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AN ENVIRONMENTAL ANALYSIS OF MACHINING

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ABSTRACT

This paper presents a system-level environmental analysis of machining. The analysis presented here considers not only the environmental impact of the material removal process itself, but also the impact of associated processes such as material preparation and cutting fluid preparation. This larger system view results in a more complete assessment of machining. Energy analyses show that the energy requirements of actual material removal can be quite small when compared to the total energy associated with machine tool operation. Also, depending on the energy intensity of the materials being machined, the energy of material production can, in some cases, far exceed the energy required for machine tool operation.

Keywords: Machining, environment, green manufacturing

INTRODUCTION

Machining is a material removal process that typically involves the cutting of metals using various cutting tools. It is a process that is particularly useful due to its high dimensional accuracy, flexibility of process, and cost-effectiveness in producing limited quantities of parts. Among manufacturing processes, machining is unique in that it can be used both to create products and to finish products. However, since it is inherently a process that removes material, machining can be wasteful in its use of both materials and energy. This paper focuses on investigating various aspects of the machining process from an environmental perspective. The result is a system-level, environmentally-focused analysis of machining.

For the context of this paper, the term “machining” will refer to processes such as milling, turning, drilling, and sawing, with much of the analysis presented here focused on milling metals. Other machining activities, such as grinding, along with newer non-traditional forms of machining, such as electrical discharge machining and waterjet machining, are excluded from this analysis.

BACKGROUND

While a great deal of research has been conducted in the area of machining, much of it has been focused on process-level activities and improvements. Some of these improvements, including optimizing material use, minimizing the use of cutting fluids, and reducing cutting energy, do have important environmental ramifications. For example, cutting fluids, with serious health and environmental issues stemming from their use and disposal, are often studied as an area for potential improvement. Various researchers have examined the benefits, drawbacks, and conditions necessary for both wet and dry machining [1-4]. Much research has also been conducted to yield detailed analyses of tool-tip cutting energies, from which energy utilization can be estimated. Such analyses are generally quite well-understood, and simple models can be found in traditional manufacturing texts [5, 6]. While these and other process-level analyses lay an important foundation for system-level analysis, few provide complete system views of machining.

Some broader system analyses focused on the environmental impacts of machining have also been completed. Papers illuminating important environmental issues related to machining, as well as the technologies aimed at alleviating some of these concerns, have been presented [7,8]. A more comprehensive system analysis of machining, which addresses energy utilization and mass flow, has also been completed [9]. This work by Munoz and Sheng explores the sensitivity of environmental impacts to process operating parameters and presents detailed process models that can be used to determine the environmental impacts resulting from the machining of a particular part.

The analysis presented here will assess the environmental impact of machining from a system-level perspective. This analysis will provide energy and material accounting for machining as a means of making a process assessment. While such process accounting has been conducted for semiconductor manufacturing, no such accounting has been conducted for machining, or for many other traditional manufacturing processes [10]. Such an accounting of resources is useful in understanding the environmental ramifications of manufacturing processes, as well as for helping to direct future process improvements.

SYSTEM DIAGRAM

In any system analysis, it is important to first identify the boundaries of the system to be examined. In the case of machining, the overall system includes activities such as tool preparation, material production, material removal, and cleaning, among others. Figure 1 shows a broad system view of machining, with important processes shown in rectangular boxes. While Figure 1 presents a wide array of different activities, specific machining scenarios may include only a subset of the processes shown, or may include other processes not shown. However, Figure 1 strives to represent a general machining scenario.

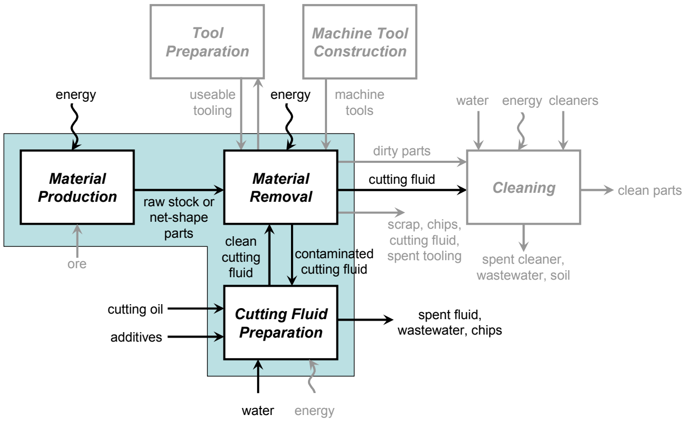

Figure 1: System diagram of machining.

In the analysis presented here, each of the processes included in the shaded region, and all flows shown in dark text, will be examined in detail. Qualitative assessments will be made for this subset of processes and flows. The processes not included in the shaded region, and the flows shown in grey, will be examined briefly in order to provide rough estimates of environmental impact. However, for these processes and flows, detailed qualitative assessments will not be provided.

