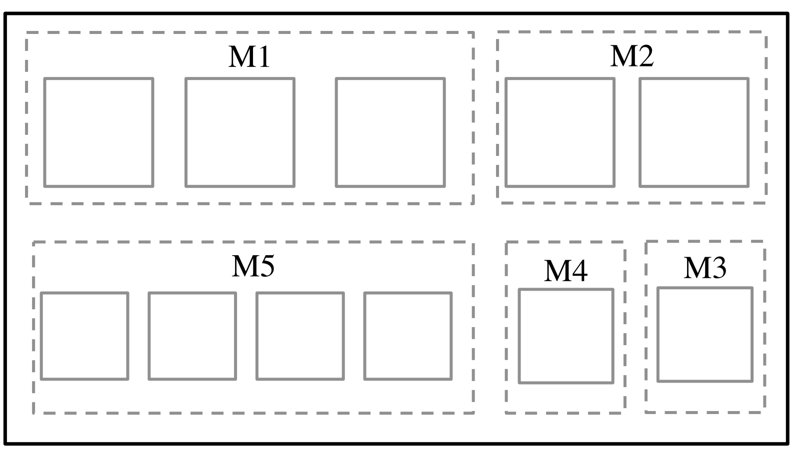


Figure 5.3: The machine tool cells of the baseline case.

The machine tools capable of producing the different part types were limited to the cell constraints in Table 5.1. That is, part type A could be produced with a machine tool in cell M1, M2, M3, or M4 while part type C could only be produced by a machine tool in cell M5 (i.e., a micromachining center).

Table 5.1: Uniformly distributed part processing parameters [72].

Part Type	Cell Constraints	MRR $[\frac{mm^3}{s}]$	$t_{process}$ $[min]$
A	M1, M2, M3, or M4	500 to 600	45 to 50
B	M2, M4, or M5	305 to 350	95 to 105
C	M5	0.75 to 1.75	120 to 135

The range of material removal rates was designed such that they were within the capabilities of the machine tools. The MRR and the processing time remained constant throughout the production of any given part. However, these parameters were uniformly distributed over the ranges outlined in Table 5.1 for each part type, thus creating a highly diverse mix of products.

5.2.4 Machine Tool Selection Criteria

Since the parts could be produced by a range of machine tools, the machine tool selection criteria will be based on the cost and energy optimization strategy. The machine tool cost was found to be dominated by labor costs and therefore proportional to process time. Given that the process time is currently independent of the type of machine tool being used, the cost was assumed to remain constant for the production of a part. Thus, the type of machine tool used to produce the part was chosen such that the energy consumed during machining was reduced.

Table 5.2: Parameters for process energy and idle power demand for machine tool cells M1–M5 (sourced from [40; 41]).

	Machining Center	k $[\frac{J}{s}]$	b $[\frac{J}{mm^3}]$	P_{idle} $[W]$
M1	Fadal VMC 4020 (dry)	1330	2.845	740
M2	Fadal VMC 4020 (wet)	1396	3.082	740
M3	Mori Seiki DV 5500 (dry)	1344	2.830	1020
M4	Mori Seiki DV 5500 (wet)	2019	2.953	1020
M5	Mori Seiki NVD 1500 (wet)	1481	3.678	924

The facility model included the machine tools and cells presented in Table 5.2. Distinctions were made as to whether or not the machines operated under dry or wet cutting conditions since this significantly affects the processing energy consumption. The cells were preferred in the following order based on lowest processing energy consumption: M1, M3, M2, M5, and M4, i.e., a machine tool in cell M1 consumed the lowest energy while processing parts at a particular MRR and one in cell M4 consumed the highest energy at the same MRR.

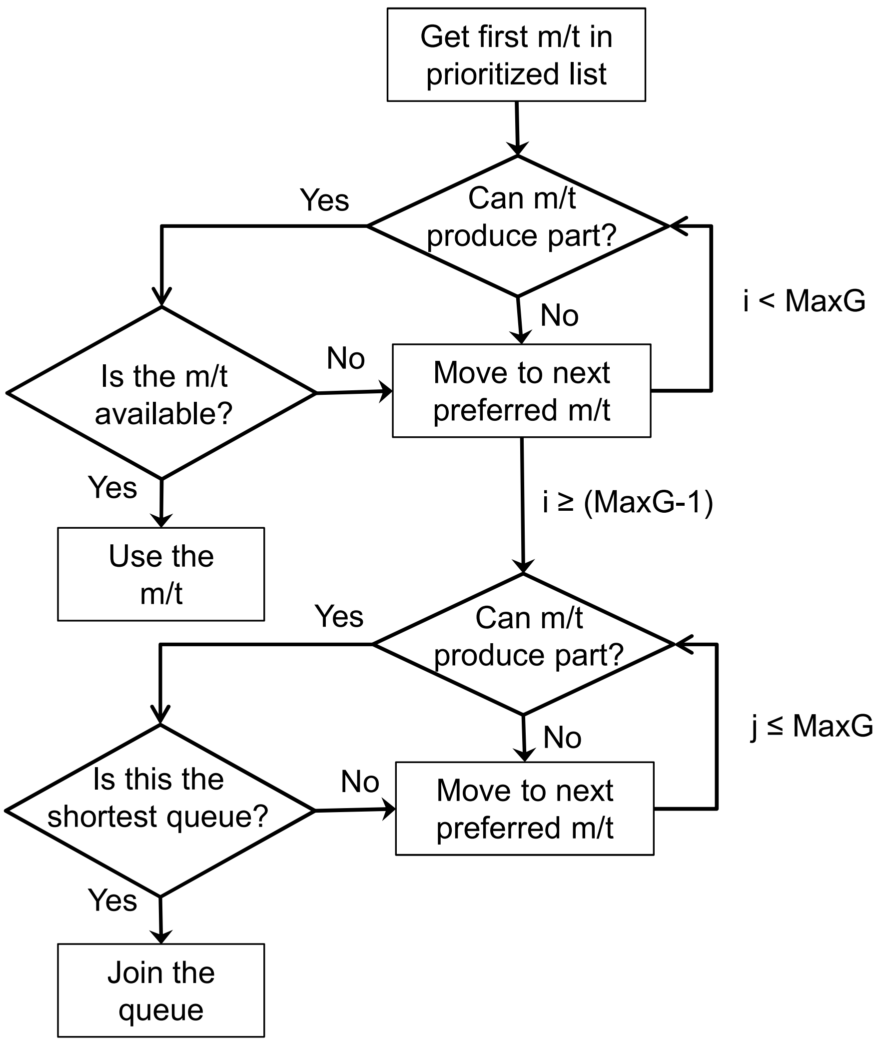


Figure 5.4: The decision tree for machine tool selection [72].

The strategy utilized for machine tool scheduling was based on the cell constraints outlined in Table 5.1 and the cell ranking based on lowest process energy consumption. The DES model tracked the number of available machine tools within a cell rather than the availability of each individual machine tool. If no machine tool was readily available to start production then the part entered the shortest queue (see Figure 5.4 where $MaxG$ is the number of cells in the facility, and i and j iterate through the number of machine tool (m/t) cells).

This machine tool selection strategy gives preference to high machine tool utilization so as to avoid the consumption of energy for non-value added time, i.e., during idling. Alternative strategies can be studied such as reducing the overall time spent in the facility (processing and wait time) or prioritizing parts in queues based on expected processing energy consumption or lead time. Since flexible manufacturing facilities such as job shops underutilize machine tools, it is also important to consider if it would be more beneficial for a part to wait for a less energy intensive machine tool to become available rather than immediately start production at an available machine tool, especially if the part has a long processing time. Such a part scheduling strategy will be studied in future work.

5.3 Discussion of Results: Machine Tool Cost and Energy Consumption

The production of 1,000 parts was first simulated for a facility with 11 machine tools, over the time span of approximately seven eight-hour shifts. The DES model allowed for cost and energy accounting at the part, cell, and facility level, information that was used to make informed decisions about cell modifications by considering underutilized and energy-intensive machine tools.

Machine tool operation cost the manufacturing facility a total of $52,801 with the process planning strategy outlined in Figure 5.4. The total energy consumed by the five manufacturing cells amounted to 11.85 GJ, 92.8% of which was used for process energy and the remaining 7.2% for idle energy (see Figure 5.5). Details regarding the further breakdown of the idle energy consumption are included; note that cells M1, M2, and M5 consumed the greatest proportions of idle energy consumption – information that was used in planning the alternative cell designs.

The energy consumption for a total of seven scenarios (each with a different number of machine tools in each cell) was estimated. Table 5.3 shows the number of machine tools in each cell for each case. The baseline, case 1, had 11 machine tools in total and the cases thereafter had between one and four fewer machine tools. The cells that were altered in this study relative to the base case are noted with an asterisk (*).

The Fadal VMC 4020 under dry cutting conditions (cell M1) had the largest fraction of idle energy consumption. Therefore, one machine tool was first removed from cell M1 in case 2. One or more machine tools from cell M1 were also removed in cases 5, 6, and 7. The Mori Seiki DV5500 from cell M4 was also removed in cases 3–7 since this machine tool consumed the greatest electrical energy while processing under wet cutting conditions. Lastly, the number of machine tools in cells M2 and M5 were varied since these cells had the second largest fraction of idle energy consumption in the baseline scenario.

The cost of machine tool operation changed only slightly in the evaluation of the cases,

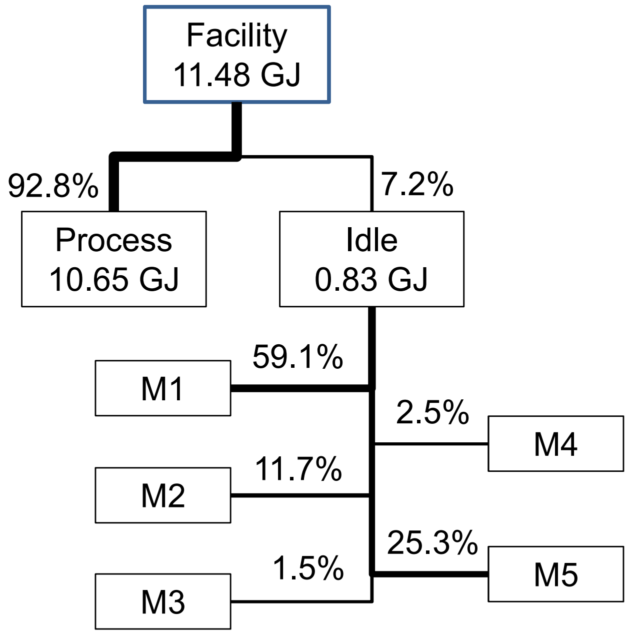


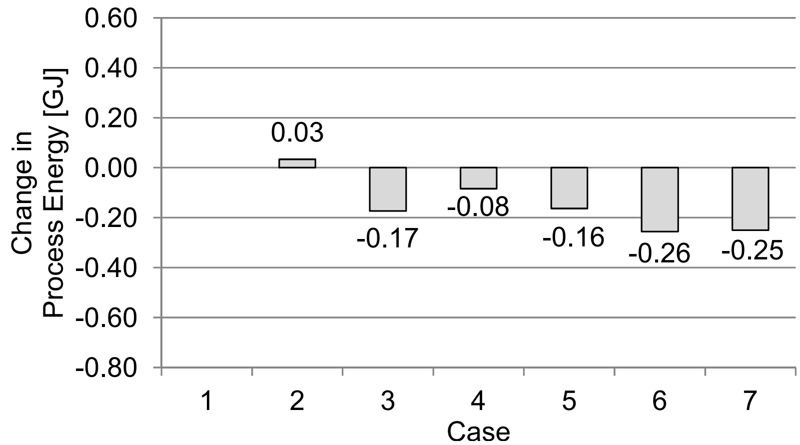
Figure 5.5: Breakdown of machine tool energy consumption [72].

