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Understanding energy consumption in a machine tool through energy mapping

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Abstract

Understanding where energy is consumed in a machine tool is an important step to reduce energy consumption. Much of the energy consumption is not due to material removal, deformation, or joining, but is due to supporting processes. To better understand the energy flow and consumption of machine tools, it would be beneficial to develop an energy flow map. From this map, opportunities for improvement can be identified along with energy related features. After creating a map, models can be generated that will help predict energy consumption and allow for optimization of machine tools and a more sustainable design of machine tools. As a start, this study focuses on breaking down the total energy consumption by main components of a representative machine tool. In particular, a major focus will be on motors since they account for a large portion of the energy consumption.

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Keywords: Sustainable manufacturing; energy flow map; machine tool; motors

1. Introduction

To shape materials for different applications, Computer Numerical Control (CNC) machine tools are often used for their precision, flexibility, and ability to manufacture complex parts. There are many different types of CNCs, which include lathes, routers, milling machines, plasma cutters, and laser cutters. Each CNC consists of many components, such as computers, coolant pumps, feed drives, fans, motors, and spindles. With all the components in these machine tools, much of the energy consumption is not associated with cutting operations but is instead consumed by the auxiliary systems, by losses from inefficient design, and by parasitic losses [1,2]. Energy consumption of the auxiliary systems can comprise up to 85% of the total energy consumption of the machine [3]. Because CNCs are so widely used in manufacturing, small improvements in energy consumption can have large effects on total energy consumption over the lifetime of the machine. However, designers rarely attempt to minimize energy consumption during the design stage of the product lifecycle.

Researchers have noted that many lifecycle costs, such as the energy consumption of a machine, are locked in during the design stage of a product [2]. To decrease the energy consumption of a machine tool, it is important to design the tool with energy consumption in mind. A fundamental understanding of the machine tool system and the main energy consumption components are required to develop design guidelines. Incorporating Jedrzejewski's and Kwasny's [4] development directions, including reduction of energy intensity, can be very beneficial.

In CNCs, the main energy consuming components are the main spindle and motors, but the specific energy consumption (SEC) profiles, including all of the auxiliary systems, vary from machine to machine. With complete knowledge of the main energy consuming components and their dependent systems, a map or model of the energy consumption can be built for a particular machine tool. The energy consumption behavior of

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multiple different machine tools and the components used in the machine tools can be analyzed to understand design tradeoffs.

There have been a number of reviews investigating energy management in industry, ranging from broad to narrow in scope. Schulze et al. [5] reviewed current approaches to manage industrial energy use. The authors developed a framework for energy management that management decision, energy audit, and an energy management team. May et al. [6] reviewed a narrower scope by focusing on energy management in manufacturing. The authors identify themes in the literature including drivers and barriers to energy management, information and communication technologies, and strategic paradigms. The authors develop a framework for energy management in manufacturing. Peng et al. [7] reviewed energy efficient machining systems. They looked at theoretical, empirical, discrete event- based, and hybrid energy consumption models. After looking at the models, the authors reviewed energy optimization methods.

In addition to these reviews of energy management, there have been efforts to develop models to understand the design of, and energy consumption in, machine tools. These models are used to understand which components consume the most energy and can help designers in their design decision making. Verl et al. [8] discussed making models of components with sub-models to better calculate energy consumption. Altintas et al. [9] created models to quicken the design process of machine tools. The authors discuss using multiple types of models to help prototype the machines. These models include finite element analysis (FEA), kinematics, and computer-aided design (CAD) models. Kara et al. [10] modeled SEC by running experiments on multiple machine tools and then fit an empirical model to the data using two coefficients and the material removal rate (MRR). Budinoff et al. [11] modeled SEC by measuring energy consumption during machining tests. Five different parts were cut and three different models were used to describe the SEC. This paper found that by using chip thickness as a parameter, the energy consumption of the process could be more accurately predicted. Wu et al. [12] modelled the energy consumption of a turning CNC machine and a milling CNC machine during the manufacturing of impeller. The authors varied the cutting parameters to determine which parameters had the largest effect on SEC. The authors found that depth of cut had the largest effect on cutting energy. While these models accurately represent aspects of the machine tools, most models experimentally measure energy consumption and develop a model to fit the data. The goal of this paper is to develop a preliminary energy consumption model based on a mechanistic understanding of machine tool behavior.