MATERIAL REMOVAL

Most of the environmental impact from the material removal process stems from energy use. In estimating the energy requirements for material removal, specific cutting energies are often used. While cutting energies for machining can depend on many factors, including material properties of the workpiece, presence of cutting fluids, sharpness of cutting tools, and processing variables, ranges of approximate cutting energies in machining are available. For aluminum alloys, specific cutting energies typically range from 0.4 to 1.1 Ws/m^3, while for steels, specific cutting energies range from 2.7 to 9.3 Ws/m^3 [11]. This knowledge of specific cutting energies can help to determine the minimum amount of energy required to remove a certain volume of material. However, this energy requirement is far from the total energy required in actual production. In production machining, in addition to providing energy to the tool tip, additional energy must be provided to power auxiliary equipment such as workpiece handling equipment, cutting fluid handling equipment, chip handling equipment, tool changers, computers, and machine lubrication systems. While these additional pieces of equipment are often found on production-level machining equipment, there are certainly many older and less advanced pieces of machining equipment that lack all of these accessories. However, the trend appears to be moving towards more auxiliary equipment on each machine.

In cases where auxiliary equipment is present, the energy requirements of the auxiliary equipment can far exceed the actual cutting energy requirements. Figure 2 shows an energy use breakdown from a large Toyota production machining center. Such a machining center is most likely part of an automated transfer line, with lubrication systems, chip recovery systems, and other equipment all included in the overall system. Figure 2 shows that machining energy, the actual energy used when removing material, is, at most, 14.8% of the total energy required in manufacturing. As shown in the diagram, 85.2% of the energy used by machining equipment is constant, independent of whether or not a part is being produced. This significant amount of energy use is required for the entire time that the machine is powered on. It represents all the energy consumed by the machine that is not directly used for the purpose of producing parts.

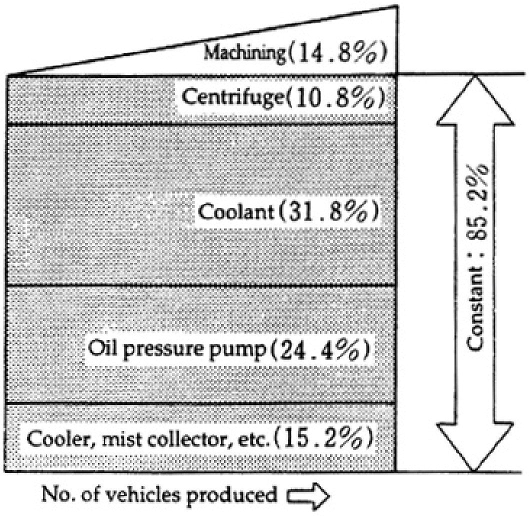

Figure 2: Machining energy use breakdown by type from Toyota. Figure from Gutowski et al. [12].

While Figure 2 shows the energy breakdown from a modern, highly automated, mass production environment, data from smaller, less-automated machines also show a great deal of energy being used in non-cutting operations. Figure 3 shows the energy breakdown for a 1998 Bridgeport automated milling machine. Figure 4 shows the energy breakdown for a 1988 Cincinnati Milacron milling machine, a machine that is functionally quite similar to the 1998 Bridgeport. While both of these machines have automated tool changers, coolant pumps, and other auxiliary equipment, the machines are not capable of as high of throughput as the production machining center shown in Figure 2.

Figures 3 and 4 show that, as in the case of the production machining center, the actual cutting energy used by the automated milling machine does not represent the entire energy used by the machine. In this case, between 30% and 50% of the energy required is spent on auxiliary equipment, depending on the machine duty cycle.

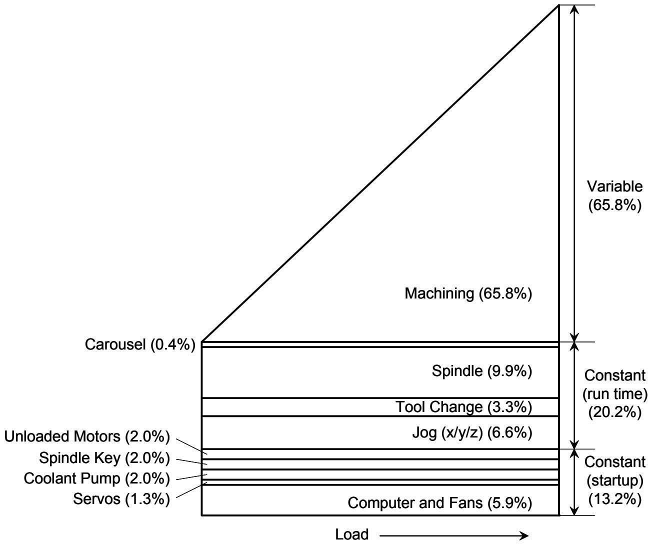

Figure 3: Machining energy use breakdown for a 1998 Bridgeport automated milling machine with a 5.8 kW spindle motor. Figure adapted from Kordonowy [13].