Table 5.3: Number of machine tools in each manufacturing cell for cases 1-7 where the asterisk (*) represents the modified cell (adapted from [72]).

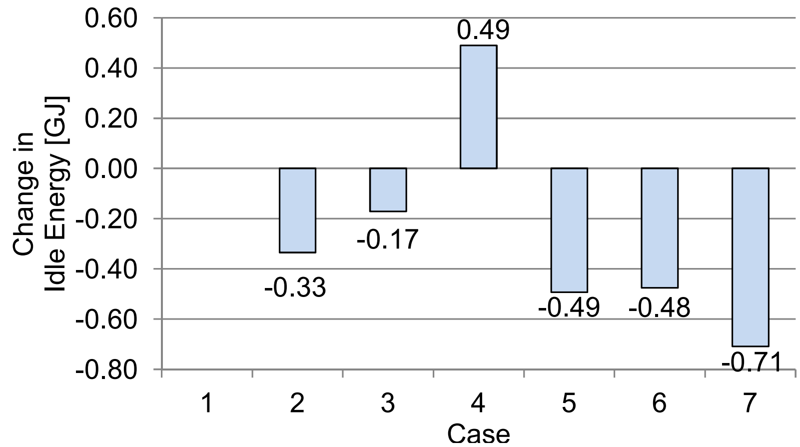
Cell	Case						
	1	2	3	4	5	6	7
M1	3	2*	3	3	2*	2*	1*
M2	2	2	2	1*	2	2	2
M3	1	1	1	1	1	1	1
M4	1	1	0*	0*	0*	0*	0*
M5	4	4	4	4	4	3*	3*

ranging from $52,769 to $52,814 for the production of 1,000 parts. The cost did not change significantly because the labor rate and process time dominated the cost, rather than the type of machine tool used. The greatest cost savings relative to the original configuration of the manufacturing cells was only 0.06% in case 7.

The energy saved for the scenarios presented are shown in Figures 5.6a and 5.6b, below. Case 4 is the only scenario that consumes more energy than the baseline. 11.1% of the total energy consumed by the machine tools (11.89 GJ) was spent on idling machine tools. The idle energy consumption increased relative to the baseline case when a machine tool from cells M2 and M4 were removed in case 4 due to part queuing.



(a) Process Energy



(b) Idle Energy

Figure 5.6: Change in process and idle energy consumed relative to case 1 [72].

5.3.1 Consequences of Layout Changes on Part Queuing

Wait time, the time that a part spends waiting in a queue, was calculated for the seven cases and is depicted below in Figure 5.7. The first-quartile, median, third-quartile, maximum, and average wait times are shown. Since setup time was ignored in this analysis, the minimum wait time in all cases is zero because a fraction of the parts begin the processing stage immediately if a machine tool is available. The greatest variability in wait times occurred in cases 4, 6, and 7. These cases also have the highest overall wait times. The variability is caused by the constraints on part production, i.e., parts are restricted to a set of machine tools for production. So when a machine tool is removed from a cell that is highly utilized, the queue length grows (potentially at an unstable rate).

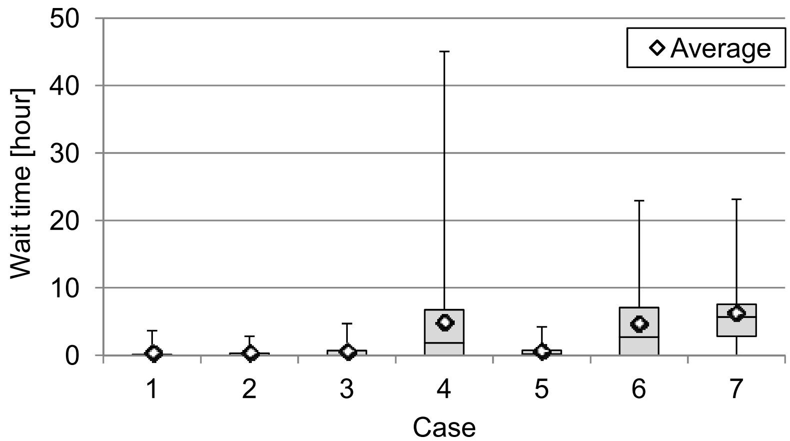


Figure 5.7: Variation in part wait time for each case [72].

For example, in case 4 the removal of a machine tool in cells M2 and M4 caused a sharp increase in wait time since part types A and B are both processed by this cell and they comprise 75% of the total parts. The cause for the variability in wait time in cases 6 and 7 is similar. Cell M5 processes many parts so when a machine tool is removed from this cell, the wait time grows and the rest of the cells are spent in idle mode as the cell finishes its queue. So although cases 6 and 7, in particular, had lower overall machine tool energy consumption when accounting for processing and idle electrical energy consumed, the parts spend a longer period of time in the facility. Thus, if overhead and holding costs were incorporated to determine the facility-wide energy consumption these cases may not in fact be ideal scenarios.

In order to determine the ideal number of machine tools for the facility, aside from concentrating on lowest energy consumed, the stability of queues should be accounted for as well. In this example, cases 1, 2, 3, and 5 had stable queues. Of these scenarios, case 5 had the lowest overall energy consumption and would therefore be the recommended option for the design of the facility. Case 5 results in an energy reduction of 6.37% as well as stable queues.

The case of a high product mix was shown in the development of a machine tool scheduling algorithm to achieve a reduction in energy consumption, but a low product mix can easily be implemented by modifying the part processing conditions. Additionally, as the degree of automation increases in the production facility, the relative proportion of electricity costs are expected to increase as well since less labor would be necessary. As such, the machine tool scheduling algorithm would result in additional cost savings since electrical energy savings would lead to reduced costs.

Chapter 6

Global Energy and Cost Trends in Manufacturing Industries

6.1 Overview of the Energy Consumption in Manufacturing

The energy consumed by industry makes up approximately one-third of the overall energy consumption of the United States [5]. The manufacturing industry is comprised of twenty-one industrial sectors as defined by the North American Industry Classification System (NAICS) [7]. These sectors consumed $1.65 * 10^{19}$ Joules of energy as fuel in 2006 [6]. The three most energy-intensive sectors, the "Petroleum and Coal Products Manufacturing" (324), "Chemical Manufacturing" (325), and "Paper Manufacturing" (322) sectors, consumed close to 60% of the total energy consumption.

Facilities that manufacture discrete products primarily consume energy for process heating and cooling; machine drive; heating, ventilation, and air conditioning (HVAC); and lighting requirements as shown in Figure 6.1. In fact, approximately 55% and 26% of the natural gas and net electricity, respectively, was utilized for HVAC, while machine drive utilized 47% of the electricity consumed, and lighting 15% of the electricity consumed by the U.S. facilities that were surveyed for the "Machinery Manufacturing" sector.

The energy requirements for manufacturing processes and equipment have been studied extensively. Gutowski et al. [12] found that the electrical energy requirements for a machine tool vary with the processing conditions. Some of the machine's components consume a constant power demand once they are turned on regardless of the processing conditions of the machine tool, while other components vary with the load from material processing, i.e., spindle motor and axis drives. The machine's components and their efficiency thus play a major role in the power demand of a machine, as does the specific process parameters used to process material. Furthermore, research has been conducted to model the energy consumption of manufacturing processes by means of empirical assessments [13; 41; 42; 43; 44; 57; 58] and the development of theoretical process models [10; 27; 93; 94].

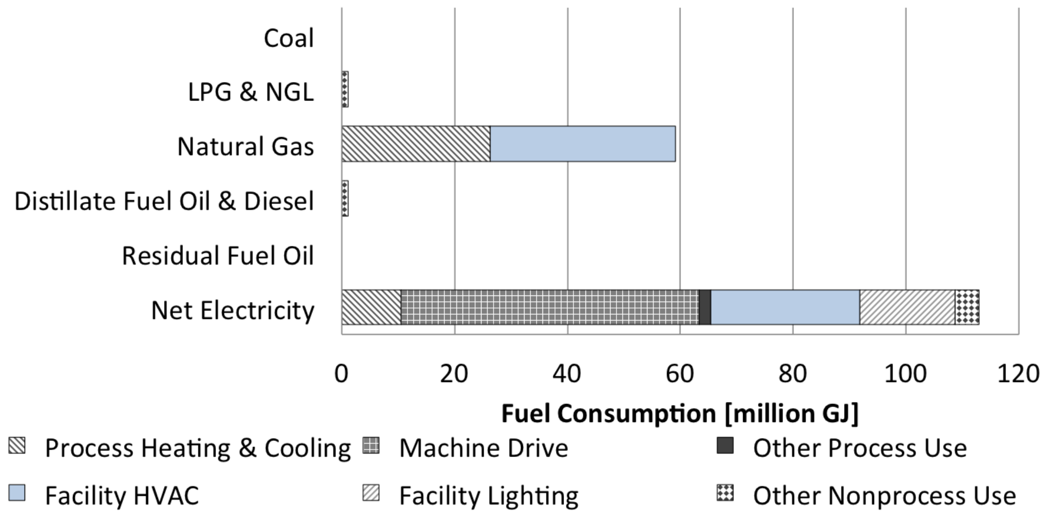


Figure 6.1: Direct end use of fuel consumption for the "Machinery Manufacturing" industrial sector (NAICS 333) in 2006 (data sourced from [6]).

Aside from processing energy, Diaz et al. [85] showed that the peripheral facility resources, such as lighting and the HVAC system, account for more than 40% of a machine tool's use phase energy consumption. The energy consumed to provide lighting for a facility is fairly straightforward to determine since it depends on the power rating of the fixtures, ballast efficiency, and operating time. However, the energy consumed for machinery and HVAC is more complex.

This chapter concerns the energy consumption and costs associated with manufacturing industries and identifies the greenhouse gas emissions of electricity consumption in a multi-country analysis. Industry data from the U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) [6], the U.S. Census Bureau's American Survey of Manufacturers (ASM) [95], and the U.S. Bureau of Labor Statistics (BLS) will be utilized, as well as energy data from the Machining, Ballscrew, Spindle and Assembly Plants of the Japanese machine tool manufacturer, Mori Seiki. Additionally, a case study will be presented for the evaluation of energy and cost of a machinery manufacturing facility in the United States, Japan, Germany, China, and India.

6.2 Energy Intensity: Characterization and Trends of Manufacturing Industries

The energy intensity of manufacturing industries is a common metric used to identify trends in energy efficiency and sectoral changes over time. The energy intensity represents the energy consumed for production per unit of output, such as production units, value added, or value of product shipments. Aggregate energy intensity is utilized to analyze the trend of the manufacturing industry as a whole, while the energy efficiencies of individual manufacturing sectors can be evaluated with sectoral energy intensities [96].