This paper outlines a framework that assists in the design of CNC tools using energy consumption as a design parameter. In this paper, the energy consumption profiles of two different model CNC systems are developed from manufacturer specifications. This simple model is extrapolated to estimate the energy consumption of the machine over a day of operation. Necessary refinements of the models are discussed, and a framework for the development of a software design tool is outlined. The end goal of this work is to aggregate enough data to understand the design tradeoffs between different machine tool components and the energy consumption of the system under different machine schedules. This framework could be synthesized into a software tool, which can enable machine tool designers to take energy consumption into account during the design process.

2. Methodology

A simplified schematic of a CNC with a list of components can be seen in Fig. 1. Broadly, these components can be divided into two categories, core components and auxiliary components. Core components are those that are essential to the core cutting operations of the instrument, and auxiliary components are those that assist the machine in performing its core operations. The categorization and power consumption of the core and auxiliary systems are shown in Table 1. This data was adapted from machine specifications from industry sources.

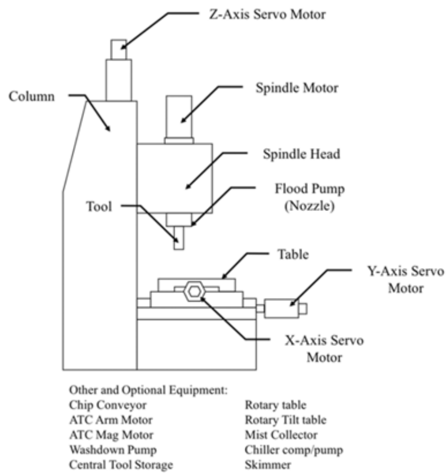

Fig. 1. Schematic of a CNC tool

From this data, power consumption profiles were developed for a high energy consumption CNC and a low energy consumption CNC, as shown in Fig. 2. Three different machining circumstances were used to develop power profiles, based on different cutting and motor characteristics, and on previous work by Zhou et al. [13].

Zhou et al. measure the power consumption of a machine from start up to shut down. For this paper, a power profile was built from specification data obtained from machine tool manufacturers. The profiles were built based on manufacturer specification data and existing knowledge of machine tool behavior. The model assumes that the machine is operating at varying percentages of its maximum power consumption during normal operation. The power profile shows the machine starting up, changing of the tool, the spindle starting, cutting, and machine shut down. The power consumption during cutting and air cutting were assumed to be 50% and 20% of the continuous rating for the spindle, respectively.

Table 1: Power consumption of core and auxiliary CNC components for low and high power machines.

Component (Core)	Low/High Power Machine (kW)	Component (Auxiliary)	Low/High Power Machine (kW)
Spindle motor	3.65/11.35	Chip conveyor	-/0.44
X-axis servo motor	0.85/2.80	Automatic tool changer arm motor	-/.05
Y-axis servo motor	0.85/2.80	Automatic tool changer mag motor	-/0.22
Z-axis servo motor	1.45/4.45	Washdown pump	-/2.45
Flood pump (nozzle)	0.19/0.70	Central tool storage	-/2.80
Rotary tilt table	-/1.80	Mist collector	-/1.75
		Chiller comp/pump	-/1.25
		Skimmer	-/0.03
Total	6.99/23.9	Total	-/9.44

It was also assumed that machining, setup and non-cutting moves would take 40%, 40% and 20% of the total machine time, respectively. The model assumes that non-cutting moves were distributed between cutting moves and that x and y motors are used both individually and in combination. Idling power was assumed to be 25% of the highest power consuming component, which is the spindle. The model and assumptions from Zhou et al. were applied to the data from the company specifications to develop a model for the energy consumption of a CNC machine tool.

3. Results

The modeled power consumption results from two machine tools are shown in Fig. 2, for a 2 minute milling sequence, and in Fig. 3, for the milling of an entire part over 25 minutes. There are several notable differences between the energy consumption behavior of the large and small CNC machines during the machining of one part. The spindle and axis motors on the large machine consume three times more energy than the motors on the smaller machine. The flood pump on the larger machine requires 3.5 times the energy of the small pump. It is also notable that power spikes during start up and shut down operations are not yet included in this model, though they have been experimentally verified elsewhere [13].

Fig. 4 is an example of the power profile of a CNC over the course of an entire day. While the energy profile of the production of a single part can identify what component draws the most power, the full-day scenario can identify whether the energy consumption in the idle state or in the cutting state is a more significant design concern. When the machine set up and non-cutting moves take more time than cutting operations, it can be possible that much of the energy consumed is not from the cutting time, but from the idle time. Furthermore, the power profile from machining an engine block will look very different from the power profile from machining a bracket. Machining an engine block requires much more time than the bracket and therefore there will be less set up time and idle time available throughout the day. With this in mind, energy consumption profiles were created for different parts. The differences in energy consumption can be seen in Fig. 5.