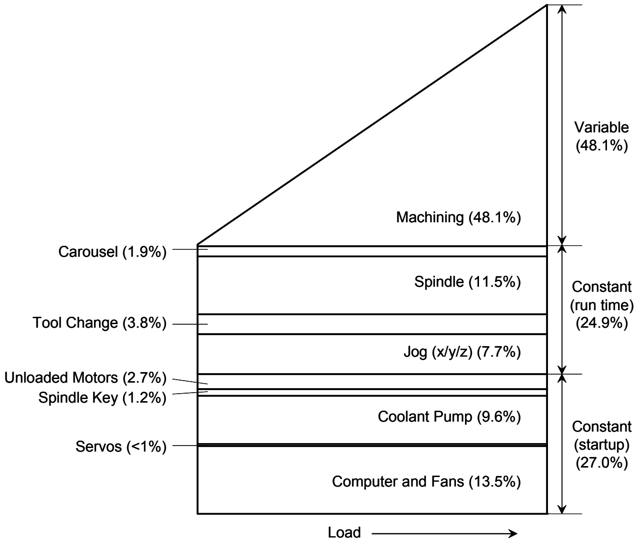

Figure 4: Machining energy use breakdown for a 1988 Cincinnati Milacron automated milling machine with a 6.0 kW spindle motor. Figure adapted from Kordonowy [13].

A comparison of the energy breakdowns from the 1998 Bridgeport and the 1988 Cincinnati Milacron reveal some insights about energy requirements and machine tool age. While the two automated milling machines are of similar size and capacity, and feature much of the same auxiliary equipment, the constant energy requirements of the older machine constitute a much larger percentage of the total machine energy use. While start-up operations for the 1998 Bridgeport account for 13.2% of the total energy requirement, start-up operations for the 1988 Cincinnati Milacron account for 27% of the energy total. Constant run-time energy use, including tool changes and jogging, accounts for 20.2% of the energy requirement on the newer machine and 24.9% on the older machine. This trend towards energy efficiency is not surprising. However, while efficiency improvements in auxiliary equipment can reduce energy requirements, these same efficiency improvements may in fact lead to increases in sales of auxiliary equipment, an effect referred to as the "rebound" effect [14].

Figure 5 shows the energy breakdown for a 1985 Bridgeport manual milling machine. Such a machine could be found in small job shop environments or in other shops where limited amounts of machining take place. Even without complex workpiece handling equipment, tool changers, and other automated equipment, over 30% of the energy required is used for running background processes, depending on the machine duty cycle.

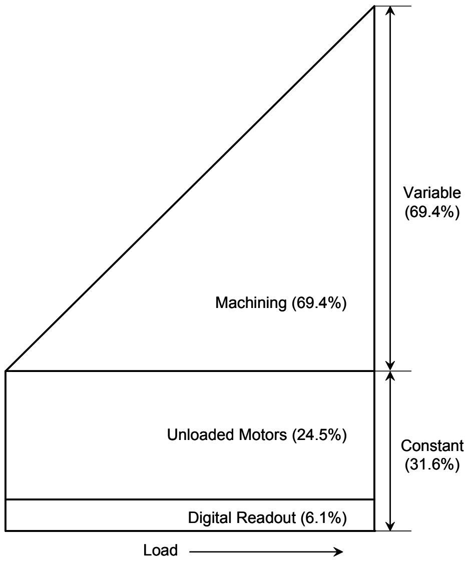

Figure 5: Machining energy use breakdown for a 1985 Bridgeport manual milling machine with a 2.1 kW spindle motor. Figure adapted from Kordonowy [13].

For all four of the systems analyzed, the energy necessary to actually cut the material is the same, assuming operating parameters, material properties, and tool characteristics remain constant. However, from the figures, it is clear that the energy necessary to actually cut the material is only a fraction of the total amount of energy required. This is an important finding in that it reveals that detailed tool tip energy models, while useful in some analyses, are not sufficient when attempting to find the total system energy requirements for material removal.

The four machines analyzed above fall into three operational classes: production machining centers, automated milling machines, and manual milling machines. According to a 1989 American Machinist survey, of these three classes of machines, manual machines are the most popular by quantity [15]. However, as new technologies have continued to propagate, the number of manual machines being sold has decreased while the number of automated machines being sold, including production machining centers, has increased.

By making some assumptions regarding various machining scenarios, the energy use per amount of material removed can be estimated. Table 1 shows assumptions and calculations for the energy use of material removal under four different scenarios: a highly-automated production machine, as analyzed in Figure 2, a modern smaller-scale automated machine, as analyzed in Figure 3, an older smaller-scale automated machine, as analyzed in Figure 4, and a manual machine, as analyzed in Figure 5. In each case, machine use scenarios are based on the specific machines.

The values shown in Table 1 come from various sources. The “Energy Breakdown” shows how total energy use is distributed among various activities, and mirror data shown in Figures 2 through 5. “Constant start-up operations” refer to start-up energy use, such as for computers, fans, and unloaded motors. “Run-time operations” include energy used to position materials and load tools. Finally, “Material removal operations” refer to the actual energy involved in cutting. The “Energy Requirements” for each different activity come from manufacturers’ specifications for various machines in the different classes. While actual energy values may vary slightly, machine specifications have been shown to be accurate enough for rough analyses [13].

