Prediction of energy consumption of numerical control machine tools and analysis of key energy-saving technologies

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Abstract
The objective of this study is to ensure the sustainable development of traditional machinery manufacturing industry under limited conditions of non-renewable energy, and reduce the environmental pollution caused by high energy consumption of machine tools. Here the energy consumption of numerical control machine tools is analysed, and the relevant energy-saving model is established. The energy consumption system of the numerical control machinery tools, including the cutting parameters, is classified. The relevant energy consumption prediction model is built to evaluate the influence of different cutting parameters, feed per tooth, and the back cutting depth on the energy consumption of numerical control machine tools. The results show that classifying the energy consumption system of numerical control machine tools can effectively predict the energy consumption of machine tools, which provides theoretical support for the subsequent energy-saving experiments. Larger cutting parameters will increase the energy consumption of numerical control machine tools, improve the energy efficiency of machine tools at the same time. Thus, reducing the feed per tooth and the back cutting depth can effectively decrease its energy consumption. The results of this study provide data support and guidance for the energy-saving experiments and practical applications of numerical control machine tools.

1 | INTRODUCTION

With the unceasing development of heavy industries, the application of numerical control machine tools is more and more extensive throughout the world. It can be seen that numerical machine tools are responsible for almost 75% of the total industrial electricity consumption as shown in Figure 1 [1]. Numerical control machine tool is a kind of control technology that connects computer to the machine tool, and by controlling the movement of the machine tool, the computer can process the parts according to the shape and size on the drawing [2,3]. It mainly includes the processing programme carrier, numerical control device, servo drive device, machine tool body, and other auxiliary devices [4]. The high machining accuracy of numerical control machine tools can improve the quality of products. Its multi-coordinate linkage reduces the time required for processing to improve production efficiency.

At the same time, its high degree of automation reduces labour intensity and management cost as well as the risk factor of workers’ operation, which enables the continuous development in the world's industrial technology [5,6]. However, the utilisation rate of numerical control machine tools is relatively low, and the energy consumption is huge. This is the major reason of continuous decay in energy intensity (amount of energy required to produce one unit of economic output) of the industry sector as shown in Figure 2, which presents new problems for sustainable energy development [7,8].

The outbreak of the industrial revolution led to the continuous rise of modern technology, and the continuous expansion of energy consumption led to the continuous reduction of the non-renewable energy. Meanwhile, the continuous emission of carbon dioxide and other harmful gases have seriously affected the ecological environment. At present, all countries are formulating corresponding policies to solve the current environmental problems [9,10]. Among them, the traditional machinery manufacturing industry is the biggest energy-consuming industry at present which consumes more than half of the total energy every year. Numerical control
machine tool is an indispensable machine in the mechanical manufacturing industry, and its involvement is expected to further increase in upcoming years. Data represented in Figure 3 highlight this fact [11]. It is known as the ‘mother of work’ and is the energy-consuming giant of the traditional manufacturing industry [12,13].

China is the world’s largest consumer of machine tools. The annual demand for machine tools is about eight million, and the total power can reach more than 70 million kW, in which the total energy consumption is very huge [14]. Studies have shown that the amount of carbon dioxide produced by a numerical control machine under normal operating conditions is equivalent to the emissions of more than 70 cars [15], which is the major contributor to air pollution being the fourth ranking major cause of deaths as shown in Figure 4 [7]. Recently, all countries have increased their research efforts to reduce the energy consumption of numerical control machine tools to solve the problem of high energy consumption. However, no practical and reliable scheme can be used in actual production. Therefore, in this study, an experimental scheme is designed to explore the energy consumption factors of machine tools and provide corresponding energy-saving measures.

To sum up, in order to save and reduce the energy consumption of numerical control machine tools, in this research, the energy consumption system of numerical control machine tools is classified, and the energy consumption of each system is predicted. According to the obtained results, an energy-saving scheme has been proposed, and a model has been established to evaluate the feasibility of the scheme, which provides data support for solving the problem of energy consumption of machine tools in actual production and an experimental scheme for energy saving and emission reduction.