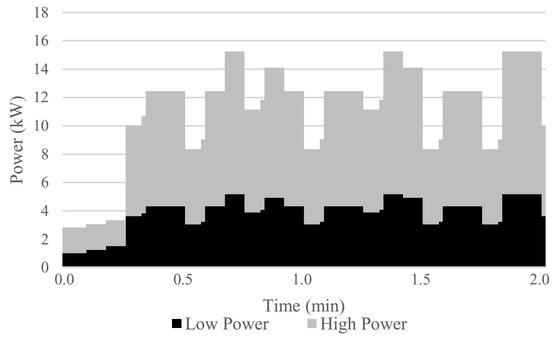

Fig. 2. Power consumption of a high energy consumption CNC machine (grey) and low energy consumption CNC machine (black) during the first 2 minutes of a machining sequence for a single part.

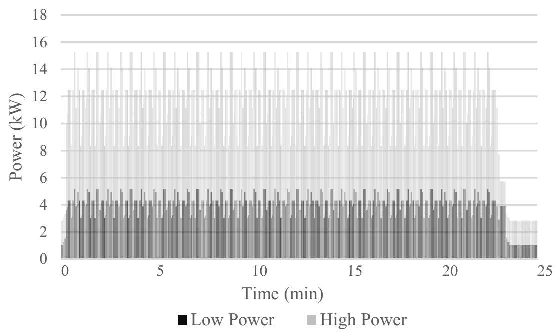

Fig. 3. Power consumption of a high energy consumption CNC machine (grey) and low energy consumption CNC machine (black) during the machining of a single part.

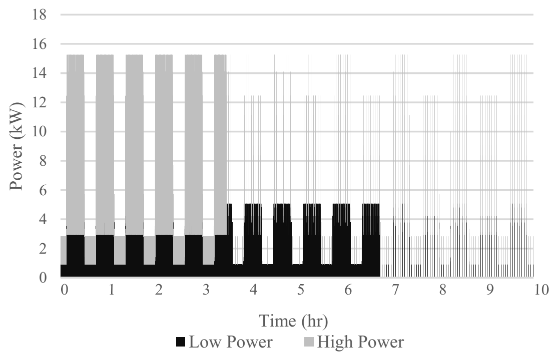

Fig. 4. Power consumption of a high energy consumption CNC machine (grey) and low energy consumption CNC machine (black) during the machining of multiple parts over 10 hours.

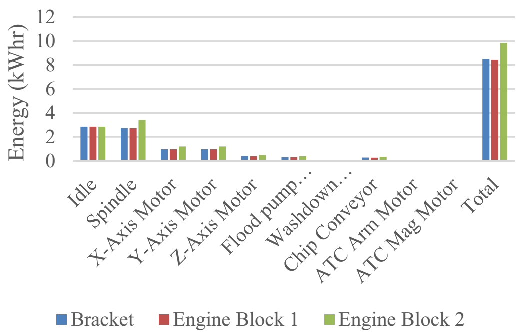

Fig. 5: Energy consumption breakdown of three different machining procedures over a 10 hour day.

The three situations compared in Fig 5. are examples of power profiles for a day of machining. The bracket (blue) represents the energy consumed during a day's worth of jobs using the 15-minute machining setup from Fig. 3. The second scenario illustrated the energy consumed during a day of 1-hour long machining jobs (Engine Block 1, orange) with the same ratio of machining to setup to noncutting moves, 40%:40%:20%. The third energy consumption scenario (Engine Block 2, gray) also assumed a 1-hour long machining time, but the setup time and noncutting moves were set to 30 minutes. These three scenarios would represent the machining of a small simple part, a large complex part, and a large simple part, respectively.

It was assumed that the power required for the machining operations would be the same across the three parts. From these assumptions, the differences in power consumption are attributed to different setup times. Since the data showed that the spindle consumed much more power than any of the other components (Table 1), the energy consumption during the cutting operations was significantly higher than during the non-cutting operations for this machine tool. Currently the model shows differences based on component specification and machining time. As the model is updated to reflect actual cutting operations better, more insight can be gained from the power profiles.

4. Discussion

The modeling of power consumption through the components' specifications can be used to reduce energy consumption since the energy consumption can be estimated without testing or direct measurement from a prototype. While currently, the model may not be as accurate as directly measuring energy consumption from a machine, it can be used to show patterns and approximations of energy consumption for some machines quickly, based on their specifications. The model can be used as a more cost-effective method to show designers the impact of their decisions.