The “Machine Use Scenario” makes assumptions about how such classes of machines are used in practice. Starting with an arbitrary number of work hours, 1000, each machine is assumed to be operational 90% of the time. For the production machining center, it is assumed that in order to purchase such a capital-intensive machine, companies must have sufficient amounts of material to be processed so as to guarantee the machine a steady stream of work. Using this assumption, it is assumed that the machine is rarely idle, resulting in 810 active machine hours for every 1000 hours. The assumptions underlying the automated milling machines and the manual milling machine are similar, although these machines, due to their lower capital costs, can afford to be idle for longer periods of time. Thus, the percentage of time during which the machine is idle increases as the capital cost of the equipment decreases.

Of the “Active machine hours per 1000 work hours,” not all are spent actively machining a part. Instead, a large portion of this time is spent positioning and loading both the workpiece and the tools. According to a diagram from Cincinnati Milacron, of the time a part spends on the machine, less than 30% of the time is spent in the cut [11]. Over 70% of the time is spent positioning, loading, and gauging the part [11]. Using these percentage values, the number of hours spent loading and positioning workpieces, as well as the number of hours spent actually cutting material, can be calculated for the manual milling machine. For the automated milling machines and the production machining center, this 30%-70% relationship will most likely be different, again due to the higher capital cost of the equipment. With higher capital costs, machine time is more valuable. Thus, on more expensive machines, much of the positioning, loading, and gauging, is done before or after the part is placed on the machine. This allows more machine time to be spent actually machining parts, as opposed to sitting inactive while positioning, loading, and gauging occurs. Because of this, the percentage of time spent in the cut increases, perhaps to 40% in the case of the automated milling machines. In the case of the production machining center, where additional equipment such as tombstones and pallets may be used, machine time in the cut may be estimated to be 70%.

The “Energy Use per 1000 work hours” can be calculated using the number of hours spent powered up but idle, the number of hours spent positioning and loading, the number of hours spent actually removing material, the energy required to run the machine while idle, the energy required to run the machine while positioning and loading, and the energy required to run the machine while removing material. These calculations yield the “Total energy use per 1000 work hours.”

	Production Machining Center (2000)		**Automated Milling Machine (1998)**		**Automated Milling Machine (1988)**		**Manual Milling Machine (1985)**	
Energy Breakdown								
Constant start-up operations (idle)	85.2%		13.2%		27.0%		31.6%	
Run-time operations (positioning, loading, etc)	3.5%		20.2%		24.9%		0% (manual)	
Material removal operations (in cut)	11.3%		65.8%		48.1%		69.4%	
Energy Requirements								
Constant start-up operations (idle)	166 kW		1.2 kW		3.4 kW		0.7 kW	
Run-time operations (positioning, loading, etc)	6.8 kW		1.8 kW		3.1 kW		0 kW	
Material removal operations (in cut)	22 kW		5.8 kW		6.0 kW		2.1 kW	
Machine Use Scenario								
Arbitrary Number of work hours	1000 hours		1000 hours		1000 hours		1000 hours	
Machine uptime	90%		90%		90%		90%	
Machine hours (idle, positioning, or in cut)	900 hours		900 hours		900 hours		900 hours	
Percentage of machine hours spent idle	10%		35%		35%		65%	
Machine hours spent idle	90 hours		315 hours		315 hours		585 hours	
Active machine hours per 1000 work hours	810 hours		585 hours		585 hours		315 hours	
Machining Scenario								
Percentage of machine hours spent positioning	30%		60%		60%		70%	
Machine hours spent positioning	243 hours		351 hours		351 hours		221 hours	
Percentage of machine hours spent in cut	70%		40%		40%		30%	
Machine hours spent in cut	567 hours		234 hours		234 hours		94.5 hours	
Energy Use per 1000 work hours								
Constant start-up operations (idle)	149288 kWh		1038 kWh		3033 kWh		600 kWh	
Run-time operations (positioning, loading, etc)	5471 kWh		1033 kWh		1818 kWh		0 kWh	
Material removal operations (in cut)	6237 kWh		673 kWh		702 kWh		100 kWh	
Total energy use per 1000 work hours	160996 kWh		2744 kWh		5553 kWh		700 kWh	
Energy Used per Material Removed								
Material Machined	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel
Material Removal Rate	20.0 cm^3/sec	4.7 cm^3/sec	5.0 cm^3/sec	1.2 cm^3/sec	5.0 cm^3/sec	1.2 cm^3/sec	1.5 cm^3/sec	0.35 cm^3/sec
Material removed per 1000 work hours	40824000 cm^3	9593640 cm^3	4212000 cm^3	1010880 cm^3	4212000 cm^3	1010880 cm^3	510300 cm^3	119070 cm^3
Energy used/Material removed	**14.2 kJ/cm^3**	**60 kJ/cm^3**	**2.3 kJ/cm^3**	**10 kJ/cm^3**	**4.7 kJ/cm^3**	**20 kJ/cm^3**	**4.9 kJ/cm^3**	**21 kJ/cm^3**

Table 1: Energy analysis of four milling machines.

