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Abstract—**A life-cycle energy consumption analysis of a Bridgeport manual mill and a Mori Seiki DuraVertical 5060 has been conducted. The use phase incorporated three manufacturing environments: a community shop, a job shop, and a commercial facility. The CO_2-equivalent emissions were presented per machined part. While the use phase comprised the majority of the overall emissions, the manufacturing phase emissions were significant especially for the job shop, which is not as efficient as the other facilities due to its inherent need for flexibility. Since the Mori Seiki is heavier, the manufacturing phase of this machine tool had a greater impact on emissions than the Bridgeport. Transportation was small relative to the use phase, which was dominated by cutting, HVAC, and lighting. These results highlight areas for energy reductions in machine tool design as well as the importance of facility type to the manufacture of any product.**

***Index Terms*—Machine tools, Energy consumption, Environmental impact**

I. Introduction

MANUFACTURING activities are responsible for 19% of the world's greenhouse gas emissions [1] and 31% of the United States's total energy usage [2]. Machining is an area of manufacturing that has been strongly targeted for energy reduction because of its size and importance – global machine tool sales alone were estimated to be $82 billion in 2008 and $71 billion in 2007 [3]. Machining – broadly defined as all material removal processes – can be viewed as a system consisting of a *workpiece* or *work* (the fabricated part), a *tool* (which performs the material removal), and a *machine* [4]. The machine and tool together are referred to as a *machine tool*. While various types of machine tools are used for different applications, one important classification is milling machine tools.

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Milling is a type of cutting process where the tool rotates on one axis and moves relative to the workpiece in a defined volume. Fig. 1 shows the components of a standard vertical milling machine tool. In this example, the workpiece is secured to the table, which moves within the horizontal plane. The spindle rotates the tool and both are moved in the vertical direction. Translational motion is provided by a lead or ball screw connected to motors or axis drives, guided by ways, and controlled by the machine control unit or controller. The bed/base and column are together called the machine tool frame, which provides stiffness and damping. Other components not shown in Fig. 1 include the thermal control unit (reduces thermal errors), the lubrication lines (lubricates the moving elements), and the cutting fluid system (delivers cutting fluid to the workpiece).

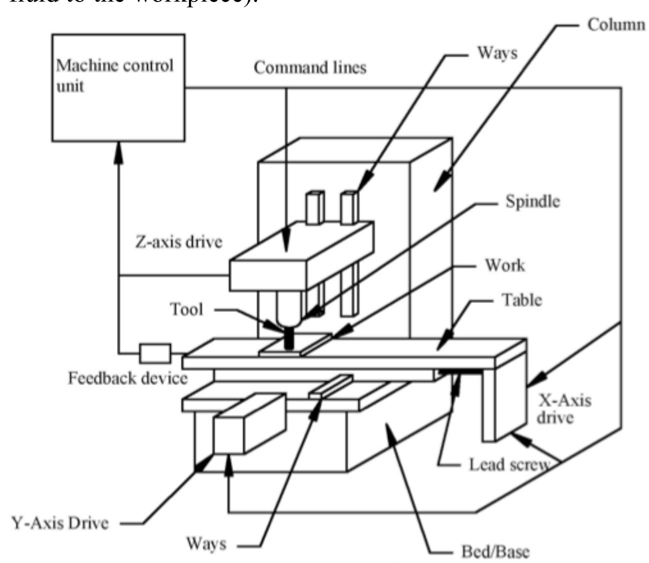

Fig. 1. Basic structure of a standard vertical milling machine [5].

The essential functions of a machine tool are to provide a source of energy or relative motion and a means to secure the workpiece, secure and orient the tool, and control the source of energy or motion and the orientation of the workpiece and tool [5]. To provide these functions, machine tools must employ four input flows, electric energy, cutting and lubrication oils, water, and compressed air, all of which have been regarded as cheap resources that can be excessively used to ensure high-quality finished products. But growing environmental awareness has necessitated increasingly efficient use of these resources. It has become important to quantify these flows and the entire life cycle of machine tools to find areas for improvement in design, processing, and resource use. This is particularly true for milling machines and machining centers (a milling machine with added functionality), which are two common tools in modern manufacturing facilities.