Figure 6.2 shows the sectoral energy intensity with respect to value added, SEI_{VA}, and value of product shipments, SEI_{VPS}, for ten U.S. manufacturing sectors. The metric was calculated with respect to total electricity consumption[1], E_{elec}, value added, Q_{VA}, and value of product shipments, Q_{VPS} (see Equation 6.1 and Equation 6.2).

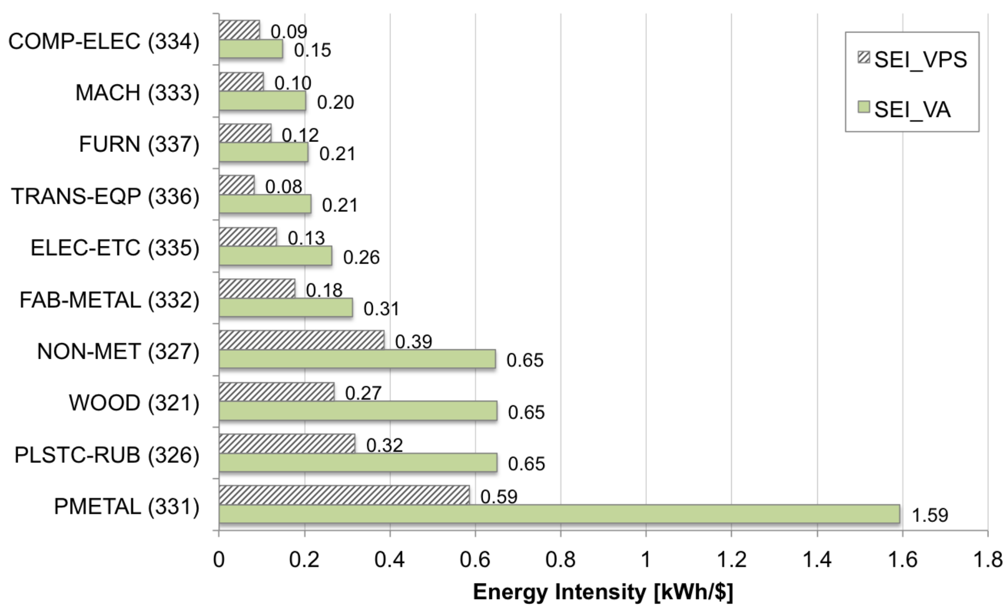


Figure 6.2: Sectoral energy intensity: total electrical energy consumption over the value added and value of product shipments in 2006 (data sourced from [95]).

$$SEI_{VA} = \frac{\sum E_{elec}}{\sum Q_{VA}} \tag{6.1}$$

$$SEI_{VPS} = \frac{\sum E_{elec}}{\sum Q_{VPS}} \tag{6.2}$$

The ten manufacturing sectors can be categorized as high energy consumers, high value added consumers, and low energy consumers. The high energy consumers consist primarily of

[1]The sum of purchased electricity for heat and power and generated electricity, minus the electricity sold and transferred.

those sectors that produce raw materials: "Primary Metal Manufacturing" (PMETAL (331)), "Plastics and Rubber Product Manufacturing" (PLSTC-RUB (326)), and "Nonmetallic Mineral Product Manufacturing" (NON-MET (327)). These sectors consume 51.8% of the total electricity consumed by the ten sectors and, consequently, have high energy intensities.

The high value added consumers consist primarily of those manufacturers that are highly involved in selling final product assemblies with a high value added: "Transportation Equipment Manufacturing" (TRANS-EQP (336)), "Computer and Electronic Product Manufacturing" (COMP-ELEC (334)), "Fabricated Metal Product Manufacturing" (FAB-METAL (332)), and "Machinery Manufacturing" (MACH (333)). These sectors generate 22.2%, 19.6%, 14.4%, and 13.1% of the total value added, respectively, and in total consume 36.8% of the electricity. Since these sectors have a high value added component, they have relatively low energy intensities as Figure 6.2 shows.

The low energy consumers consist of the "Furniture and Related Products Manufacturing" (FURN (337)), "Electrical Equipment, Appliance, and Component Manufacturing" (ELEC-ETC (335)), and "Wood Product Manufacturing" (WOOD (321)) sectors. These sectors have relatively low energy intensities as well, except for the WOOD (321) sector, which aside from being a low energy consumer also has a relatively low value added component.

In order to analyze the trends in energy intensity over time and identify the dominant factors influencing change, decomposition analysis is commonly used. For the decomposition analysis of energy intensity, these factors typically include intensity and structural changes. To further explain decomposition analysis, take as an example a company that produces steel. This company would have a relatively large energy intensity because of the nature of this industry (a high energy consumer). The manufacturing operations are energy-intensive and add less value in comparison to complex products that require the processing and assembly of several sub-components and types of raw materials. If this company added fabricated metal products to their product mix, the energy intensity of the company would decrease due to a structural change since these products are less energy-intensive and result in a higher value added. Alternatively, if they maintained the original product mix of steel production and implemented energy-efficient technologies, then the reduction in energy intensity would be the result of an intensity change. A detailed overview of eight methodologies used to conduct index decomposition analyses on the aggregate energy intensity of industry is provided by Liu et al. [96].

Liu and Ang surveyed index decomposition analyses that have been conducted since the late 1970s and provided a multi-country analysis of the results [97]. They found that the United States, Japan, and China experienced a decrease in the aggregate energy intensity of their manufacturing industries, primarily due to a reduction in intensity. That is, although these countries experienced changes in the structure of their manufacturing industries, the intensity change had a greater effect on the reduction of aggregate energy intensity over time. Goldar attributes the post-1992 decline in energy intensity of Indian manufacturing firms to the application of energy-efficient measures and technologies in order to accommodate the rise in the price of energy [98]. Germany also experienced a reduction in energy intensity between 1998 and 2005 due to both structural and intensity changes as shown by Pardo

Martinez [99].

6.3 The End Use of Fuel

Table 6.1 shows the breakdown of the fuel consumed by the manufacturing sectors in 2006 and Table 6.2 the total energy consumed by each sector. The tables are ordered by the percentage of processing heating energy from lowest to highest. Process heating consumes the greatest proportion of energy - between 9.3% and 55.1% of the energy consumed by each sector. Machine drive consumes between 11.1% and 35.4% of energy, while HVAC consumes 4.9% to 30.7% and lighting 0.8% to 7.9%.

Table 6.1: Breakdown of energy consumption by end use for manufacturing sectors (data sourced from [6]).

Sector	Heating	Machines	HVAC	Lighting	Boiler	Cooling	Other
COMP-ELEC (334)	9.3%	13.6%	30.7%	7.9%	14.3%	7.1%	17.1%
MACH (333)	16.3%	24.8%	27.7%	7.9%	7.9%	1.5%	13.9%
FURN (337)	17.0%	24.5%	22.6%	7.5%	3.8%	0.0%	24.5%
PLSTC-RUB (326)	18.1%	29.1%	13.5%	4.9%	19.9%	4.9%	9.5%
TRANS-EQP (336)	21.9%	16.3%	26.5%	6.2%	10.3%	3.0%	15.7%
WOOD (321)	26.3%	35.4%	5.3%	3.3%	9.6%	0.5%	19.6%
ELEC-ETC (335)	38.4%	18.6%	16.3%	5.8%	8.1%	2.3%	10.5%
NON-MET (327)	40.7%	11.1%	2.8%	0.8%	2.1%	0.4%	42.1%
FAB-METAL (332)	46.9%	18.5%	12.8%	3.6%	9.2%	1.3%	7.7%
PMETAL (331)	55.1%	14.0%	4.9%	1.4%	2.8%	0.5%	21.3%

The raw material sectors consume a large percentage of energy for process heating. Process cooling requirements are very important for the production of electronic products, and the share of energy consumption is as high as 7.1% for the computer and electronic product manufacturing sector. Additionally, lighting has a larger presence in those facilities requiring product assemblies (e.g., computers, machinery, furniture, etc.).

Table 6.2: Total energy consumption in 2006 (data sourced from [6]).

Sector	Total Energy [10^8 GJ]
COMP-ELEC (334)	1.48
MACH (333)	2.13
FURN (337)	0.559
PLSTC-RUB (326)	3.44
TRANS-EQP (336)	4.91
WOOD (321)	2.21
ELEC-ETC (335)	0.907
NON-MET (327)	10.2
FAB-METAL (332)	4.11
PMETAL (331)	11.7

The energy requirements for facility resources, such as HVAC and lighting, of a large facility would be expected to consume more energy than that needed for a small space. As such, the energy intensity for the net demand for electricity[2] consumed for machines, HVAC, and lighting was calculated with respect to the floorspace of the manufacturing sectors (see Figure 6.3).

The energy intensity of machines range from 73 to 992 kWh per m^2. The "Furniture Manufacturing" sector has the smallest energy intensity for machines, which is most likely attributed to the manual labor involved in the production of furniture and related products. In fact, the energy intensity for machines is less than half of the other industries. The high energy consumers (namely the raw material industries: PMETAL (331), PLSTC-RUB (326), and NON-MET (327)) and the WOOD (321) sector have a relatively high machine energy intensity.

The yearly HVAC energy intensity ranges from 24 to 177 kWh per m^2. The Computer and Electronic Products industry consumes the greatest amount of energy over its allocated floorspace. This is most likely a result of the strict temperature control required of the HVAC system in computer and electronic product manufacturing.

The energy intensity of lighting has the smallest range, ranging from 25 to 110 kWh per m^2. Lighting requirements become more intensive with detailed, manual assembly and when large pieces of production equipment are used in a facility since the ceiling height requirements can increase significantly. By comparing the energy intensity of a factory to

[2]The sum of purchases, transfers in, and total onsite electricity generation, minus sales and transfers offsite [6]. It is the total amount of electricity used by establishments. "Net Demand for Electricity" is not directly comparable with "Net Electricity", which specifically excludes electricity generated onsite by combustible energy sources.

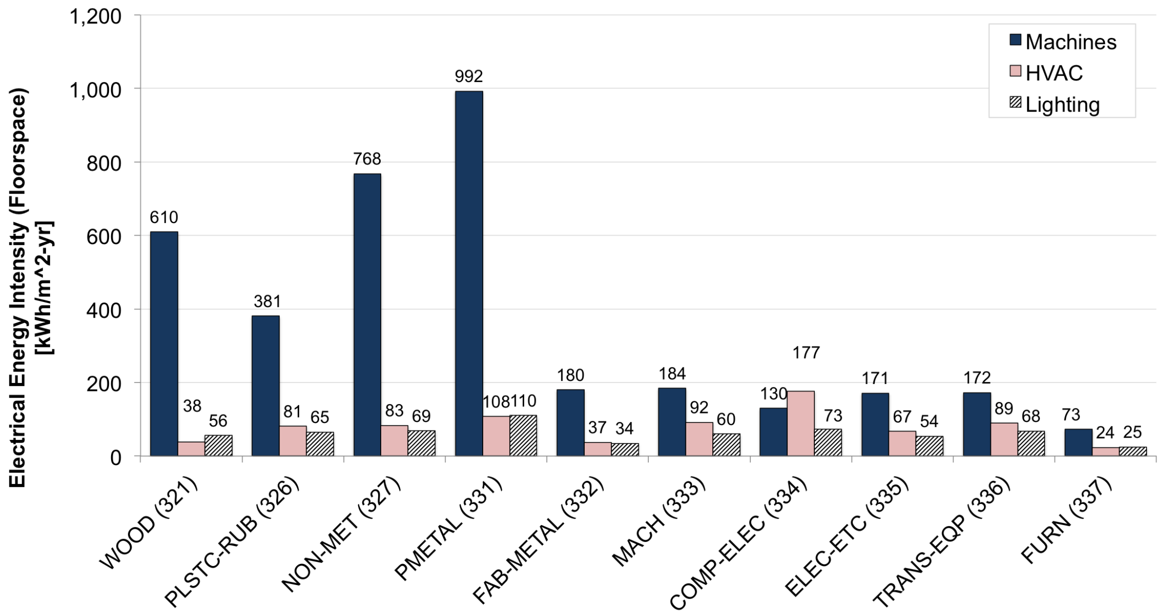


Figure 6.3: Electrical energy intensity of the manufacturing sectors in 2006 (data sourced from [6]).

the national averages, the potential impact of HVAC equipment and lighting upgrades could be deduced, which will be a part of the analysis in the following section since factory-level data is available.