The "Material removed per 1000 work hours" can be obtained by estimating a material removal rate. This estimation is difficult, as material removal rates depend on numerous parameters, including tool material (high-speed steel versus carbide), part material (aluminum versus steel), part design (fine versus rough geometry), and processing parameters (wet versus dry machining). Using the "Speeds and Feeds" section of a standard *Machinery's Handbook*, precise material removal rates can be calculated given various operating conditions [16]. While such detailed analyses are important for machinists, the models presented here attempt to show a general material removal scenario. Thus, the material removal rates used are based on averages, and are intended to represent mid-range values. Because of this, the material removal rates may appear higher than typical material removal rates for finishing operations or for operations where complex geometries are involved. However, the material removal rates may appear lower than typical material removal rates for hogging or other operations where coarser finishes are acceptable. The material removal rates used in this analysis correlate to machine size. As machines increase in power, the machine's ability to apply larger forces at higher velocities improves. This relationship is often shown in machining tables that relate material removal rates to the rated capacity of spindle motors [17]. Such tables allow machinists to correctly size machines for the type of material removal rates desired.

With energy and material removal data for each machine, the amount of energy required per amount of material removed can be calculated. These values provide a general estimate of the energy requirements for material removal operations in machining. Actual values may show some deviation from these estimated values, due to different machine use scenarios, machining scenarios, and material removal rates. However, the values shown do provide a good order-of-magnitude estimate of the energy requirements for the material removal process.

MATERIAL PRODUCTION

The production of aluminum and steel are energy- and resource-intensive processes. While material production may at first seem to be outside the system boundaries of machining, machining can be viewed as a process that pulls in raw materials, altering them dramatically in the course of producing products. Thus, the energy requirements of the raw materials, in this case metals, should be examined.

In creating products, machining often uses large amounts of material. In many cases, only a fraction of the total material entering into the manufacturing plant leaves in the form of a product. Estimates of scrap production in machining range from 10% to 60% [5]. While these chips and scraps can be recycled, the machining process itself requires the inflow of a large amount of pure material. In the case of machining aluminum, much of this raw material comes from virgin sources. Given that aluminum from virgin sources requires around 270 MJ/kg to produce, while aluminum from recycled sources requires only 16 MJ/kg, this is an important process requirement that must be considered when evaluating machining [18].

According to major aluminum producers, the recycled content of machineable aluminum is on the order of 20%. Thus, the average aluminum used in machining has an embodied energy of 219 MJ/kg. With the density of aluminum around 2.7 g/cm^3, the embodied energy per cubic centimeter of input material is around 590 kJ/cm^3, or 40 to 120 times larger than the material removal energies calculated in Table 1. Thus, the importance of tracing back material flows to material production is obvious.

For steel, the embodied energy is significantly less than for aluminum, as is the savings from using recycled sources. Producing steel from virgin sources requires 31 MJ/kg, while producing steel from recycled sources requires only 9 MJ/kg [18]. With the density of steel around 8.0 g/cm^3, the embodied energy per cubic centimeter of virgin steel is around 250 kJ/cm^3. Although the material removal energies associated with steel are higher than aluminum, the embodied energy of virgin steel is still four to 25 times larger than the machining energy. However, if steel with a high recycled content is used, the embodied energy of the material may be on the same order-of-magnitude as the material removal energy.

Material production is also important to consider due to its other environmental implications. Metal smelting can result in sulfur dioxide emissions, heavy metal emissions, and particulate emissions, all of which have serious local and global effects on the environment. More detailed examinations of such emissions have been conducted, and will not be repeated here [19, 20].

CUTTING FLUID PREPARATION

Cutting fluids are an important part of machining, both in terms of operation and in terms of environmental impact. The most popular type of cutting fluid, and the one that will be focused on here, is soluble oil. In use, soluble oils are typically diluted with water, such that around 95% of the cutting fluid, by volume, is water [21, 22]. The other 5% is a combination of oil, emulsifiers, and additives.

The oil used in soluble oil cutting fluids is typically either a naphthenic or paraffinic oil [22]. Common emulsifiers, which help to suspend the oil droplets in water, include sodium sulfonate, nonylphenol ethoxylates, PEG esters, and alkanolamides [22]. Additives are used to limit corrosion, control acidity, control microbial growth, improve lubricity, and prevent foaming. To prevent rust, additives such as calcium sulfonate, alkanoamides, and blown waxes can be used [22]. Maintaining a slightly basic acidity, with a pH between 8.8 and 9.2, is typically accomplished through the addition of amines as alkaline sources [22]. Controlling growth of bacteria, yeast, and mold is accomplished using biocides such as formaldehyde condensates [23]. Pesticides, including biocides, are regulated by the Environmental Protection Agency (EPA) under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), which requires that the users of pesticides register their purchases with the EPA and that the pesticides purchased are themselves registered with the EPA [24].

In addition to the many oils and chemicals making up cutting fluid, a large amount of water is also required. Table 2 shows the calculations and assumptions behind determining the amount of water used in machining. The values shown account for water used in the cutting fluid preparation process, but do not take into account water used elsewhere in the machining process.

The values in Table 2 come from various sources. The "Total sales volume" figure represents the average of two values for 1990. One value comes from the Independent Lubricant Manufacturers Association while the other comes from the National Petroleum Refiners Association [25, 26]. These values seem to be in line with older industry estimates found in other texts [27]. The total number of metalworking machines comes from the 1989 American Machinist Inventory [15]. The total number of metalworking machines includes milling machines, turning machines, sawing machines, drilling machines, grinding machines, and non-traditional machines such as electrical discharge machines and waterjet machines. Since the focus here does not include grinding or non-traditional machining, these are broken out from the total number of metalworking machines given in the American Machinist Inventory.