II. Background

The following section highlights significant contributions to the green machining literature. The first green machining approaches aimed to reduce environmental impact by focusing on process and design level improvements in the use phase. They were popular since they did not alter the machinery or process, thus allowing potentially great benefits at minimal cost. Much of this early work was guided by the framework and strategies for green machining developed by [6], which identified three areas for "clean" machining: the reduction in cutting and cleaning fluids, the use of improved cutting tool materials to support cutting fluid reductions, and the incorporation of monitoring to better understand the cutting process and shed light on other areas to reduce environmental load. Of the three areas identified, cutting and cleaning fluid reduction was the biggest area of research activity, which led to the development of minimum quantity lubrication (MQL) and dry machining techniques; [7] presents a comprehensive review of both methods. Other important research areas include the development of thermal control within the machine tool frame in place of a thermally controlled environment around the machine tool to reduce overall electricity use [8], the use of remanufacturing, reuse, and recycling particularly of the machine tool frame to reclaim the large amount of material used and prevent further processing costs [9], the introduction of design for disassembly to aid remanufacturing, reuse, and recycling approaches [10], [11], and the reduction of processing time to better amortize constant energy expenditures and thus reduce specific cutting energy [12], [13].

Throughout the early work in green machining, there was an observed need for a set of quantifiable dimensions to evaluate trade-offs when faced with process planning decisions [14]. The next major thrust of research activity focused on models to capture the convoluted nature of machining physics. [14] provided the seminal model that comprehensively links relevant machining parameters (e.g., speed, feed, depth of cut, and tool angle) to the environmental impacts of the machining process (e.g., energy consumption, process rate, and mass flow of waste streams). Subsequent research in the literature established better ways to compare the input and output flows of the machining process as well as evaluate multiple processing alternatives [15]-[18].

The literature also recognized the need for a system-level approach to capture the environmental impacts of the entire life cycle. This latest thrust of research has focused on life-cycle assessment (LCA) [19] of the machining process and machine tools. Early LCA studies found that the use of recycled material in the manufacture of the machine tool frame provided a minimal decrease in the CO_2 emitted over the entire life-cycle due to electricity use since the use phase is presumed to be long [20]. However, the use of cutting fluid reduction techniques such as MQL and dry machining were found to provide substantial CO_2 and energy savings. The literature has also found that highly automated machine tools have significantly larger environmental impact due to the high electricity consumption of the peripheral equipment required for the machinery [21]. Also, downsizing of machine tools (i.e., reducing the work volume) reduces electrical energy consumption by shrinking the volume that must be environmentally controlled [22]. Finally, recent work has connected the LCA results found in the literature to process planning so that it can be used in the design stages of a product [23], [24].

While the current literature provides extensive knowledge of the environmental impacts of machine tools, it is limited by the assumption that the use phase dominates the overall impact of a machine tool due to the machine tool's perceived long service life. However, this may not be true depending on the manufacturing environment in which a machine tool operates since the production rate influences specific energy. Much of the literature also does not consider transportation, material inputs (e.g., cutting fluid), or facility inputs (e.g., HVAC and lighting) each of which potentially represents a sizable energy sink. The level of automation also influences energy consumption since more automated tools require more peripheral equipment.

The goal of this study is to analyze the lifetime energy consumption of a machine tool including the effect of manufacturing environment, transportation, cutting fluid, HVAC, lighting, and automation. The results of this analysis provide greater value to previous work by highlighting the areas with greatest opportunities for energy optimization. This analysis is not limited to machining. It may also be extended to other manufacturing processes, and can serve to reduce the uncertainty of LCAs of products by providing greater clarity on the manufacturing phase as the purpose of a machine tool is to manufacture other products.