The paper is organised as follows. Section 2 covers a detailed description of the literature reviewed. In Section 3, various ways of energy consumption are discussed, and parameters are selected for the proposed model. In Section 4, we have discussed models for energy decomposition and energy consumption. Based on that discussion a model was proposed in this section and the effects are studied taking a sample iron material. Section 5 concludes this paper.

2 | LITERATURE REVIEW

To provide an effective solution for the energy consumption problem, some of the relevant literature was studied, and it has been found that the energy consumption model of a machine tool can be instrumental in solving these problems. Zhao et al. [16] have proposed a model to optimise the design of the CNC machine tool for energy saving. But that was for the moving components of the CNC. Another work has provided the energy consumption model by Li et al. [17], but that work was particularly dedicated for hand to process material turning. Similarly, Hu et al. [18] have proposed a model energy efficiency evaluation model based on the energy that has been considered the thermal stability. Bilga et al. [19] have also proposed a method for the optimising the process parameters.

It is a knowledge-driven method of adaptively optimising process parameters, but that was dedicated to the energy-efficient turning. Similarly, Wang et al. [20] has proposed a Taguchi method, studied how turning parameters can affect the energy consumption of machine tool and concluded that three most crucial factors for energy consumption are, feed rate, cutting speed, and cutting depth.

FIGURE 1 Percentage of machining in industrial electricity consumption (Source: EIA, 2011 annual energy review) [1]

FIGURE 2 Energy intensity decay over the years (Source: Our World in Data) [5,6]
Gupta et al. [21] has performed the ANOVA analysis and carried out an experimental design to conclude that tool rake, cutting speed and chip thickness also affect the energy consumption of the machine tool. They have further concluded that plastic deformation energy was inversely proportional to the cutting speed. Similarly, Li et al. [22] have carried out turning experiments based on RSM and found how cutting fluid types and cutting parameters affect tool wear, cutting force and surface roughness. Another similar work was carried by Mull et al. [23]. They proposed a multi-objective model of various cutting parameters on cutting efficiency and energy consumption by combining the response surface method with the Taguchi method.

In another referred article, authors have found surface roughness and specific energy consumption of machine tools as important indicators for the evaluation of energy consumption and surface quality. The more accurate prediction will result into more accurate optimisation and least energy
consumption. Authors have further explained that one cannot avoid tool wear but the consequences may be minimised; therefore, a model has been proposed for the specific kind of energy consumption of machine tools, keeping special attention to the tool wear evolution. Authors have considered tool flank wear, spindle speed, feed rate and cutting depth as input variables and used orthogonal experimental results as training points for developing their model. The use of support vector regression algorithm was done for the model. In addition to this, authors have performed several experiments for the validation of the proposed model and verified the simulation results [24].

3 | METHODS

In this section, a detailed discussion has been exploited to show various methods and their applications in the energy consumption of numerical control machine tool.

3.1 | Energy consumption model of numerical control machine tool

According to the different tasks of each part, the numerical control machine tool can be divided into the machining power system, auxiliary system, and electrical control system. From all these, the machining power system includes the spindle drive (drive the tool or workpiece to do high-speed rotating motion and provide cutting power) and the feed drive (drive the tool or workpiece to do linear motion along the direction of the feed axis). The auxiliary system includes heat-removal system (fan), cooling system (cooling pump), tool changing system (motor), and chip removal system (chip removal machine), which is mainly responsible for the peripheral adjustment of the electromechanical system. The electrical control system includes a numerical control device (calculator display), spindle control (spindle driver), and feed shaft control (feed shaft driver). It is mainly responsible for data processing and the transmission of numerical control instructions for spindle and feed shaft. Figure 5 is a schematic diagram of the energy-consuming components of the numerical control machine tools [25].

