Lean energy analysis of CNC lathe

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Abstract. The industrial sector in Malaysia is one of the main sectors that have high percentage of energy demand compared to other sector and this problem may lead to the future power shortage and increasing the production cost of a company. Suitable initiatives should be implemented by the industrial sectors to solve the issues such as by improving the machining system. In the past, the majority of the energy consumption in industry focus on lighting, HVAC and office section usage. Future trend, manufacturing process is also considered to be included in the energy analysis. A study on Lean Energy Analysis in a machining process is presented. Improving the energy efficiency in a lathe machine by enhancing the cutting parameters of turning process is discussed. Energy consumption of a lathe machine was analyzed in order to identify the effect of cutting parameters towards energy consumption. It was found that the combination of parameters for third run (spindle speed: 1065 rpm, depth of cut: 1.5 mm, feed rate: 0.3 mm/rev) was the most preferred and ideal to be used during the turning machining process as it consumed less energy usage.

1. Background

Malaysia’s electricity demand continues to increase rapidly throughout the years and excessive use of the demand may leads to the future power shortage. According to the international energy agency (IEA), the energy demand in Malaysia has doubled in the past decade [1]. In year 2012, the energy consumption in Malaysia has reached up to 134 billion kilowatt-hours and are expected to rise by more than 3% throughout 2020. Peninsular Malaysia as a high demand center is currently facing fuel shortages especially in natural gas while the need for generation capacity is getting higher. Malaysia try to overcome the problems by modifying the portfolio of power generation fuels and reducing the use of expensive fuel sources.

As stated by the Energy Commission of Malaysia, the main source of power demand in Malaysia is controlled by industrial sector by 45% of the total in year 2012. The percentages for commercial and residential demand was 33% and 21%. The percentage of energy demand for transportation sector and agriculture sector is less than 1%. These conclude that major contribution of energy consumption is from the production area.

Fujishima, Mori and Oda [2] stated that highest rate of energy consumption was coming from the usage of machine tool compared to other manufacturing equipment. The implemented methods to reduce the energy consumption were by reducing the energy required by the machines, reduce the cycle time and reduce the idle time of machine. Energy consumption of a factory would become uncontrolled if daily usage of the energy was not being observe carefully. The waste of energy would leads to the loss of a production and company. As stated by Donelly, Kummer and Drees [3],
opportunities for energy efficiency can be identified by assessing the portfolio of a building and this method will lead to cost savings and improved building performance. Instead of that, energy analysis was one of the effective method to keep track on the energy consumption of the factory. Kuo, Fu & Cho [4] had stated several fundamental factors such as orientation, building area, total annual electricity consumption, and number of customer which are identified to affect the energy consumption of convenience store. Pramadona and Akhbar Adhiutama [5] mentioned that lean manufacturing system has been applied in industries for cost reduction and quality improvement and productivity by reducing variance and deficiency of product. Based on the Kisscock and Seryak [6], the lean energy method could be used to predict energy cost for every energy consumption, measures savings, and to determine cost structures. The energy consumption could be analyzed by using lean energy analysis based on several factor which affect the analysis such as buildings layout and weather. The standby period is when the machine is halted and not performing any machining process. All activities such as coolant operation, servo motors, chip conveyor and displays are also stopped during the period. According to research made by Fujishima et al. [7], the average power consumption time for 10,000 units of machines was 268 hour/month and the average operation time was 150 hour/month. The difference was 118 hour/month and this was when the machines were in idle and halted.

This research was conducted to discuss about the approach of improving energy efficiency in a company by optimizing cutting conditions of the machine tools. The type of machine tool used in this research was an altered Mini Lathe Machine and the cutting parameters that were spindle speed (rpm), feed rate (mm/rev) and depth of cut (mm).

2. Problem Statement and Objectives
Energy sources has become one of the major factors that contribute to the increasing of the cost production of a company. The example of the energy consumption of a company are from facilities, space-conditioning and production-related components. These are among of the crucial aspect that usually being evaluated to improve a performance of a company. However, a focus is given to the production equipment such as machine tools as it stated the highest rate of energy consumption compared to other aspects in a production area. The improvement process of machine tools can be proposed in order to reduce the energy consumption of the machine tool to the minimum level.

Energy consumed the most during machining process of machine tool. However, the rate of energy consumption can be controlled if suitable cutting parameters are selected during the machining process. One of the effective ways to reduce energy usage during machining is by optimizing certain cutting parameters such as spindle speed (rpm), feed rate (mm/rev) and depth of cut (mm). By implementing this technique, energy efficiency of machine tool can be increased.

High amount of energy consumption could affect the production cost and this will lead to the company loss. Cost spent on waste will decrease the profit margin of a company. An applicable approach by enhancing the cutting parameters of machine tool is proposed to reduce the energy consumption and spending cost on the waste can be saved and thus will give benefit to the company in future.

The objective of this research: (1) to identify the techniques used for minimizing the energy consumption of turning machine. (2) to analyze the impact of the cutting parameters on energy consumption of turning machine tools, (3) to select the suitable cutting parameters which affect the energy consumption of turning machine and (4) to minimize the energy consumption of turning machine tools by enhancing the cutting parameters.