III. Methodology

Two types of machine tools were studied in this LCA: (1) the Bridgeport Manual Mill Series I (a computerized numerical control (CNC) milling machine that represents a low level of automation), and (2) the Mori Seiki DuraVertical 5060 (a machining center that represents a high level of automation). These machine tools were selected because of their high use in industry. Energy consumption and CO_2 emissions were calculated for each life-cycle stage in different environments.

A. Manufacturing Phase

Each machine tool was divided into its primary components (machine tool frame, spindle, ball/lead screws, X/Y axes, tool changer, casing, and controller) to determine the energy consumed during manufacturing. The energy required to manufacture all primary components, except for the controller, was calculated using process data, while EIO-LCA [25] was used to analyze the controller. All primary components, except for the controller, were assumed to be composed of one material to simplify the use of process data. The machine tool frame was assumed to be gray cast iron, the casing was low carbon steel, and the remaining components were low alloy steel. Each material selection included industry standard recycled content [26].

The following processes were considered in calculating the energy consumed in manufacturing each component: casting, extrusion, rolling, stamping, turning, grinding, case hardening, annealing, tempering, and heat treatment. The embodied energy of deformation processing from [26] was used for the extrusion, stamping, and rolling processes. Specific energies for machining, turning, grinding, heat treatment, annealing, and case hardening processes were taken from [3], [27]-[29]. To compute CO_2 emissions, a Japanese energy mix was used for the Mori Seiki (380 g of CO_2-e/kWh [26]) and a weighted average emission factor for a Connecticut energy mix including indirect emissions was used for the Bridgeport (420 g of CO_2e-kWh [30]-[33]).

B. Transportation

Supply-chain transportation energy consumption and CO_2 emissions were calculated for both machine tools. The Mori Seiki was assumed to travel from Iga, Japan to Nagoya, Japan (from manufacturer to port) by a 14-tonne diesel truck, then to Los Angeles, CA by ocean freighter, and finally to San Jose, CA by another 14-tonne diesel truck. The Bridgeport was assumed to travel from Bridgeport, CT to San Jose, CA also by a 14-tonne diesel truck. The use phase was assumed to occur in San Jose. Both machine tools were trucked from San Jose to Los Angeles for end-of-life treatment.

Emissions factors from [26] were used for each travel segment. (In future research, truck emission factors will be based on [34].) Because these emissions factors are normalized by load, they had to be adjusted to determine actual CO_2 emissions by assuming that the ocean freighter and diesel truck utilization were both 75%. The emissions due to ocean freight for one Mori Seiki was calculated by taking the ratio of the Mori Seiki's mass to the total load of the ocean freighter. Each diesel truckload was assumed to contain three Bridgeports or one Mori Seiki; this difference was due to the need for more Bridgeports relative to Mori Seikis to compensate for the Bridgeport's lower productivity.

C. Use Phase

To analyze the effect of different facility characteristics and production schedules, the use phase of both machine tools was studied across three different manufacturing environments: a community shop, a job shop, and a large commercial facility. The functional life of a machine tool in each environment is dependent on its performance. Once performance sufficiently degrades, used machine tools may be downgraded, retrofitted, or resold. Given this uncertainty, the functional life of the machine tool was defined as ending once it left the original owner's possession. A standard part made over the functional life served as the functional unit considered in this analysis.

In addition to the electricity required to produce parts, this analysis considered the electric energy required to produce machine tool fluids, facility lighting, and HVAC. Labor was omitted because of the complexity and uncertainty associated with its consideration. Because this analysis was concerned with the production of a widget, the extraction and preprocessing of the workpiece material were also excluded.

A standard part (see Fig. 2) was developed to quantify and compare the actual use phase energy associated with the Bridgeport and the Mori Seiki. The widget was made from 4"x4"x1" AISI 1018 steel and was designed to incorporate many features commonly used in product design that require a variety of the machine tool's capabilities. Energy consumption was measured and recorded during production of this part. Setup time to determine standby energy was taken from [21]. Standard cutting parameters were used for machining. The widget was machined in 949 seconds on the Bridgeport and in 609 seconds on the Mori Seiki.