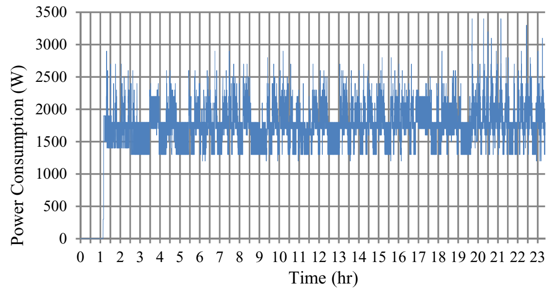

Fig. 6. The experimentally measured power consumption of a CNC machine.

The performance and accuracy of the model can be improved by incorporating data from more CNC machine tools. As more components and use scenarios are added to the model, non-linear models of energy consumption can be developed to address the effects of variable motor speeds and forces, material related effects, and other parameters on energy consumption and performance. Fig. 6 is an example of measured power data from a CNC machine. It is clear that the current model does not match measured data. Notably, the machining schedule is more variable than the optimal schedule proposed here, and there are more spikes in the data. However, as the model is updated, it can more accurately match measured data. Some factors that can be taken into account are SEC, tool selection, workpiece material, and parasitic losses.

Other researchers have investigated SEC and the effects various cutting parameters have on it [10-12,14]. Models from these papers of SEC have been created based on experimental data. These works will be taken into account for the proposed model in this paper. While the methods found in [10-12] require the calculation of MRR, the model will be able to use data from suppliers, which include the RPMs of the spindles, along with standard machining practices to better predict the SEC and overall energy consumption of the machines. Despite designers having no control over operating parameters used by customers, designers can suggest best practices for operation. Other research has examined the choice of operating parameters to help reduce energy consumption. Mori et al. [15] has shown that using high spindle speeds and feed rates can reduce power consumption, as long as they do not compromise tool life or part quality. Therefore, investigation into the factors that affect SEC is beneficial.

Similarly, tool selection has been shown to affect the energy consumption of cutting. Since forces and stresses on the tool can vary significantly based on the tool shape, surface finish, and material, it is clear that energy consumption would depend on the tool selection. Diaz et al. [2] investigated the selection of tools. They have shown varying tools provides different energy consumption. The authors showed the use of a kinetic energy recovery system (KERS) reduced the power consumption on a vertical milling center by 5 to 25%. Because tool selection dramatically affects power consumption, the accuracy of the model can be increased by including different alternative tools.

Another factor to be considered is the effect the material of the workpiece has on the cutting power. Different materials have different suggested operating parameters and conditions.

Some require cutting fluid to cool the tool or assist in chip removal while other materials do not. Different components will be necessary to handle these materials, and so the energy consumption of the tool will change, based on the materials used. In [16], Diaz et al. investigate the effects the workpiece material has on power demand. The authors found that out of steel, aluminum, and polycarbonate, steel had the highest cutting power demand due to the high tensile strength of steel. However, since spindle speed for aluminum cutting was higher than that used for cutting steel, the overall energy demand is higher for aluminum. By investigating workpiece material effects on power consumption, the model can be adjusted to provide a better approximation of power requirements.

Parasitic losses are also important to consider. Since motors are one of the primary energy consumers in this model, investigating the losses from the motors will be beneficial. Motors operate more efficiently at 75% of the rated load and higher [17]. When motors operate lower than 50% of the rated load, they are operating inefficiently. Since loads vary during machining, the efficiency of the main spindle motor and other motors will vary greatly throughout the machining process. Investigating the different losses in motors will greatly benefit the model and designers. Non-linear models will be developed to map motor performance to energy consumption, and, in particular, wasted energy. By showing potential losses, the designers can better design their machines to match intended purposes.

The inclusion of representative use scenarios for different machine tools and processes will be important to model correctly. Currently, the authors assumed that the spindle consumed 50% of the continuous power rating during cutting and 20% while spinning but not cutting. In practice, the power consumption may likely be lower than the continuous rating, and it cannot be assumed to be constant. A relationship between cutting and power consumption should be included in the model. More information on idling, start up, and shut down of the machine should be included as well [13]. If a significant percentage of power is consumed by non-cutting components, then the designer may decide to focus more on the auxiliary components instead of the spindle. With more knowledge of the entire usage of the machine, including startup and shut down, decisions can be made about when components need to be operated. Components can then be activated only when needed.

As stated earlier, knowledge of the physics of machining will also improve the model. For example, when the spindle motor is turned on, it must overcome not only the required torque to machine the part but also the inertia of the motor. This is similar for the axis motors. These motors must overcome the motor inertia and forces from the table, workpiece, and the cutting. The calculation of the cutting energy can be very complicated, but should be included in the model to help in accurately predicting the total energy consumption of the machine.