6.4 Electricity Use for Machinery Manufacturing at Mori Seiki

Mori Seiki is a Japanese machine tool manufacturer. One of Mori Seiki's primary production and assembly sites is located in Iga, Japan, which consists of many plants including casting, machining, assembly, and precision manufacturing plants. Energy data for production equipment, HVAC, and lighting from 2011 was utilized from four of their plants: the Assembly, Ballscrew, Spindle, and Machining Plants. The spindle and ballscrew are two primary components of a machine tool. Specifically, the components drive the cutting tool and the table axes of the machine tool, respectively. The Spindle and Ballscrew Plants are responsible for manufacturing these particular components of the machine tool. The Assembly and Machining Plants are utilized for large-scale assembly and machining operations. This section will present facility-level data and the development of an HVAC energy model based on historical energy consumption.

6.4.1 The End Use of Electricity

The energy intensity with respect to floorspace for three Mori Seiki plants and the combined values for the Machining and Assembly Plants are shown in Figure 6.4. Since Mori Seiki's Assembly Plant requires much more manual labor than the Ballscrew and Machining Plants, the energy intensity of Machines for this plant is relatively low. The Ballscrew Plant manufactures fabricated metal products and requires both high precision machining operations and assembly. This plant has a relatively small floorspace (3,150 m^2) and strict temperature control requirements, thus the high HVAC energy intensity. The Machining Plant is less constrained with respect to its HVAC requirements and is utilized primarily for machining. It therefore has a low HVAC energy intensity and high machine energy intensity.

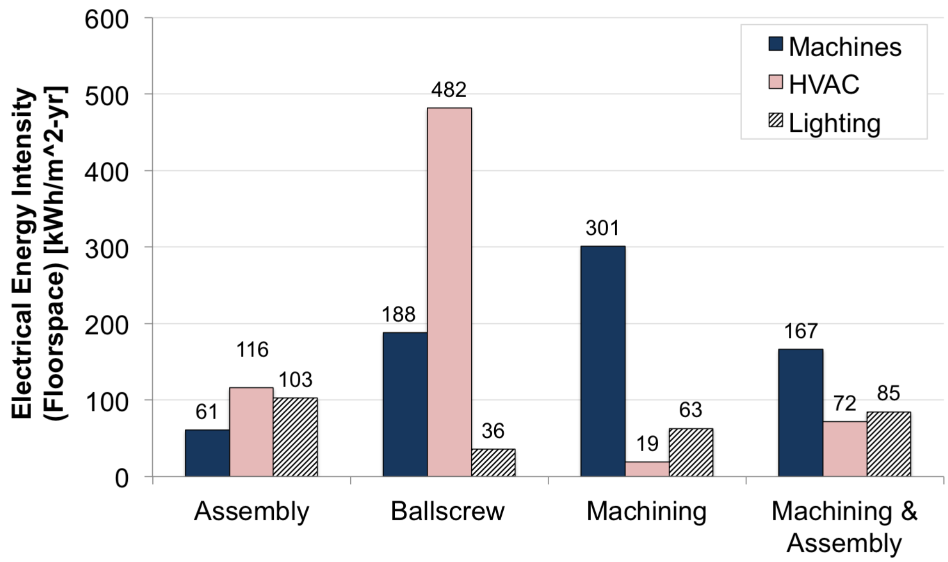


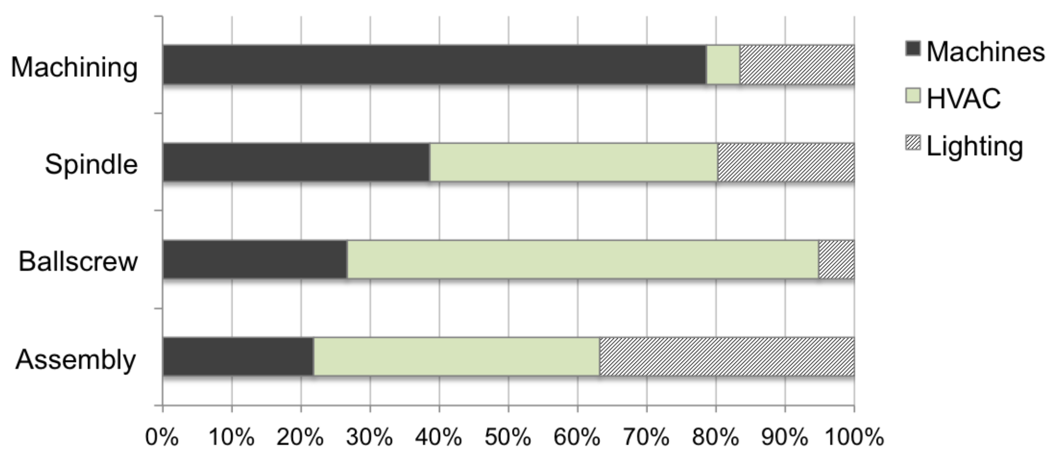
Figure 6.4: Electrical energy intensity of three Mori Seiki plants in 2011.

The yearly lighting energy intensity ranges from 36 to 103 kWh per m^2. While the energy intensities for the U.S. manufacturing sectors represents the average energy intensity and data is not provided for the maximum and minimum energy consumption, the results still emphasize the potential for saving energy by installing energy-efficient lighting fixtures in Mori Seiki's Assembly Plant. Mori Seiki had implemented energy-efficient lighting upgrades to its Ballscrew Plant and partial upgrades to its Machining Plant, which is evident by its close proximity to the average lighting energy intensity of the U.S. manufacturing sectors.

6.4.2 The Effect of Machine Utilization on Plant Energy Consumption

The breakdown of a facility's energy consumption varies based on a variety of factors, from the industry it participates in to the process parameters and efficiency of the equipment used. This section focuses on how the extent of machine utilization affects the overall energy breakdown of a facility. Energy data from four plants within the Mori Seiki Iga campus will be utilized.

It is hypothesized that the energy consumption of facilities that have a high utilization of production equipment would be dominated by the energy of production equipment. In contrast, in a facility where manual labor is more pervasive the HVAC and/or lighting requirements may dominate the overall energy consumed by the facility. Figure 6.5 shows the energy breakdown of machines, HVAC, and lighting for the four Mori Seiki Plants. Since the Assembly Plant is representative of a plant that predominantly uses manual labor for product assembly, while the Machining Plant predominantly uses production equipment during its operations, one can see the effect of manual labor on the energy distribution.



	Assembly	Ballscrew	Spindle	Machining
Machines	3081	593	1644	12602
HVAC	5828	1518	1769	796
Lighting	5184	114	841	2644

Figure 6.5: A comparison of the effect of machine utilization on plant energy consumption with energy in units of MWh per year.

The relative proportion of energy consumed for machines increases as ones moves from the Assembly Plant to the Machining Plant. In fact, the percentage of machine energy in the Machining Plant is nearly four times as much as that in the Assembly Plant. The energy consumed for HVAC varies significantly, ranging from 796 to 5,828 MWh per year.

The percentage of HVAC energy generally decreases as the machine utilization increases. However, HVAC energy makes up more than two-thirds of the overall energy consumed by the Ballscrew Plant. The Ballscrew Plant had some areas of the facility dedicated to precision assembly and therefore required strict temperature control. This explains the greater fraction of energy consumed for HVAC relative to the other plants. This shows that the HVAC system and operations plays a critical role is adequately identifying energy trends.

For example, a new machining facility at Mori Seiki's Iga campus requires very strict temperature control. Specifically, the temperature within the factory must be maintained within +/- 0.5 degrees Celsius of the set temperature. These operating conditions result in a significant increase in energy for the HVAC system. In the case of the new Mori Seiki machining plant, the HVAC energy consumed more than 60% of the overall energy consumed by the facility, even though the plant primarily consists of machining operations. Therefore, in such cases where strict temperature control is enforced, the HVAC energy requirements are expected to dominate overall energy consumption.

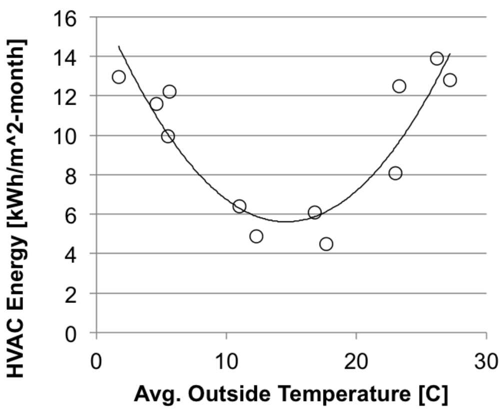
The magnitude of lighting energy ranges from 114 to 5,184 MWh per year. The Assembly and Machining Plants have a large floorspace and therefore require a significant amount of resources dedicated to lighting. Although the power requirements and ballast efficiencies varies for the lighting fixtures across the plants, the percentage of lighting energy tends to decrease as the use of machinery increases. Once again, the Ballscrew Plant shows a deviation in the trend because of the relative amount of energy used for the HVAC system. Additionally, a facility that uses energy-efficient lighting may require a small amount of energy dedicated to lighting in comparison to the rest of the energy requirements.

6.4.3 Modeling the HVAC Energy of Factories

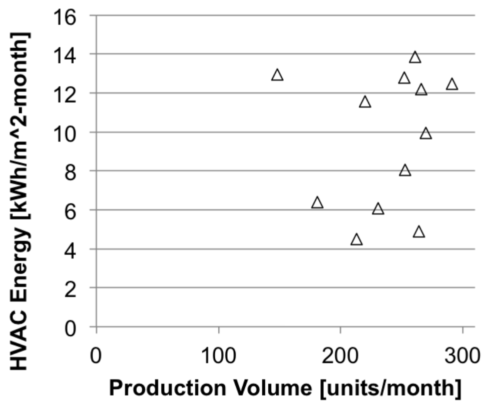
The HVAC energy consumption has been shown to constitute a significant portion of the total energy consumed by a facility. The airflow and energy consumption of HVAC systems remain complex to model, thus the emergence of a host of software tools for conducting HVAC energy and Computational Fluid Dynamics (CFD) analyses such as Autodesk Simulation CFD, the Hourly Analysis Program (HAP), DOE-2, and ANSYS. This section presents a simple methodology that utilizes inverse modeling to characterize Mori Seiki's HVAC energy consumption for the Assembly and Machining Plants with respect to temperature and production volume data.