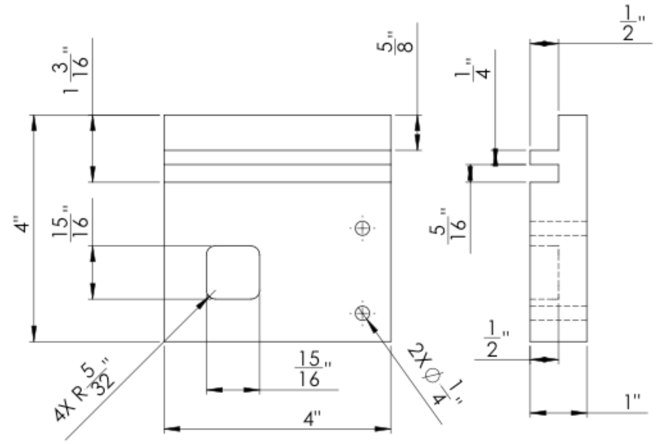

Fig. 2. Drawing of standard widget.

To ensure a fair comparison with respect to the functional unit, the number of machine tools required in each facility so that a given set of machine tools achieved similar production rates was calculated (see the results in Table 1). Fluid consumption and shop floorspace values for the community shop and job shop were based on data collected from the Mechanical Engineering Student Shop at the University of California, Berkeley and Kalman Manufacturing in Morgan Hill, CA. The commercial facility values were estimated based on assumed standard factory usage.

As described in Section I, machining processes consume two types of fluids: cutting fluid and lubricating oil. Cutting fluid is considered for only the Mori Seiki because the amount consumed by the Bridgeport is relatively small. Lubricating oil is considered for both machine tools. Fluid consumption per year for all three environments is provided in Table 1. An embodied energy analysis of the oil constituents provides the total energy input due to the fluids [23]. The electricity consumption associated with the HVAC system and lighting of the different manufacturing facilities was calculated based on energy intensities related to the square footage of the facility, obtained from [35]. Total HVAC and lighting energies were computed according to the size of the machine tool workspace required for their use (see Table 1), where the workspace includes space for tooling and operator mobility. To compute CO_2 emissions, a weight average emission factor for a California energy mix including indirect emissions was assumed, 320 g CO_2e-kWh [31]-[33], [36], [37].

TABLE 1

FACILITY INFORMATION

	Community Shop		Job Shop		Commercial Facility	
	Bridgeport	Mori Seiki	Bridgeport	Mori Seiki	Bridgeport	Mori Seiki
Machine tool functional life [years]	20		10		16	
Production volume [parts/day]	130		871		31,283	
Number of machine tools	9	6	28	18	467	300
Cutting fluid – Oil [gal/year]	0	210	0	1,300	0	11,000
Cutting fluid – H_2O [gal/year]	0	1,900	0	12,000	0	99,000
Lubricating oil [gal/year]	2	110	3	660	52	5,500
Shop Floorspace [ft^2]	1,600		25,000		750,000	
Machine tool workspace [ft^2]	75	180	75	180	75	180
HVAC [MJ/year-tool]	3,200	7,600	2,900	6,900	5,200	13,000
Lighting [MJ/year-tool]	1,100	2,600	1,000	2,500	2,400	5,800

D. End of life

There is significant uncertainty regarding the end-of-life of a machine tool since they are constantly resold in the used machine tool market. Because of these uncertainties, no credit was assigned for the potential future use of a machine tool after the conclusion of its functional life with one user. However, one of the major potential credits, material recyclability, has been accounted for in the manufacturing phase analysis similarly to [38].

IV. RESULTS

The energy required to manufacture the Bridgeport and Mori Seiki was found to be 18,000 MJ and 100,000 MJ per machine tool, respectively (Table 2). Overall, material extraction was the most energy-intensive process, making up approximately 70% of the total energy consumed in manufacturing, followed by the casting of the material.