Metalworking Fluid Sales (1990)	
Total sales volume	97 million gallons/year
Metalworking Machines (1989)	
Total metalworking machines	1.871 million machines
Cutting machines (inlcudes milling, turning, sawing, and drilling)	1.394 million machines
Percentage of Cutting machines	75%
Grinding machines	0.435 million machines
Percentage of Grinding machines	23%
Non-traditional machines	0.042 million machines
Percentage of Non-traditional machines	2%
Cutting and Grinding Machines	1.829 million machines
Concentrated Metalworking Fluid Use (without water)	
Metalworking Fluid used per Cutting Machine	53 gallons/machine/year
Total Metalworking Fluid for all Cutting machines	74 million gallons/year
Diluted Metalworking Fluid composition (with water)	
Percentage of Metalworking Fluid	5%
Percentage of Water	95%
Total Water for all Cutting Machines (without evaporative losses)	1405 million gallons/year
Evaporative losses	1%
Evaporative replacement	14 million gallons/year
Total Water for all Cutting Machines	1419 million gallons/year
Water used per Cutting Machine	1018 gallons/machine/year
Work Scenario	
Work days per year	250 days/year
Daily Use	
Daily Metalworking Fluid used per Cutting Machine (concentrated)	0.21 gallons/machine/day
Daily Water used per Cutting Machine	4.07 gallons/machine/day

Table 2: Metalworking fluid analysis.

While grinding machines are not part of the focus of this paper, the term "metalworking fluids" typically refers to both cutting and grinding fluids [25]. Thus, in the "Concentrated Metalworking Fluid Use (without water)" section, the values represent an equal distribution of the total metalworking fluid sales among all cutting machines and grinding machines.[1] Inherent in this distribution is the assumption that cutting machines and grinding machines use the same amount of metalworking fluid, a reasonable assumption for this analysis. The values of 53 gallons per machine per year and 74 million gallons per year in total, refer to concentrated metalworking fluid without water.

In the "Diluted Metalworking Fluid Composition (with water)" section, water is included in the calculation. Using the 5 to 95 ratio of concentrated metalworking fluid to water, the amount of water needed for mixing with the concentrated metalworking fluid can be determined. This amount of water also takes into account that the water in metalworking fluid evaporates over time. Therefore, additional water must be added so that the concentration of metalworking fluid does not become too high. The calculation of water use also assumes that all concentrated metalworking fluid sold is mixed with water. This is not entirely true, as some cutting fluids are used without dilution. However, due to their fire and health hazards, as well as their difficulty in cleaning, such fluids are being replaced in favor of water-miscible metalworking fluids [28]. This assumption that all concentrated metalworking fluids are diluted in water, probably results in a slight overestimate of actual water use.

The work scenario simply represents 50 work weeks per year, with 5 work days per week. Thus, given the estimations of metalworking fluid use along with work scenarios, values for the amount of concentrated metalworking fluid and water used per machine per day can be obtained.

Once formulated, cutting fluids can be circulated through a system numerous times. However, losses frequently occur, often through vaporization or through chips, scrap, and workpieces leaving the material removal process [8]. In fact, some suggest that as much as 30% of the annual total cutting fluid consumption may be lost through these mechanisms [29]. Others claim a lower, but still significant, loss rate on the order of 10% [26]. With either estimate, it is clear that a fair amount of cutting fluid is lost through everyday activities.

Over time, the cutting fluid will pick up contaminants such as metal chips, fines, and tramp oil. Such contaminants can be removed using a separation or filtration process, or, alternatively, the cutting fluid can be disposed of and replaced with fresh fluid. While disposal of spent metalworking fluid was once virtually cost-free, today disposal costs are approximately equal to the cost of the replacement fluid [30]. With increasing environmental regulations, such as the Resource Conservation and Recovery Act (RCRA), disposal of metalworking fluid is becoming more highly controlled and more costly [30].

TOOL PREPARATION

While tooling plays a major role in the machining process, the direct environmental impact of tooling is limited. Due to their relatively long life, the environmental cost of tools and tool maintenance is often amortized over numerous products, thereby making the environmental impact relatively insignificant on a per part basis. However, the effect of tool materials on allowable cutting speeds, and thus on material removal rate, should not be overlooked. Selection of appropriate tools can allow for increased material removal rates, thereby reducing the total machining energy required.

Today, most metal cutting is done using carbide tools [16]. A large proportion of these carbide tools are sold as indexable inserts, cutting inserts that attach to specially designed tool holders. These indexable inserts, because they can be repositioned, have multiple cutting surfaces, depending on their geometry. Triangular inserts have six available cutting edges, three per side; rectangular inserts have eight cutting edges, while circular inserts can be rotated to numerous positions. Once all the cutting edges have been used, the insert is typically discarded [16].