The energy data utilized herein consists of data for 2011 since Mori Seiki implemented HVAC upgrades in the Assembly Plant in 2010, therefore modifying the energy consumption from one year to the next. The set temperature in the winter and summer months are 18 and 20 degrees Celsius, respectively. Though the ventilation rate was not observed, this parameter has been previously shown to have the potential for significant energy reductions in HVAC energy requirements [14].

From Figure 6.6a below, the monthly HVAC energy consumption and outdoor temperature are observed to have a parabolic trend. It is expected that there will be greater HVAC requirements at low and high temperatures when the heating and air conditioning equipment have to maintain a comfortable indoor climate for factory employees. The HVAC energy requirements are the lowest for the system in the temperature range of 10 to 17 degrees Celsius.



(a) HVAC energy versus average monthly outside temperature.



(b) HVAC energy versus production volume.

Figure 6.6: HVAC energy versus temperature and production volume of the Assembly Plant.

The production volume and the HVAC energy requirements exhibit a positive trend as shown in Figure 6.6b. The left-most point in this sub-figure deviates from the positive trend partly because of the significant influence of the average outside air temperature. Specifically, this data point represents the HVAC energy during the cold, winter month of January where the average outside air temperature was 1.7 degrees Celcius. The positive trend between HVAC energy and production volume agrees with the notion that a greater amount of activity within the factory results in an increase in the release of heat from workers and production equipment. Consequently, more energy is required to maintain a set temperature with increased production volumes.

Combining both the outdoor temperature and production volume data, Figure 6.7 shows a holistic representation of the HVAC energy requirements for the facility. The best-fit model for the HVAC energy, E_{HVAC} in Equation 6.3, consisted of a multivariable polynomial. The coefficients for the Assembly Plant and the 95% confidence bounds can be found in Table 6.3. The r-square value and root mean square error were found to be 0.86 and 1.25, respectively.

$$E_{HVAC} = a + b * v + c * t + d * t^2 \tag{6.3}$$

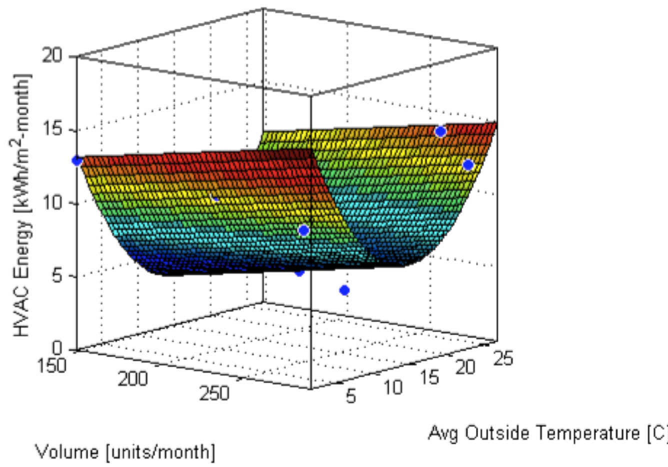


Figure 6.7: Best-fit model for the HVAC energy consumption of the Mori Seiki Assembly Plant.

Table 6.3: The coefficients of Equation 6.3 for the Assembly Plant.

Coefficient	Value	95% Confidence Bounds	
a	13	6.2	19
b	0.023	-0.0048	0.050
c	-1.7	-2.2	-1.1
d	0.055	0.038	0.072

The relationship between HVAC energy, temperature, and production volume was also confirmed for the Machining Plant (see Table 6.4 for the model's coefficients). This plant required significantly less energy consumption than the Assembly Plant, thus the coefficients are smaller by one order of magnitude. The r-square value and root mean square error were found to be 0.88 and 0.20, respectively.

These models represent the empirically-derived relationship between HVAC energy consumption, production volume, and outside temperature. The relationship is expected to be similar for other plants, however, the absolute magnitude of the HVAC energy consumption depends on a variety of factors that are specific to the plant such as the facility size, the properties of the building insulation, the efficiency of the HVAC system, and its operational parameters.

Alternative metrics such as worker hours or production lead-time could be utilized in lieu of production volume in order to capture the heat that is generated in the plant. Additionally, climate details such as humidity and wind speeds can be incorporated in the HVAC energy

Table 6.4: The coefficients of Equation 6.3 for the Machining Plant.

Coefficient	Value	95% Confidence Bounds	
a	2.2	1.2	3.2
b	0.0025	-0.0020	0.0071
c	-0.27	-0.36	-0.18
d	0.0094	0.0066	0.012

model. Lastly, the mode of operation and efficiency of the HVAC system will greatly affect the magnitude of the HVAC energy consumption, as will the time of operation (i.e., day shifts versus night shifts). Incorporating such details and parameters may in fact improve the HVAC energy model, though the model currently shows a good correlation.

6.5 Case Study: Energy and Costs of a Machinery Manufacturing Facility

This section concerns a multi-country analysis in which the effect of plant location on energy consumption and costs of a facility in the Machinery Manufacturing industry is assessed. The top three producers of machine tools, holding approximately 64% of all machine tool production, are China, Japan, and Germany [100]. China, Japan, Germany, the United States, and South Korea are the top five consumers of the world output of machine tool production, accounting for 70% of overall machine tool consumption [100]. Additionally, India represents a prominent contributor to global manufacturing operations. Therefore, the energy and cost of a manufacturing facility in the United States, Japan, Germany, China, and India are evaluated.

6.5.1 Electricity Use, Greenhouse Gas Emissions, and Associated Costs

The previous section showed that the energy consumed by an HVAC system can be modeled as a function of outside temperature and production volume. Iga, Japan sees near zero degree Celsius temperatures in the winter months and relatively hot and humid summer months. Therefore, in locations where the weather is not as extreme, the energy consumed by the HVAC system should be lower. The opposite is also expected to be true, i.e., the energy consumed is greater in areas with more extreme climates.

There are regions that have fairly steady climates throughout the year. A city, such as San Jose, California in the United States, does not maintain very high summer temperatures or very low winter temperatures. The average monthly temperature in 2011 is shown in

Figure 6.8 and Table 6.5, along with additional cities in the United States, Japan, Germany, China, and India.

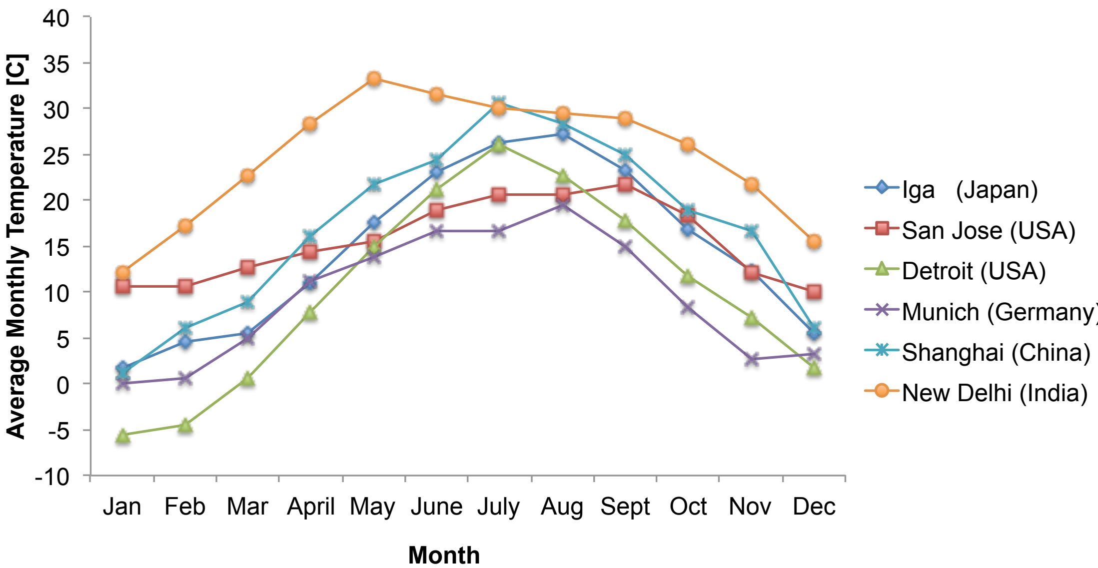


Figure 6.8: Average monthly temperature data from [101; 102].

Table 6.5: Average monthly temperature data, $t_{m,l}$, for 2011 [101; 102].

City	Country	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Iga	Japan	1.7	4.6	5.6	11.0	17.7	23.0	26.2	27.2	23.3	16.8	12.3	5.5
San Jose	USA	10.6	10.6	12.8	14.4	15.6	18.9	20.6	20.6	21.7	18.3	12.2	10.0
Detroit	USA	-5.6	-4.4	0.6	7.8	15.0	21.1	26.1	22.8	17.8	11.7	7.2	1.7
Munich	Germany	0.0	0.6	5.0	11.1	13.9	16.7	16.7	19.4	15.0	8.3	2.8	3.3
Shanghai	China	1.1	6.1	8.9	16.1	21.7	24.4	30.6	28.3	25.0	18.9	16.7	6.1
New Delhi	India	12.2	17.2	22.8	28.3	33.3	31.7	30.0	29.4	28.9	26.1	21.7	15.6

The HVAC energy consumption was then calculated for a factory in the Machinery Manufacturing sector. First, the HVAC energy intensity for the Machining Plant and Assembly Plant was calculated for each month, m(see Equation 6.4), where $E_{HVAC,M}$ represents the HVAC energy intensity of the Machining Plant, $E_{HVAC,A}$ represents the HVAC energy intensity of the Assembly Plant, and $Area_M$ and $Area_A$ represent the floorspace area of the Machining and Assembly Plant, respectively. This resulted in a yearly HVAC energy intensity, EI_{HVAC}, of 72 kWh per m^2.

$$EI_{HVAC} = \frac{\sum(E_{HVAC,M}) + \sum(E_{HVAC,A})}{\sum(Area_M) + \sum(Area_A)} \tag{6.4}$$

The energy intensity was then scaled to the average HVAC energy intensity of the Machinery Manufacturing sector (92 kWh per m^2) in order to determine the coefficients of the energy model for a typical facility in this sector at location, l, (see Equation 6.5). Note that the HVAC energy model utilized in this case study does not include production volume since production volume data is not available for the average "Machinery Manufacturing" facility. Regardless, the correlation of HVAC energy with the outside air temperature is still fairly high (an r-square value of 0.82) because of the large dependency on outside air temperature.

$$EI_{HVAC,l} = \sum_{m=1}^{12}(0.043 * t_{m,l}^2 - 1.2 * t_{m,l} + 13) \tag{6.5}$$

With the coefficients for this new model and the average floorspace, $Area_{MM}$, of an establishment in the Machinery Manufacturing sector of 7,012 m^2, the HVAC energy for each location was calculated given the average outside temperature, $t_{m,l}$ in month m and location l. This methodology assumes that the building infrastructure and the efficiency of the HVAC system remains the same for all facilities in location l. Figure 6.9 shows the variation in energy consumption with location. The New Delhi facility consumes the greatest amount of energy (970 MWh per year); the facilities in Detroit, Shanghai, Iga, and Munich require between 620 and 820 MWh per year; while San Jose requires the least amount (460 MWh per year).