3. Methodology
The energy consumption of the machine tool can be analyzed by conducting several experiments on different aspects. In this research paper, the experiment is focusing on increasing the energy efficiency of the machine tool by optimizing the cutting conditions.
Optimization of the cutting conditions refer to the several factors that highly affect the energy efficiency of machine tool are generally caused by cutting parameter used during the machining process. The example of the cutting parameter includes feed rate, depth of cut, cutting speed, cutting condition and tool geometry. By optimizing certain cutting parameter, critical cutting condition that consumed high energy consumption can be identified and eliminated.

The type of machine used in the experiment is CNC Mini Lathe Machine. The main function of the machine is to machine or to cut small size of workpiece. The machine has two axis of the movement of tool and constant position of workpiece at spindle which are x-axis and z-axis. The movement of the stepper motors for the X-axis and Z-axis are controlled by using coding generated in Arduino software. The mini CNC turning machine is shown in the figure 1.

The type of workpiece used in the experiment is an acrylic material which is in a form of cylindrical rod. The acrylic materials are widely used in industrial applications as it provides good electrical properties, good chemical resistance, lightweight, good weatherability and high durability. Figure 2 shows the measurement of the workpiece used in the turning process. The diameter of the workpiece is 20 mm and the length is 60 mm. The main aim of the machining is to reduce the workpiece diameter to 14 mm and workpiece length to 57 mm.

![Figure 1. Mini CNC Lathe Machine](image1)

![Figure 2. Work piece Measurement](image2)

A voltage and current detector device is built to detect a current and voltage flow of lathe machine during machining process. The device consists of several main components such as Arduino board, screen display, current sensor and voltage divider. The device is connected to the motor to detect the amount of current and voltage flow through it. The current and voltage value of the motor are later shown on the display screen. In addition to that, power consumption and cycle time are also displayed on the screen.

The type of the Arduino board used in the device is UNO R3. The board consists of several features as shown in table 1. Another main component of the device is a current sensor. The type of the current sensor used in the circuit is a 50A Current Sensor (AD/DC). The specification of the current sensor is also shown in table 1.

| Board Specification | Sensor Specifications: |
|---------------------|------------------------|
| 6 Analog Inputs     | Peak Measuring Voltage:3000V(AC),500V(DC) |
| 32k Flash Memory    | Sensitivity:40 mV/A |
| 16Mhz Clock Speed   | Operating Temperature: -40~150°C |
| 14 Digital I/O Pins (6 PWM outputs) | Dimension:34x34mm |
Input voltage 7-12V
ATmega328 microcontroller
Operating Voltage (analog): 5V
Current Measuring Range: -50~50A

The current sensor used in the circuit gives an ability to the user to monitor current flow in the circuit especially for energy saving purposes. The example of the current sensors are shown in figure 3 and figure 4.

![Figure 3. Arduino Board and Current Sensor](image1)

![Figure 4. Voltage and Current Sensor](image2)

Furthermore, voltage divider also holds an important function in the device. The function of the voltage divider used in the circuit is to convert large amount of voltage into a small value of voltage. It consists of two different values of resistors which are $R_1$ and $R_2$. The value of $R_1$ is set as 0.46 kΩ and $R_2$ is unknown. The voltage divider formula is used to find the value of the $R_2$:

$$V_{out} = \frac{V_{in} \times R_2}{R_1 + R_2} \tag{1}$$

The given values of $V_{out} = 5$ V, $V_{in} = 12.6$ V and $R_1 = 0.46$ kΩ. $R_2$ is solved by substituting the given values in the formula. $R_2$ is calculated by using Equation (2):

$$R_2 = -\frac{V_{out} \times R_1}{V_{out} - V_{in}} - R_1 \tag{2}$$

The value for $R_2$ is 0.303 kΩ and as the nearest value of resistor available is 0.21 kΩ, the value of $R_2$ is set as 0.21 kΩ. Both of the transistors ($R_1$ and $R_2$) are connected in a series connection in the circuit.

Figure 5 shows the block diagram of the turning process. The noise factors consists of the absent of coolant during machining and the hardness of the material work piece. The control factors represent the cutting parameters such as depth of cut (mm), feed rate (mm/rev) and spindle speed (rpm).

Table 2 shows the process parameter and the levels selected for the experiment. The type of operation performing by the mini lathe machine is turning operation. This process is a process of metal removal from the work piece to produce flat surface. All possible combinations of operation need to be carried out during the experiment to analyze the effects on power and energy consumption. Taguchi’s orthogonal array technique is implemented to compose the operation combinations.
Design-Expert 9.0.6 software is used to generate the experimental design and L9 Taguchi’s orthogonal array technique is selected to compose the operation combinations. The technique consists of nine operation combinations and three experiment trials.