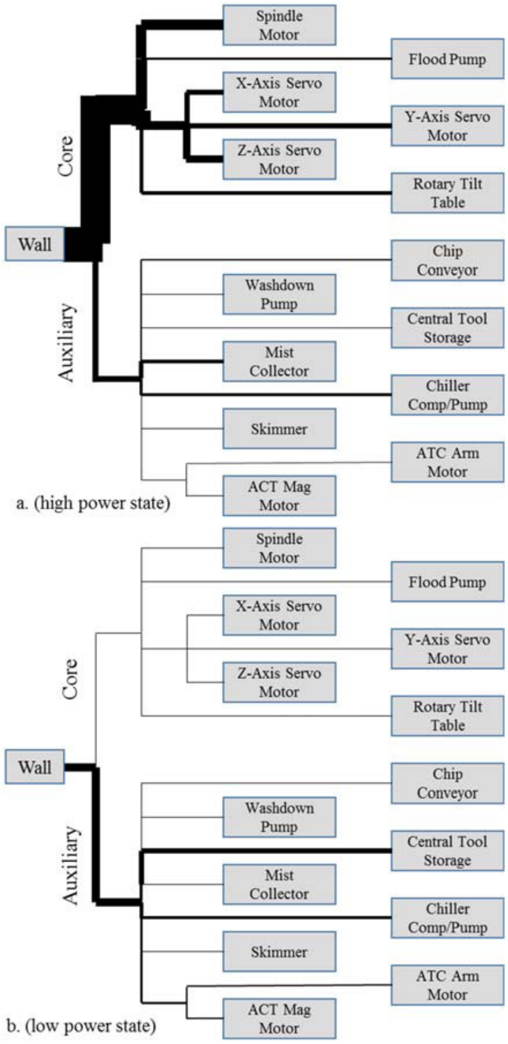

Fig. 7. Energy map of (a) high power state and (b) low power state of a CNC machine tool.

After including SEC, tool selection, workpiece material, and parasitic losses into the model, measured data will be used to improve the model further. The goal is to provide a model built on machine specifications instead of experimentally measured data. However, to build a better model, experimental data is needed to describe machine tools more accurately. As part of the future work, the authors will run experiments on a machine tool to compare the measured values to the theoretical values.

From the refined model, the authors intend to develop a software framework that will assist designers in choosing components. The software will show performance, cost, and energy consumption tradeoffs between multiple components. If the designers can see the tradeoffs and the energy consumption throughout the life of the machine, they will be more likely to design with energy in mind. The software will be able to make power profiles for the machines during design, and it can give an approximate value of energy consumed throughout the entire life of the machine. It will show differences in choices of components. The designers will see the contribution to the power profile and the lifecycle energy for a single component. Along with these power profiles, energy maps will be created similar to the energy maps created in [18]. Vivadinar et al. [18] mapped the energy consumption of multiple industry sectors within Indonesia. The paper showed the sources of the energy, where it was consumed, and the losses. By showing the energy flow and losses, opportunities for improvement can be identified. Fig. 7 is an example of the energy maps that will be created. These maps will show where energy is consumed under varying use conditions.

To build this framework, the authors will use data from multiple machine tool designs. The data will be aggregated into a single library from which designers can choose components. With the library, the authors will be able to program the software to create power profiles. However, the software will also need example parts that the designed tools can machine. The data for this library will be acquired from machine tool manufacturers or other sources. With the model, library, and machining plans, the software can be made.

5. Conclusion

Since industry has a large environmental footprint, it is important to reduce the energy consumption of manufacturing and machine tools. However, machine tools are very complicated, multicomponent, and multipurpose machines. Reducing the energy consumption of the machine tool in its use phase during the design of the tools can be difficult unless knowledge of the components and the energy consumption of the parts is gained.

In this paper, the authors focused on CNC machines and the components within them. The authors received power consumption data for parts within multiple machine tools. With this data, a preliminary model was created to show the power consumption of two machines. Two power profiles were created and compared. The profiles identified the components that consumed energy and the differences in the consumption of the two machines. Currently the model shows differences based on component specification and machining time. As the model is updated to reflect actual cutting better, more insight can be gained from the power profiles

The goal of the authors is to provide tools to designers to make decisions with energy consumption in mind. The models of the machine tools are a step to creating software tools for designers. The models will be improved through the addition of more components, more knowledge of the workings of the machine tools, and the use of measured data. As the model is improved and the library of components is expanded, the software tool will be able to provide more assistance to designers.

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