TABLE 2

MANUFACTURING PROCESS ENERGY FOR MACHINE TOOL MANUFACTURE

Process	Bridgeport (MJ)	Mori Seiki (MJ)
Material Extraction	13,000	73,000
Casting	3,200	19,000
Annealing	630	3,800
Tempering	440	2,700
Milling	170	1,200
Rolling	0	990
Stamping	0	990
Case Hardening	110	240
Extrusion	27	120
Electronics	7	74
Turning	34	69
Grinding	13	59
Total:	17,631	102,242

Fig. 3 summarizes the manufacturing energy of the primary components of the machine tool, excluding material extraction. The machine tool frame consumed the most energy to manufacture because it contains the majority of the machine tool mass and it requires casting. The machine tool frame of the Mori Seiki required ten times more energy than the Bridgeport because the Mori Seiki had greater mass and required additional machining and heat treatment. The machine tool casing and tool changer were only present for the Mori Seiki.

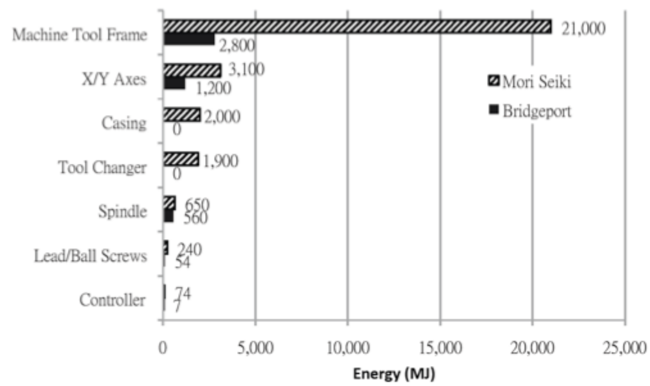

Fig. 3. Energy consumption by machine tool component.

Table 3 presents the energy consumption and CO_2 emissions from transporting the machine tools from their place of manufacture to a facility in San Jose, CA. Approximately 40% of the total transportation energy consumed for the Mori Seiki is due to the ocean freight from Nagoya to Los Angeles.

TABLE 3

TRANSPORTATION ENERGY CONSUMPTION AND CO_2-EQUIVALENT EMISSIONS

	Distance Traveled (km)	Energy Consumed (MJ)	CO_2-e Emitted (kg)
Bridgeport	5,362	17,000	1,200
Mori Seiki	10,174	19,000	1,600

Part production energy consumption varied by machine tool and not by facility; the Bridgeport consumed 600 kJ per part while the Mori Seiki consumed 1,000 kJ per part (see Table 4). Energy consumption for maintenance was relatively small – the job shop had the maximum of 75 kJ per part. HVAC and lighting were found to be significant, consuming 40-65% of the total use phase energy. The most energy intensive scenario was the Mori Seiki in the community shop because its production capabilities could not be capitalized. The community shop was the least energy efficient environment since it had the smallest production volume, but comparable HVAC and lighting energy intensities to the job shop. Commercial facilities take advantage

TABLE 4

ENERGY CONSUMPTION PER PART DURING USE PHASE (KJ/PART)

	Community Shop		Job Shop		Commercial Facility	
	Bridgeport	Mori Seiki	Bridgeport	Mori Seiki	Bridgeport	Mori Seiki
Part Production	600	1,000	600	1,000	600	1,000
Maintenance	1	14	8	75	4	40
HVAC	880	1300	460	710	310	480
Lighting	290	460	170	260	140	220
Total:	1,771	2,774	1,238	2,045	1,054	1,740

of economies of scale to amortize energy requirements over a large volume of parts. Warehouse facilities, which are used by commercial facilities and job shops, are best suited for large-scale manufacturing, and as a result higher productivity is needed to reduce per part energy requirements. Job shops frequently employ additional machines and extra space to be able to have greater flexibility to respond quickly to customer demands and new business; the drawback is that HVAC and lighting increase and comprise the majority of the use phase energy consumption. Because large energy inputs need large quantities manufactured to become environmentally competitive, job shops perform poorly due to the nature of their high-mix, low-volume manufacturing.