Because the energy dissipation system of numerical control machine tool is complex, it is classified and different calculation models are established. The auxiliary system only plays peripheral auxiliary functions in the machine tool, such as lighting, cooling, and heat removal, so its energy consumption is only related to the working time of its operation, and its calculation formula is as follows [26]:

\[
E_{aux} = E_{computer} + E_{light} + \cdots + E_{cool} = \sum_{i=1}^{n} g_i(t_i \times p_i)
\]

Compared with the auxiliary energy-consuming system, the processing power system consumes a lot of energy and has many complicated links. The amount of energy consumption depends not only on the operating parameters of the electromechanical system but also on the size of its load. Its energy consumption formula is as follows:

\[
E_{driven} = \int_{t_1}^{t_2} p_a(t)dt = \int_{t_1}^{t_2} (p_u + p_{cut} + p_d)dt
\]

The above formula is reorganised as follows:

\[
E_{driven} = \int_{t_1}^{t_2} f(n, n_w) + g(C, a_p, f, v) + b(p_{cut})dt
\]

The symbols’ meanings in the above formula are shown in Table 1:

3.2 | Selection of energy consumption parameters

The main energy-consuming system of numerical control machine tool is the processing power system. According to the energy consumption equation of the machining power system, its operation mode is mainly controlled by different parameters, and when the set parameters are different, the energy consumption is also different. The cutting power is mainly determined by the cutting parameters, and the cutting speed, cutting time, and cutting thickness are directly proportional to the energy consumption of the machining power system. At the same time, the no-load energy consumption of the machine tool is also affected by the cutting parameters, which means that the machine tool does not perform the energy consumed in the cutting process under the premise of normal operation. The cutting parameters also indirectly affect the cutting environment. According to the different cutting parameters, the cutting temperature would be different to change the external condition of the tool and affect the energy consumption of the machine tool. The feed per tooth \( f \) and the back cutting depth also determine the energy consumption of numerical control machine tools. Therefore, these three parameters are selected for analysis to explore the influence of different given parameters on the energy consumption of numerical control machine tools [27].

3.3 | Energy-saving measures for numerical control machine tools

The numerical control machine tool CKD6150 is selected to study the energy consumption performance of the machine tool. The cutting speed, the feed per tooth, and the back cutting depth are selected as variables. Under the same other conditions, different cutting speed parameters are set to analyse the influence of different cutting speeds on the efficiency and energy consumption of the machine tool and to explore the influence of feed per tooth and the back cutting depth on the
numerical control machine tool under the same given conditions. The obtained data are analysed to explore the influence of different machine tool parameters on the energy consumption of the machine tool, and the corresponding measures for energy saving of the numerical control machine tool are found [16].

### RESULTS

In this section, the detailed results have been discussed for the various models for the energy consumption. A detailed discussion of proposed model was presented with various performance parameters as follows:

#### TABLE 1  Meaning of formula letters

| Symbols | Meaning |
|---------|---------|
| $E_{aux}$ | Energy consumption of the auxiliary machining system of machine tool |
| $E_{computer}$ | Energy consumption of the numerical control system |
| $E_{light}$ | Energy consumption of the lighting system |
| $E_{cool}$ | Energy consumption of the cooling system |
| $p_i$ | Power of the energy-consuming subsystem |
| $t_i$ | Run time |
| $g_i$ | On the state of energy consumption subsystem in operation or not in operation |
| $p_{cut}$ | The output cutting power of the machining system |
| $p_d$ | Total power of the main drive system |
| $p_a$ | Loss power of the additional load |
| $V$ | Cutting speed |
| $H$ | Cutting thickness |
| $n_w$ | Speed of the feed shaft |
| $T$ | Cutting time |
| $F$ | Feed per tooth |
| $d_p$ | Back cutting depth |
4.1 Energy decomposition of a numerical control machine tool

The energy consumption of a numerical control machine tool is the product of time and power and is given by the area under the machine tool power load curve as shown in Figure 6. This figure shows that the entire curve is divided into several parts, representing different ways of energy consumption. According to the research requirement and the desired workflow, the energy consumption can be divided by various factors such as composition function, component energy consumption attributes and operation status, considering the limitations of the system energy consumption that all the possible sources can not be included in the presentation. Sometimes certain assumptions are to be made, within certain limits for the sake of simplicity. As in some cases, it has been observed that certain researchers have assumed constant spindle speed in the machining process, and some have ignored the energy consumed by the feed unit [28].