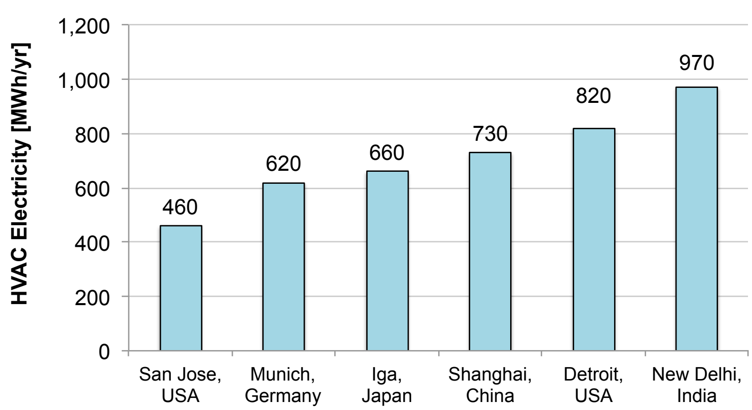


Figure 6.9: HVAC energy consumed for a factory in location, l, with characteristics that mirror the average facility in the Machinery Manufacturing industry.

There are additional advantages to being located in an area with steady and comfortable temperatures like San Jose. For example, the air conditioning can be turned off during relatively cool months in the spring and summer. If the facility is located far enough away from coastal waters such that the possibility of corroding machinery with salty, humid air is low and it is free from other environmental influences such as dust, some facilities may even opt to keep their windows and doors open as part of their common practice. Now, in a site like India a heating system may not be necessary because of the year-round, hot climate; investing in an air conditioning system may in fact suffice. Therefore, HVAC operations for such scenarios would be more energy-efficient than what is shown in Figure 6.9.

In order to calculate the total electricity consumption for each facility, the average energy intensities of the Machinery Manufacturing sector for machines, EI_{Mach}, and lighting, EI_{Light}, were utilized (see Equation 6.6). The total electrical energy consumption varied between 2,200 and 2,700 MWh per year.

$$E_{Total,l} = (EI_{Mach} + EI_{Light} + EI_{HVAC,l}) * Area_{MM} \tag{6.6}$$

To calculate the greenhouse gas (GHG) emissions, the energy mix was first found for each country and state (in the case of the United States) [2; 3; 103; 104; 105]. Table 6.6 exhibits the energy mix of each of the countries in this case study. Germany, Michigan (MI), India and China had a relatively high proportion of coal and peat use (above 43.40% of the total energy) while Japan and California (CA) utilized significantly more nuclear, natural gas, and hydro power.

Table 6.6: The energy mix utilized for electricity generation [2; 3; 103; 104; 105]

	Japan	USA (CA)	USA (MI)	Germany	China	India
Coal and Peat	26.67%	0.98%	57.83%	43.40%	78.82%	68.56%
Oil	8.74%	1.29%	0.74%	1.63%	0.45%	2.90%
Gas	27.19%	46.71%	11.21%	13.31%	1.37%	12.36%
Biomass	1.34%	2.91%	2.09%	4.38%	0.06%	0.22%
Nuclear	26.70%	18.08%	27.02%	22.77%	1.90%	2.07%
Hydro	7.84%	19.88%	0.29%	4.17%	16.66%	11.89%
Geothermal	0.28%	6.51%	0.00%	0.00%	0.00%	0.00%
Solar	0.26%	0.27%	0.00%	1.11%	0.01%	0.00%
Wind	0.28%	2.13%	0.00%	6.52%	0.73%	1.99%
Other Sources	0.71%	1.23%	0.83%	2.70%	0.00%	0.00%

The emissions factors were calculated based on the values reported by Hondo [106] and Gagnon et al. [107] (see Table 6.7 and Table 6.8). Note that the average emissions factor for solar energy from [106] was utilized. These emissions factors do not account for the "Other Sources" referenced in Table 6.6, but these values are all less than 3%. Had the average emissions factors of fossil fuels been utilized in place of "Other Fossil Fuel" for the California and Michigan energy mixes, the emissions factors would be 323 and 653 g CO2-e per kWh, respectively (i.e., a change of less than 3%, which is negligible overall).

Table 6.7: Emissions factor for each type of energy.

Energy Type	Emissions Factor [g CO2-e/kWh]
Coal and Peat [106]	975.2
Oil [106]	742.1
Gas [106]	607.6
Biomass [107]	118
Nuclear [106]	24.2
Hydro [106]	11.3
Geothermal [106]	15
Solar [106]	39.5
Wind [106]	29.5

Table 6.8: Emissions factor for each country given the energy mix in Table 6.6.

	Japan	USA (CA)	USA (MI)	Germany	China	India
Emissions Factor $[\frac{gCO2-e}{kWh}]$	499	315	647	530	783	768

The GHG emissions were thereafter calculated for each facility and the results are displayed in Figure 6.10 for each country and factory resource. The facility located in San Jose, CA emitted the least emissions and consumed the least amount of electrical energy while the Shanghai and New Delhi factories emitted the greatest amount of GHG emissions. Since nuclear energy is a relatively clean form of energy (i.e., emissions associated with electricity generation from nuclear power plants is relatively low), it would be interesting to see the expected changes in emissions based on the proposed energy mix considering that Japan is expected to reduce its dependence on nuclear energy in the future.

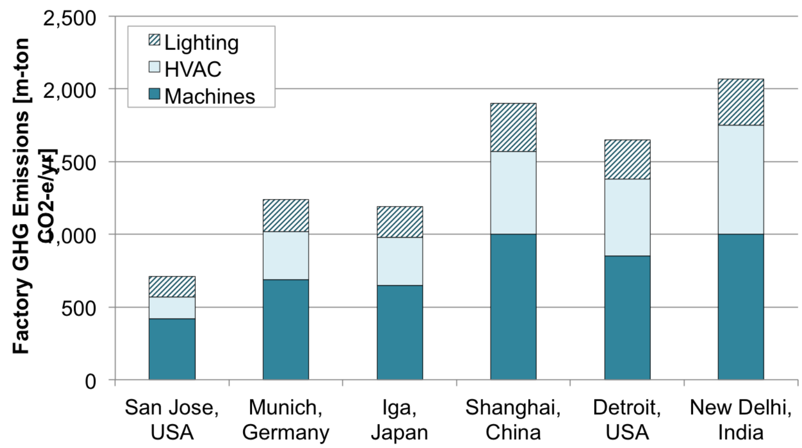


Figure 6.10: Greenhouse gases emitted by each factory per location and resource.

The overlay of the total electricity consumption and the GHG emissions is shown in Figure 6.11. Although the electrical energy consumption is sorted from lowest to highest, the GHG emissions of the facilities located in Iga, Japan and Detroit, Michigan veered away from the increasing trend because of the cleaner energy mix relative to facilities in Germany and China, respectively.

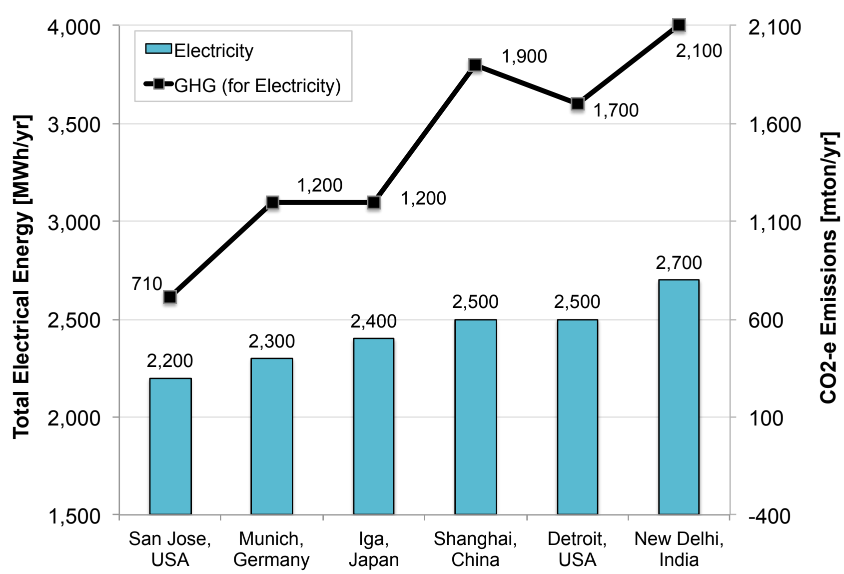


Figure 6.11: Total energy consumed for a factory in the "Machinery Manufacturing" industry in various locations.

In 2010, the price of electricity charged to industrial customers per kWh was the greatest in Japan ($0.154), followed by Germany ($0.136), India ($0.099), China ($0.081), and the United States ($0.068) [108; 109; 110]. The cost of GHG emissions is estimated to be approximately $10 per mton of CO2-e [111]. The total cost of electricity and its associated GHG emissions can be found in Figure 6.12.

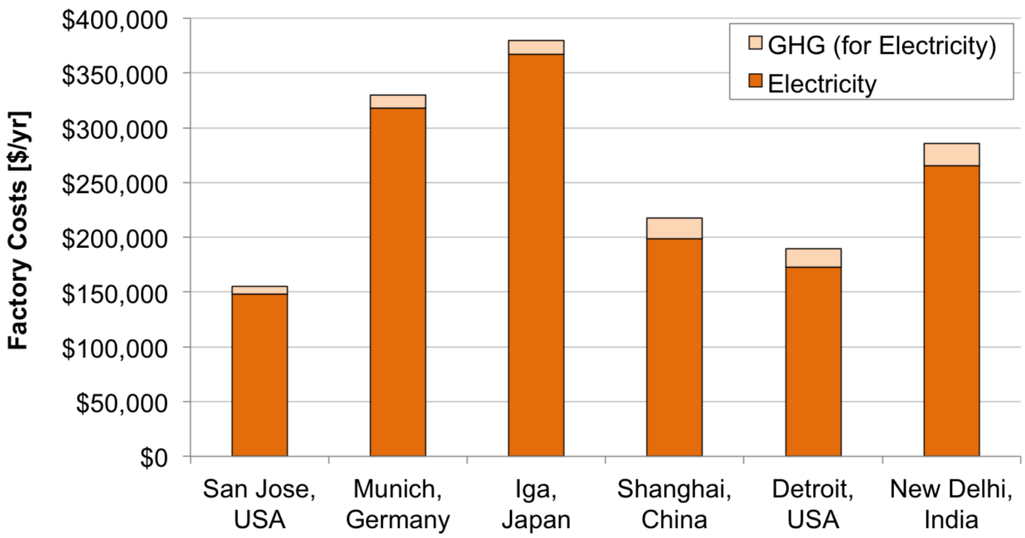


Figure 6.12: The 2010 yearly cost of electricity and GHG emissions per factory in Japan, the USA, Germany, China, and India.

The cost of electricity in Germany and Japan has been rising much more rapidly than the cost of electricity in the United States. Electricity costs in Japan are expected to rise at an even faster rate because of the destructive 2011 earthquake that hit the Fukushima nuclear power plant, and the subsequent restructuring of Japan's electricity generation facilities. Additionally, industrial facilities in India face high electricity costs relative to the United States and China because of the distribution of costs. Specifically, industrial facilities are asked to pay more for electricity than residential and commercial sites [112]. A manufacturing site located in India is also likely to experience disruptions in their operations due to the inconsistency of power availability, which is another important factor to take into consideration as siting decisions are being made. An alternative to reduce the impact of disruptions in power would be on-site power generation, which would also affect the energy mix of the electricity utilized at the manufacturing site.