4. Power measurement system
The data for average current and voltage during the turning process are monitored by using two multimeters which are directly connected to the motor circuit of the machine. The first multimeter is connected in series to detect the amount of current used during process. The second multimeter is connected in parallel to detect the amount of voltage used during the process. This is one of the method used to measure the voltage and current flow of the motor besides using the detector device. This method is suggested when the measured voltage is very high. The average power can be obtained by calculating the value of voltage and current using the Power formula as shown in Equation (3):

\[
Power (W) = Voltage (V) \times Current (A)
\]

(3)

The cycle time for each operation is also recorded in order to obtain the rate of energy consumed by the lathe machine for each operation.

5. Result and Discussion
The data collected for the experiment is tabulated in the table 3. The table contains four main columns which are Parameter, Power Demand (Watt), Cycle Time (Sec) and Energy (Joules). The parameter column consists of three cutting parameters which are A, B and C. The parameter A represent spindle speed (rpm), the parameter B represent depth of cut (mm) and the parameter C represent feed rate (mm/rev).

The Power Demand column is divided into P1, P2, and P3 which consists of the amount of power consumption for three trial of experiments. P (Average) is an average amount of power consumed by the machine for three trials of experiments. The Cycle Time column is referring to the total time required for each machining process to complete. The cycle time is recorded and energy consumption is calculated.

Table 3. Experimental Data of Power Consumption during Machining
The energy consumption for each of the machining process is calculated by multiplying the average of power consumption and cycle time (Sec). This calculation is simplified by using Energy Formula as shown in Equation (4).

\[
\text{Energy (Joules)} = \text{Power (Watt)} \times \text{Cycle Time (Sec)}
\]

(4)

The information about the machining process can be analyzed by plotting the data in form of graph as shown in figure 6. The type of graph plotted is main effects graph which is used to examine the trend pattern of each of the parameters selected. The relationship of graph is between the cutting parameter and power consumption.

According to the slope of the graphs, it shows that all of the selected cutting parameters give effect towards the energy consumption. However, the cutting parameter of depth of cut and feed rate are highly influence the amount of energy usage during machining process. The statement agreed with the research done by Camposco-Negrete et al. [8] which mentioned that the depth of cut and feed rate give the most impact towards the response.

As referring to the graph for spindle speed, as the value for spindle speed increased, the value for power consumption is also increased. This is because high force is needed to move the motor spindle faster. Hence, the energy consumption can be reduced by using the low level of spindle speed during the machining.

In addition to that, the parameter of cutting depth also affects the amount of power consumed during the machining. Based on the figure 6, the trend for power consumption increased as the cutting depth increased. This is cause of high force is needed to remove the part of material. This correspond with the research done by Camposco-Negrete et al. [8] which mentioned that the system required to consume more power as high force is needed to cut the material because of the increment of cutting depth value. As to reduce the power usage during machining, minimum value of depth of cut is recommended to cut the workpiece.

Another cutting parameter that influences the rate of power consumption during machining process is feed rate. Referring to the figure 6, when the value of the feed rate increased, the amount of power consumption decreased. This relationship happened caused by the reduction of cycle time. High amount of material being cut per revolution will reduce the time taken, thus less amount of power required to complete the process.
Figure 6. Main Effects Graph (Power vs Cutting Parameter)

The SN ratio graphs were used to examine the variation of cutting parameters towards power consumption. The type of signal-to-noise ratio selected in this experiment is Smaller-The-Better characteristic as the main aim of this experiment is to minimize the energy consumption in the machining process. The levels minimize the power consumption and ensure that the process stay within the target value. The final equation in terms of actual factors for the model is as shown in Equation (5). The equation can be used to predict the value of the energy usage for the each level of factors.

\[
Energy = -538.87533 + 2.07080 \times \text{spindle speed} + 6.38900 \times \text{depth of cut} + 5378.51633 \times \text{feed rate} - 0.76517 \times \text{spindle speed} \times \text{depth of cut} - 4.05866 \times \text{spindle speed} \times \text{feed rate}
\]

(5)

6. Conclusion

Industrial sector is one of the major sectors that contribute to the high power demand in the world. It is important for the sector as electrical energy is required to move the machine tools in manufacturing a product. However, uncontrolled amount of power demand may lead to the power shortage and environmental impact in future. Thus, another alternative need to be implemented in order to minimize the energy consumption.

The main purpose of the research is to reduce the energy consumption of the machine tools by enhancing the cutting parameters. The type of cutting parameters selected in the experiment is spindle speed (rpm), depth of cut (mm) and feed rate (mm/rev). The amount of energy consumption for each combination parameters may not be the same although it has the same amount of material removed. This research concluded that the third run consumed the least amount of energy usage while machining the workpiece. The run consists of the parameter combination of:

- Spindle speed: 1065 rpm
- Depth of cut: 1.5 mm
- Cutting depth: 0.3 mm

By implementing the selected parameter combination, the energy efficiency of machining process is improved and thus, energy usage can be saved.

Nonetheless, there are also some limitation occurred during conducting the experiments. The type of workpiece used for this experiment is different to the past research which may cause some variation in
results. Moreover, there are also some difficulties in handling the lathe machine as it has to be operated by generating the Arduino code. The movement of machine motor is may not be as accurate as the CNC software as the rotation of motor has to be manually calculated.

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