Energy assessments of machine tools need to take these ancillary needs into consideration. Based on our observations, the effects of HVAC and lighting could be minimized when machine tools are more closely packed together. Being able to fit additional machines onto the same floor space would lower the per-part impact of these energy costs. Consequently, a metric such as parts produced per square foot may be a reasonable method of tracking the efficiency of different factories.

The CO_2-equivalent emissions calculated for both machine tools in all three manufacturing environments resulted in measurable differences (see Fig. 4). Contrary to [20], the manufacturing phase is significant relative to the use phase. The percentage of CO_2-equivalent emissions during the manufacturing phase was smallest for both machine tools in the commercial facility because of the higher production rates possible. Since transportation energy was amortized over the parts produced, it was found to be small relative to manufacturing and use phases. The use phase dominated the total emissions, varying from 70-90% of the Bridgeport's emissions and 60-85% of the Mori Seiki's emissions.

V. CONCLUSION

This life-cycle energy consumption analysis of two milling machines placed in three environments has quantified the CO_2-equivalent emissions associated with producing a standardized part over the lifetime of a machine tool. Several findings show significant differences from previously published literature, such as the manufacturing phase impact. However, the manufacturing phase results are a lower bound since they rely on an embodied energy approach that may neglect the manufacture of the machines required for each fabrication step. Also, since HVAC and lighting requirements are a significant portion of the use phase emissions, future studies should use specific facility HVAC and lighting data since average national energy intensity data were used in this study.

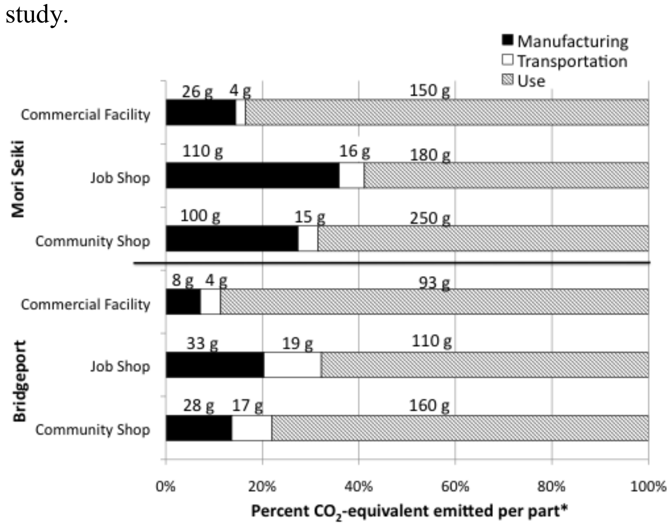

Fig. 4. CO_2-equivalent emitted per standard part produced with the Bridgeport and Mori Seiki in three manufacturing environments. (*) Values provided have units of grams of CO_2-equivalent emitted per part

In addition to the significant impacts of parameters that have been disregarded in the literature, the results suggest areas for reducing energy consumption. For example, a more energy efficient thermal control system could reduce the overall energy usage since HVAC is energy intensive. This analysis may also provide greater clarity to other LCA studies by highlighting potential impacts on a product's manufacturing phase since machine tools are key to manufacturing all other products. Finally, these results may be extended to other manufacturing processes by showing new areas to consider for energy and environmental impact reductions.

There were sources of error in this analysis that may be improved upon in future studies. For example, the manufacture of a machine tool is much more complicated with many steps that are more difficult to quantify than we present in this analysis. Also, material extraction and processing were influenced by aggregate effects since each machine tool component is made from several materials. Focusing on the use phase, labor was not considered due to its inherent complexity even though machine tools require operators and maintenance technicians, and the widget itself is simpler than many manufactured parts. In addition, the experiments performed to determine the energy consumed to produce a widget were limited by the available resources and thus likely employed process parameters that were not reflective of a true production run. Despite these sources of error, the analysis was designed to provide a broad initial assessment of energy consumption over the life of a machine tool. Future work will strive to improve the data used in this analysis as well as refine the analysis itself by incorporating other potentially significant factors. We hope to also extend this work to include other environmental impacts such as water [39] and more detailed work on end-of-life options (e.g. shredding [40]).

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