6.5.2 The Cost of Labor

While the cost of electricity and the expected cost of GHG emissions combined amounted to nearly $375,000 per year, the cost of labor also has a significant contribution to the overall manufacturing cost and varies tremendously based on the location of the factory.

The labor costs, $C_{labor,l}$, for country l can be calculated with the following equation:

$$C_{labor,l} = N_{total} * r_{production} * p_{worker,l} * t_{worker} \tag{6.7}$$

which is a function of the number of production workers, $N_{production}$, the hourly labor compensation, $p_{worker,l}$, and the average number of hours worked per year t_{worker}. The number of production workers per establishment was calculated based off of the total number of employees per establishment, N_{total}, and the percentage of employees that were production workers, $r_{production}$ from the United States Census Bureau [113] and the ASM [95], respectively.

$r_{production}$ was found to be 64.8% for the "Machinery Manufacturing sector. The remaining sectors, as well as the average production worker hours and labor rate for each manufacturing sector, can be found in Table 6.9. Overall, between 47% and 81% of the employees in the ten manufacturing sectors are production workers. Production workers in the "Machinery Manufacturing" sector worked, on average, 2,065 hours per year, which is consistent with that expected for the average full-time employee in the United States with 40 hour work weeks and one to two weeks of holiday.

Table 6.9: Labor statistics for each manufacturing sector (data sourced from [95]).

Sector	$r_{production}$ [%]	t_{worker} $[\frac{hours}{year}]$	Labor rate [$]
WOOD (321)	80.6	2,053	$14.41
PLSTC-RUB (326)	77.9	2,057	$15.80
NON-MET (327)	77.7	2,148	$17.88
PMETAL (331)	79.7	2,184	$21.80
FAB-METAL (332)	74.5	2,090	$17.33
MACH (333)	64.8	2,065	$19.26
COMP-ELEC (334)	46.8	2,015	$20.19
ELEC-ETC (335)	71.4	2,018	$17.05
TRANS-EQP (336)	71.7	2,009	$24.45
FURN (337)	77.9	2,018	$14.40

The cost of labor is very sensitive to the labor rate and the number of production workers. The United States Census [113] provided data concerning the total number of employees, establishments, and firms for enterprises of various sizes. Therefore, the total number of employees per establishment, N_{total}, was calculated. The product of $r_{production}$ and N_{total} was thereafter used to estimate the average number of production workers per establishment, $N_{production}$, which is summarized for all sectors in Table 6.10. It is clear that the average number of production workers depends largely on the size of the enterprise. The average of all manufacturing establishments in the "Machinery Manufacturing" sector was assumed, i.e., 28 production workers per establishment.

Table 6.10: Estimated number of production workers per establishment, $N_{production}$, in each manufacturing sector (data sourced from [95; 113]).

Sector	All Est.	100-499	<500	500+
WOOD (321)	28	84	18	122
PLSTC-RUB (326)	48	81	26	136
NON-MET (327)	22	38	14	44
PMETAL (331)	68	103	29	221
FAB-METAL (332)	20	76	14	115
MACH (333)	28	74	15	152
COMP-ELEC (334)	34	56	12	173
ELEC-ETC (335)	49	95	21	190
TRANS-EQP (336)	92	106	24	382
FURN (337)	20	104	12	239

The hourly wages also differ amongst the various manufacturing sectors in the United States [113] and India [114]. Specifically, in the United States in 2006 the hourly wages vary from $14.40 per hour in the "Furniture Manufacturing" sector to $24.45 per hour in the "Transportation Equipment Manufacturing" sector. Since this level of detail was not available for all countries represented in the analysis, the hourly compensation for the average production worker was assumed in the calculation of the labor cost. The labor rates for production workers overall in 2008[3] [115] are summarized in Table 6.11. These rates were converted to 2010 dollars using the Consumer Price Index [116] to be consistent with the 2010 electricity prices.

The factory costs associated with labor compensation, electricity, and GHG emissions are shown in Figure 6.13. Although the price of electricity in China and India was comparable to Japan, Munich, and the United States, the total cost of manufacturing operations is less than one-fifth the cost of operations due to the significant difference in the hourly labor compensation.

The U.S. Bureau of Labor Statistics (BLS) distinguished between "All Employees" and "Production Workers" in their report on the hourly labor compensation rates in 2008, which amounted to $32.26 and $25.65 per hour, respectively [115]. Thus, the hourly compensation for the average employee is approximately 20% greater than that of the average production worker. This accounts for the significant difference in the labor compensation rates in future

[3]The labor rate data for India was available only until 2005, so 2005 data is provided and converted to 2010 dollars.

Table 6.11: Hourly labor compensation in 2008 [115] and 2010 dollars.

Country	2008 Labor Rate	2010 Labor Rate
Japan	$23.15	$23.45
USA	$25.65	$25.98
Germany	$36.07	$36.53
China	$1.36	$1.38
India	$0.91	$1.02

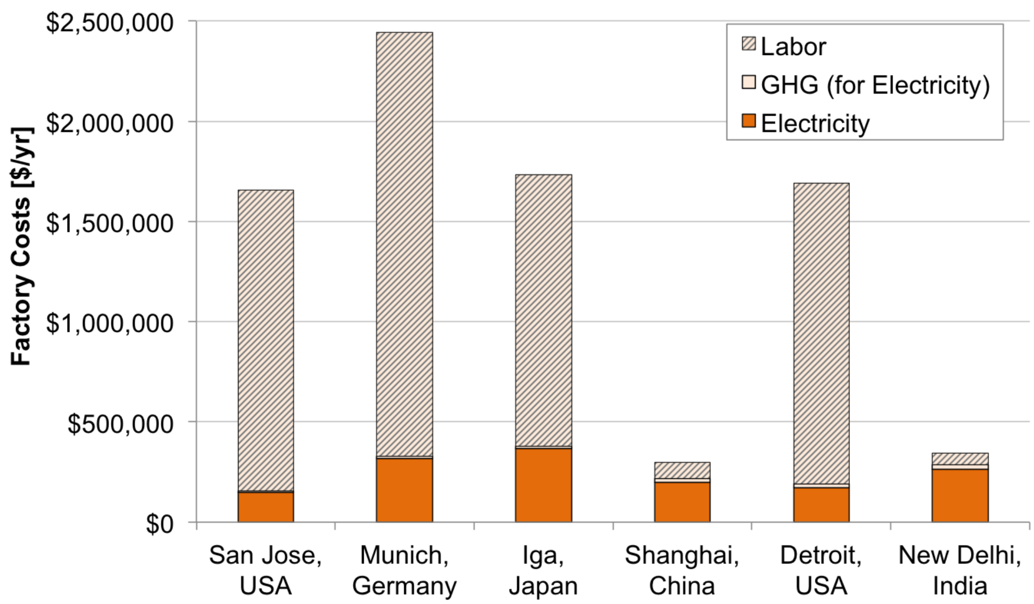


Figure 6.13: The 2010 yearly costs of electricity, GHG emissions, and labor compensation per factory.

releases by the BLS, which did not report the average labor compensation rate of production workers.

6.6 Conclusions

The difference in energy consumption based on the climate of the plant location has been shown. These values represent an ideal, comfortable environment for production workers.

Additional energy savings could be realized by implementing energy-efficiency measures on the HVAC system (e.g., retrofitting or upgrading the HVAC system entirely). And although all manufacturing facilities may not provide adequate climate control or ventilation within the factory walls, which results in an even lower HVAC energy consumption, it is important to provide a comfortable working environment for the production workers. Reducing energy expenses at the cost of production workers undermines social responsibility. Aside from the discomfort associated with very hot or cold work environments, ventilation plays a critical role in managing the air quality inside the facilities and is especially important for facilities with manufacturing operations that release particulate matter into the air such as grinding, machining, and woodworking operations.

The costs presented thus far represent those costs associated with electricity use, greenhouse gas emissions, and labor costs. Manufacturing labor, machinist, and service costs have been found to be increasing at a faster rate than the cost of machine tools since 1998 [117]. If companies begin utilizing more advanced manufacturing technologies that result in higher levels of automation, labor costs will not play as significant of a role in identifying the optimal location of manufacturing sites. Thereafter, the cost of electricity and greenhouse gas emissions will become more prominent, therefore encouraging the implementation of energy-efficient manufacturing strategies even further.

Chapter 7

Summary of Contributions and Outlook on Future Work

7.1 Summary of Contributions

This dissertation provided energy models and assessments at three levels of manufacturing: production equipment, factory operations, and industry. The contributions of the research presented are highlighted below:

- Production Equipment
  - Characterized the energy consumption of production equipment
  - Contextualized the product design with respect to machine energy
  - Developed a methodology to estimate the energy of machining a toolpath with variable MRR and validated the energy model for a sample part
- Factory
  - Designed and implemented a machine tool prioritization algorithm for energy reduction, while incorporating a high product mix and machine tool capability constraints
  - Developed an HVAC energy model for the factory
  - Analyzed the influence of siting decisions on electricity, GHG emissions, and costs.
- Industry
  - Identified trends in energy consumption and intensity

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

7.1.1 Characterization of the Energy Consumption of Production Equipment

First, insight was provided as to the breakdown of the power demand of production equipment. Specifically, components of production equipment were found to contribute to one of three forms of power: constant, variable, and processing, the last of which increases with the load on the machine. These power components were verified with experimental studies of a milling machine tool. Variations in power were defined with respect to depth and width of cut experiments, as well as experiments that varied the type of work piece material.

7.1.2 Contextualization of the Product Design with Respect to Machine Energy

Key areas were highlighted for product designers to consider that affect energy, namely: feature design, material selection, and surface roughness specification. The design of standard features has the ability to reduce the number of cutting tool changeovers and setup time, thus reducing the energy necessary to manufacture a part. The ranking of workpiece materials with respect to cutting speeds (and therefore the expected energy consumption) from lowest to highest was found to be: copper, aluminum, plastic, low alloy steel/grey cast iron, stainless steel, and titanium. Steel and cast iron can be cut without MWF for some machining processes, which results in a decrease in the power demand of machining by approximately 25%. The surface roughness was also found to be dependent on the processing and MWF conditions. Since dry machining reduces the power demand of the machine tool, this scenario would be preferred as long as the surface roughness requirements can be met.

7.1.3 Methodology Development and Validation of Energy Estimate for a Variable MRR Profile

The energy model for machine tools was presented and validated for milling a spiral part design under a variable MRR profile. A generic approach was utilized to define the MRR profile and estimate the energy consumption so that the same methodology could be applied to other toolpaths. The energy consumed to manufacture nine features was measured and estimated with the energy model. The error ranged from -17.3% to 16.9% and the average error ranged from -12.9% to 8% for the features produced for the machining of six parts. The error was due to: the inherent variability in the power demand of the machine tool; the low MRR's (where the magnitude of the specific energy model changes rapidly); the short machining time to construct some features; and the initial cutting tool engagement that caused a sharp increase in the power demand of the machine.

Although the range of errors per feature varied significantly, the energy model for the part as a whole was found to have an average error of -2.6% with a range of -5.4% to 4.9%. Overall accuracy of the energy model is expected to improve with higher process rates and longer processing times, which would serve to stabilize the power demand. Given the high accuracy in estimating the energy to manufacture the part, product designers and manufacturers alike can utilize this energy model to estimate the energy consumed to machine a part without needing to manufacture sample parts.