Producing carbide tools does require some energy-intensive materials and processes. Tungsten, with an embodied energy of approximately 400 MJ/kg, comprises most of the mass of carbide cutters [31]. Some of the manufacturing steps, including sintering, which is used to form the carbide tool, and physical vapor deposition (PVD) or chemical vapor deposition (CVD), which is used to coat the carbide, are also quite energy intensive, with estimates on the order of 1 to 2 MJ per process per cutting insert [31]. While these energy values are not

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[1] The term "cutting machines" refers to milling, turning, sawing, and drilling machines.

trivial, the fact that carbide cutting tools can be used numerous times on multiple surfaces means that this energy investment is distributed over numerous parts. Thus, the per part energy contribution from tool production can be more or less ignored, particularly in light of the material removal and material production analyses presented earlier.

Alternatives to carbide tools do exist, the most popular being high-speed steels. High-speed steels are still used in the majority of drilling applications, as well as in many milling applications [32]. Like carbide tools, high-speed steel tools can also be coated through PVD or CVD processes [32].

As mentioned earlier, perhaps the biggest difference between high-speed steel tools and carbide tools lies in the machining time. With carbide tools, allowable cutting speeds are much greater. In the case of end-milling wrought aluminum such as 6061-T6, the optimum[2] cutting speed for high-speed steel tools is 165 feet per minute while the optimum cutting speed for uncoated carbide inserts is 620 feet per minute [16]. In the case of end-milling using a 2-tooth, 1 inch diameter tool with a 0.2 inch depth of cut and a 1 inch width of cut, the recommended material removal rate for high-speed steel tools is around 1 cm^3 per second, while the recommended material removal rate for carbide tools is close to 4 cm^3 per second. This example highlights the drastic difference in material removal rate arising from differences in cutting tool material. From Table 1, the importance of material removal rate in energy use in machining is clear; higher material removal rates can lead to drastically decreased machining energy requirements per unit of material volume removed. Again, material removal rates are not dependent on tool material alone, as part geometries and surface finish requirements are also important.

MACHINE TOOL CONSTRUCTION

Much like tooling, while machine tools clearly play a major role in the machining process, their direct environmental impact is limited. Most machine tools are in use for many years. In 1989, 60% of metalcutting machines in the US were more than 10 years old [15]. These long lifetimes mean that the environmental impact of machine tool construction is amortized over numerous products over many years. Thus, the environmental impact per part is relatively small.

The larger effect of machine tools on machining has to do with energy efficiency. Newer machine tools can be significantly more energy-efficient than older machine tools, resulting in energy savings during material removal. Such efficiency improvements are described earlier, and can be seen in Table 1 by comparing the automated milling machine from 1998 with the automated milling machine from 1988. The efficiency improvements reduce energy requirements per unit of material volume removed by approximately 50%, as shown in Table 1.

CLEANING

Of the processes that play a role in machining, cleaning is one of the most often cited when discussing environmental impact. However, the importance of cleaning, and the environmental impact of cleaning, is highly dependent on the product being made. High-end painted products must often undergo multiple cleaning steps, while other products might be acceptable with a simple rag wipe down. This highly diversified cleaning landscape, both in terms of amount of cleaning and type of cleaning, make general qualitative analysis of this process difficult.

The cleaning methods and chemicals currently being used are also changing. Prior to US and international regulations of the late 1980's and early 1990's, metal cleaning was dominated by several large-use chemicals that could be used in a wide array of different situations [33]. The most widely used of these chemicals was the chlorinated solvent, 1,1,1-trichloroethane (TCA) [34]. However, since the phase-out of TCA, and with no "drop-in" replacement available, numerous different cleaning solutions have been implemented [34, 35]. Many of the new cleaning processes rely on aqueous cleaners instead of solvent cleaners.

ENVIRONMENTAL CONCERNS

The analysis of machining presented above, and particularly the analyses of the material removal and material preparation processes, focus heavily on energy use. Energy use and energy sources are important to examine when investigating environmental impacts.

In the case of the material removal process, the energy for this activity comes from electricity from the power grid. In the United States, over 50% of electric power comes from burning coal [36]. Other major contributions come from nuclear, 20%, and natural gas, 18% [36]. Thus, electricity comes burdened with its own environmental ramifications. An average MJ from the US electricity grid is accompanied by 167 g of CO_2, 0.7 g of SO_2, and 0.3 g of NO_x [36]. Other environmentally important emissions also result from electricity generation, including mercury, chromium, and lead [37]. It is also important to note inefficiencies in the electricity generation system. Large coal-fired electricity generation facilities are only around 35% efficient [38]. Thus, for every 3 kJ of coal that are burned, 1 kJ of electricity results. In short, electricity values are heavily burdened.

The material production process relies on a mix of energy sources, including electricity. While the exact energy mix depends on material, location, and other factors, it is important to note that this energy must also be appropriately burdened. In some cases, such as the case of aluminum produced in the Northwest, some of the energy may come from greener sources, such as hydropower. Analysis and inclusion of these energy sources is beyond the scope of this paper, but it is important to note the different sources of energy and electricity.