7.1.4 Development of a Machine Tool Prioritization Algorithm for Energy Reduction

At the facility level, a methodology was presented for implementing green machine tool scheduling while accounting for a high product mix. Alternative factory designs were suggested where the number of machines tools within the factory were modified and compared to the baseline case. The baseline case, case 1, consisted of five milling machine tool cells, M1 through M5. These cells had 3, 2, 1, 1, and 4 machine tools, respectively, and cells M1 and M3 operated under dry cutting conditions, while cells M2, M4, and M5 operated under wet cutting conditions. The cells were ranked with respect to energy consumption from lowest to highest to implement the green machine tool scheduling strategy.

While the difference in cost for the scenarios was negligible, the energy consumption for processing parts and idling machine tools varied significantly with savings of up to 8.53% relative to the baseline case, for the cell organization of case 7 where M1 through M5 had 1, 2, 1, 0, and 3 machines in each cell, respectively. Although this produced a solution with the least amount of processing and idling energy consumption, the part's waiting time increased significantly with the reduction of the number of machines in each cell. Taking into consideration the stability of the cell queues, case 5 was the most promising, which consisted of 2, 2, 1, 0, 4 machine tools in cells M1 through M5, respectively. Case 5 produced energy reductions of 6.37% and maintained stable queues. Although the cases evaluated in this dissertation focused on modeling a high product mix and defining the optimal number of machines in the facility, a simulation tool can be built for other types of manufacturing systems and analyses under the DES environment.

7.1.5 Identification of Industrial Energy Trends and the Assessment of Factory Siting Decisions on Electricity, GHG Emissions, and Costs

Lastly, an energy and cost analysis of manufacturing industries and facilities was presented. Ten manufacturing sectors were assessed, and they were categorized as high energy consumers, high value added consumers, or low energy consumers. HVAC energy was found to be significant, varying from 2.8% to 30.7% of the total energy consumption of a factory. Machine drive had a greater impact, ranging between 11.1% and 35.4% of the total energy consumption. The average energy intensity data from the Manufacturing Energy Consumption Survey agreed with actual data from the Mori Seiki machine tool company's Iga facility.

By comparing the two data sets, recommendations as to where energy-efficiency upgrades could be made became evident, especially concerning lighting and HVAC upgrades.

From the Mori Seiki energy data, a model characterizing the monthly HVAC energy was developed to forecast the HVAC energy requirements of facilities located in different regions around the world in a case study. Aside from highlighting the difference in electricity requirements, the case study evaluated the manufacturing costs based on the location. The electricity and associated greenhouse gas emissions were calculated with respect to the local energy mix, as well as the costs associated with electricity and labor for sites in San Jose, California; Detroit, Michigan; Munich, Germany; Iga, Japan; Shanghai, China; and New Delhi, India. China and India were found to have the lowest manufacturing costs; in fact, they were less than or equal to one-fifth the cost of the third lowest site, San Jose. Consequently, the electricity costs of sites in China and India constituted a greater percentage of the total costs, therefore, further justifying the use of green manufacturing strategies in these developing countries. China and India also have a significant dependence on fossil fuels, as does Detroit in the United States, resulting in the highest greenhouse gas emissions for production out of the sites analyzed in this case study.

7.2 Future Work

Future research efforts should concentrate on advancing manufacturing simulations of the factory for energy optimization, developing a framework for the holistic acquisition of data, incorporating water use into the factors affecting decision-making, and identifying how sustainable solutions can influence systems beyond manufacturing.

Discrete-event simulation is a very versatile software tool, which allows a skillful programmer to build any system imaginable. Future research should focus on varying machine tool selection strategies and accounting for performance metrics such as machine tool availability. Additional work should also develop a methodology to accurately define the variability of the MRR during part production – a result of the inherent complexity of toolpaths. Currently, CAM software does not provide this capability, but with an accurate MRR profile, additional information about the design of energy-efficient toolpaths can be inferred.

The availability of data is quite often a limiting factor in conducting environmental impact assessments. Factories need a cost-effective and simple-to-maintain solution for acquiring manufacturing data such as processing times, energy consumption of machines, and product flows. This data infrastructure is especially important for firms that manufacture high mixes of products, since production data and schedules are often managed at the department level by managers. The prevalence of data acquisition across factories and industries would establish a stronger foundation for conducting environmental assessments. Many companies are already interested in implementing green and sustainable solutions, but having a good data infrastructure available will help them achieve their goals more rapidly.

This dissertation focused on reducing the energy consumption of manufacturing processes and systems, but the role of water will continue to become increasingly important. Important factors to take into consideration are the consumption of water, especially relative to its regional availability; the environmental impact of its distribution; and the associated costs. Water is consumed in manufacturing for common processing operations such as cutting fluid mixtures, and post-processing operations such as the cleaning of parts. Different water sources exist, including ocean water, which requires desalination, brackish groundwater, and recycled water. Implementing energy optimization solutions in the factory and industrial ecology principles related to water consumption could result in significant advances towards a sustainable future.

Finally, the sustainable solutions developed for manufacturing need to be applied elsewhere in society. For example, many similarities exist amongst the machine tools in factories and the machinery utilized for construction and mining. The knowledge gained from developing energy-efficient toolpaths for machining metal and plastic workpieces, can be applied to develop strategies to consume less energy for the excavation of land, i.e., the removal of land in a three-dimensional environment. Principles for generating toolpaths for a workpiece can also be applied to the design of vehicle and airplane routes, which are merely two- and three-dimensional movements through a medium, in this case, air. By identifying the commonalities in the basic function of an operation, the lessons learned can be applied across seemingly different processes and systems to apply sustainable principles in a more effective manner.

Collaborative efforts will facilitate the development and application of sustainable solutions. By working together, systems and processes can be well characterized in order to implement change and diffuse successful, green strategies across factory floors, industries, and society.

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Appendix A

Glossary of Energy Intensity, MECS, and ASM Terms

Decomposition: The act of splitting a time series into its constituent parts by the use of statistical methods. A typical time series is often regarded as composed of four parts:
(a) a long-term movement or trend;
(b) oscillations of more or less regular period and amplitude about this trend;
(c) a seasonal component;
(d) a random, or irregular, component.
Any particular series need not exhibit all of these but those which are present are presumed to act in an additive fashion, i.e. are superimposed; and the process of determining them separately is one of decomposition. [118]

Economy-wide energy intensity: (also referred to as aggregate energy intensity). This is the energy intensity of the entire U.S. economy. It is the aggregate of the intensity of the four major energy consuming end-use sectors (transportation, industrial, residential buildings, and commercial buildings) and the electricity producing sector.

Electricity demand: Electricity demand is the amount of electricity actually consumed onsite, regardless of where or how it was produced. It is a useful measure of electricity consumption without regard to the consumption of other energy sources. Electricity demand is estimated as the sum of electricity purchases, transfers in, and total onsite generation minus the quantities of electricity sold or transferred offsite. [119]

End-use sectors: The four sectors that consume primary energy and electricity: transportation, industry, residential building and commercial buildings.

Energy intensity: The amount of energy used in producing a given level of output or activity (see also Energy Efficiency vs. Energy Intensity). It is measured by the quantity of energy required to perform a particular activity (service), expressed as energy per unit of output or activity measure of service.

Establishment: An establishment is a single physical location where business is conducted or where services or industrial operations are performed. Data in this sector includes those establishments where manufacturing is performed. A separate report is required for each manufacturing establishment (plant) with one employee or more that is in operation at any time during the year. An establishment not in operation for any portion of the year is requested to return the report form with the proper notation in the Operational Status section of the form. In addition, the establishment is requested to report data on any employees, capital expenditures, inventories, or shipments from inventories during the year. [120]

As defined by the Standard Industrial Classification Manual 1987, "...an economic unit, generally at a single physical location, where business is conducted or where services or industrial operations are performed." See Manufacturing Establishment. [119]

Machine drive: The direct process end use in which thermal or electric energy is converted into mechanical energy. Motors are found in almost every process in manufacturing. Therefore, when motors are found in equipment that is wholly contained in another end use (such as process cooling and refrigeration), the energy is classified there rather than in machine drive. [119]

Manufacturing establishment: An economic unit at a single physical location where mechanical or chemical transformations of materials or substances into new products are performed. Manufacturing operations are generally conducted in facilities described as plants, factories, or mills, and characteristically use power-driven machines and materials-handling equipment. In addition, the assembly of components of manufactured products is considered manufacturing, as in the blending of materials, such as lubricating oils, plastics, resins, or liquors. See Establishment. [119]

Net demand for electricity: The sum of purchases, transfers in, and total onsite electricity generation, minus sales and transfers offsite. It is the total amount of electricity used by establishments. "Net Demand for Electricity" is not directly comparable with "Net Electricity", which specifically excludes electricity generated onsite by combustible energy sources. [6]

Net electricity: Net electricity is estimated for each manufacturing establishment as the sum of purchased electricity, transfers in, and generation from noncombustible renewable resources minus the quantities of electricity sold and transferred offsite. Thus net electricity excludes the quantities of electricity generated or cogenerated onsite from combustible energy sources. [119]

Process heating: The direct process end use in which energy is used to raise the temperature of substances involved in the manufacturing process. Examples are many and include the use of heat to melt scrap for electric-arc furnaces in steel-making, to separate components of crude oil in petroleum refining, to dry paint in automobile manufacturing, and to cook packaged foods. Not included are heat used for heating of buildings or for cafeteria and personal cooking. See Manufacturing Establishment. [119]

Production workers: The production workers number includes workers (up through the line-supervisor level) engaged in fabricating, processing, assembling, inspecting, receiving, storing, handling, packing, warehousing, shipping (but not delivering), maintenance, repair, janitorial and guard services, product development, auxiliary production for plants own use (e.g., power plant), recordkeeping, and other services closely associated with these production operations at the establishment covered by the report. Employees above the working-supervisor level are excluded from this item. [120]

Sector energy intensity: This is energy intensity calculated at the sector level. When primary energy is considered, intensity is calculated for five sectors, the four end-use sectors and the electricity producing sector. When total energy is considered intensity is calculated for the four end-use sectors only.

Structural decomposition analysis: An analytical technique allowing to identify and quantify the factors of the changes in emissions over time. [118]

Subsector energy intensity: This is the energy intensity for subsectors within a given sector (See subsectors). Subsector intensity is energy use divided by the activity of the subsector.

Value added: This measure of manufacturing activity is derived by subtracting the cost of materials, supplies, containers, fuel, purchased electricity, and contract work from the value of shipments (products manufactured plus receipts for services rendered). The result of this calculation is adjusted by the addition of value added by merchandising operations (i.e., the difference between the sales value and the cost of merchandise sold without further manufacture, processing, or assembly) plus the net change in finished goods and work-in-process between the beginning- and end-of-year inventories. For those industries where value of production is collected instead of value of shipments, value added is adjusted only for the change in work-in-process inventories between the beginning and end of year. For those industries where value of work done is collected, the value added does not include an adjustment for the change in finished goods or work-in-process inventories. Value added avoids the duplication in the figure for value of shipments that results from the use of products of some establishments as materials by others. Value added is considered to be the best value measure available for comparing the relative economic importance of manufacturing among industries and geographic areas. [120]

Value of product shipments: Includes the total value of all products produced and shipped by all producers, not just those with values of $100,000 or more. However, for selected products, this can represent value of receipts, value of production, or value of work done. Industries that are published on these unique basis are separately. [120]