While the environmental concerns associated with material removal and material production are focused on energy use, the environmental concerns associated with cutting fluid preparation and cleaning are tied more closely to liquid and hazardous waste. These pollutants raise issues at both local and global levels. While some of the chemicals used in these processes can be harmful to workers, such as some additives to cutting fluids, other chemicals, such as TCA, are associated with high-level ozone depletion. Such environmental impacts further stress the importance of research in areas such as dry machining and aqueous cleaning.

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[2] According to the *Machinery's Handbook*, "the *optimum* feed/speed data are approximate values of feed and speed that achieve minimum-cost machining by combining a high productivity rate with low tooling cost at a fixed tool life." [16]

SUMMARY

This environmental analysis of machining highlights a few important points. From the energy analysis of the material removal process, it is clear that the actual cutting energy can be quite small when compared to the total energy required during material removal. Figures 2 through 5 clearly illustrate this result. It is also important to note that the energy used to power machine tools typically comes from the electricity grid. Thus, electricity requirements for the material removal process must be correctly burdened to reflect their true environmental impact.

Another important point is that the energy involved in the material production process can, in some cases, dominate the energy involved in the material removal process. This result is particularly true if the material being machined is virgin aluminum, or an equally energy-intensive material. However, in the case of recycled steel, or an equally non-energy-intensive material, the material production energy and material removal energy may be on the same order of magnitude.

With regards to cutting fluid preparation and cleaning, the focus shifts from one of energy to one of liquid and gaseous emissions. While further research must be done in these areas to complete this environmental analysis, it is important to note that these processes will tend to dominate liquid use, liquid waste, and hazardous waste categories, much like material production and material removal dominated energy use categories.

Future work on this project will focus on completing this environmental analysis, and more closely linking energy use, water use, and emissions information for machining to actual environmental concerns.

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APPENDIX A: DATA SOURCES

Gathering environmental data for system-level manufacturing models is quite difficult. One important resource for industrial information, the federal government, does have a large amount of data from agencies such as the Department of Energy (DOE) and the Environmental Protection Agency (EPA). The Energy Information Administration (EIA), an agency of the DOE, provides data on industrial energy consumption obtained through its Manufacturing Energy Consumption Survey (MECS), the latest of which was conducted in 1998. While this survey provides a comprehensive look at energy use in the industrial sector, industry information is organized by North American Industry Classification System (NAICS) code or, for data prior to 1997, by Standard Industrial Classification (SIC) code. While some NAICS and SIC codes correspond to specific processes, machining is spread out among numerous different product-specific codes. According to the 1989 American Machinist Inventory, 98.2% of all metalcutting machines are distributed among just four major product-specific SIC code groups, namely,

Major Group 34, Fabricated Metal Products, Except Machinery and Transportation Equipment
Major Group 35, Industrial and Commercial Machinery and Computer Equipment
Major Group 36, Electronic and Other Electrical Equipment and Components, Except Computer Equipment
Major Group 37, Transportation Equipment.

While these major groups are known to contain metalcutting machines, and the energy requirements of each of these major groups can be obtained using EIA information, the major groups defined by the SIC code contain far more than simply metalcutting equipment. Therefore, the amount of energy used by one of the major groups listed above cannot be entirely traced back to metalcutting machines. Instead, the energy demand must be divided among metalcutting machines and other machines that are required by that major group. In short, product-specific energy data cannot be easily converted to process-specific data, as required by this analysis.

This inability to link product-specific data to individual processes also prevents the effective use of Toxic Release

Inventory (TRI) data provided by the EPA. TRI data, self-reported company data on releases of toxic chemicals, is available at both the level of the firm and at the level of SIC or NAICS codes. However, as in the case of EIA data, TRI data cannot be easily converted to process-specific data. Firms typically have numerous pieces of equipment, not just metalcutting equipment, making the allocation of firm-level TRI releases to specific processes impossible without further information. Likewise, the products contained in product-specific SIC codes can be made using numerous different processes, making it impossible to trace any SIC code-specific TRI releases to specific processes without additional information. Even if such TRI data could be linked to specific processes, there is some question as to how representative TRI data is of actual emissions [Williams 2002]. Given that TRI data is self-reported, and that not all firms are required to file a TRI, TRI data for an industry as a whole may often be lower than the actual releases.

Outside of government surveys, little system-level industrial information is available. While industrial trade publications such as American Machinist do report on overall industry statistics, environmental issues are rarely reported on. Also, as there are no requirements to release energy use and environmental data outside of the government requirements, it is not surprising that companies do not release additional, more detailed information. In fact, more detailed information may, in some cases, be seen as a valuable trade secret. Perhaps contributing to this lack of information is the fact that the industry landscape is constantly changing. With the beginning of the North American Free Trade Agreement (NAFTA) in 1994, the continuing movement of manufacturing offshore, and the rise of contract manufacturers, machining, and the manufacturing sector as a whole, is in constant flux.

An alternative approach to gathering data is to begin with process-specific data. While such data is available, and is already directly linked to the process under investigation, process-specific data can place undue emphasis on a certain machining method or piece of equipment. When relying on process data, it is important that the machining process analyzed is representative of machining processes in general. If it is not, it is important to understand how this process differs from the average process. Much of the analysis presented in this paper relies on process-specific data, as opposed to system-level data.