4.2 Prediction and analysis of energy consumption of numerical control machine tools

To explore the energy consumption of numerical control machine tools, they are divided into different energy consumption systems. Among them, the energy consumption of the auxiliary system is mainly affected by the external lighting system, refrigeration, heating, and other devices. Therefore, to improve the energy consumption of this part, paying more attention is required for saving the electrical energy. [29].

Figure 7 shows that the energy consumption of the numerical control machine tool constitutes the parts such as machining power system. The energy consumption of its power system is mainly determined by the relevant performance parameters. It is found that the energy consumption equation of the processing power system is different from the energy consumption. All the parameters in the equation are positively proportional to their energy consumption. Therefore, the energy consumption of numerical control machine tools can be increased or decreased by changing the related parameters. For example, reducing the cutting parameters, feed per tooth, and back cutting depth may reduce the energy consumption of the machine tool, which provides theoretical support for the subsequent energy-saving measures. Figure 7 shows the influence factors of energy consumption of numerical control machine tools. It can be observed from the figure that the main energy consumption factors of numerical control machine tools are the no-load energy consumption and the cutting energy consumption. However, the cutting data and back cutting depth under the main drive system and servo system are the main factors that affect cutting energy consumption. The influence of the characteristics of the numerical control machine tool on the no-load energy consumption of the machine tool needs to be evaluated on the production materials and production process of the machine tool to minimise the influence of the characteristics of the machine tool on the energy consumption.

4.3 Influence of cutting parameters on energy consumption of numerical control machine tools

Taking CKD6150 numerical control machine tool as the model, the influence of cutting parameters on energy consumption of the numerical control machine tool is studied. When the conditions are fixed, different cutting speeds are set and the energy consumed by the machine tool is calculated by Equation (2). Figure 8 shows the actual energy consumption of machine tools at different cutting speeds. It can be observed from the figure that when the cutting speed is 60 mm/min, the energy consumption of the numerical control machine tool is about 1.5 J. However, as the set speed different, its energy consumption is also increasing, which indicates that the larger is the cutting speed, the higher will be the energy consumption of the machine tool. Therefore, choosing a lower cutting speed
can achieve the function of saving the energy of the machine tool.

Figure 9 shows the influence of different cutting depths on the loss of the machine tool. It can be observed from the figure that when the depth of the machine tool is 0.8 mm, the power loss of the machine tool is about 14 W. When the depth increases to 1.8 mm, the power loss is about 85 W, which increases by almost six times. From this, it can be concluded that the increase in the cutting depth makes the loss of the machine tools constantly increase, which indirectly affects the energy consumption of the machine tools and increases the energy consumption of the machine tools. Therefore, a reasonable cutting depth setting can achieve the effect of energy-saving numerical control machine tools.

In conclusion, by changing the cutting parameters (cutting speed and cutting depth) to calculate the energy consumption of the machine tool, the corresponding increase in cutting parameters will increase the energy consumption of the machine tool, which provides data support for saving the energy of the machine tool.

### 4.4 Effect of other parameters on energy consumption of numerical control machine tools

According to the calculation equation of energy consumption of the numerical control machine tool and the reason of energy
consumption, a practical model is established to discuss the influence of machine tool parameters on the energy consumption of the machine tool. The feed per tooth and back cutting depth are taken as the input value of the model, and the energy consumption of the numerical control machine tool is taken as the output value. The iron block is selected as the raw material for processing, the cutting speed of the machine tool is set to 100 mm/min, and the tool cutting edge angle is set to 90°.

Table 2 shows the energy consumption of the machine under different values. It can be observed from the table that with the increase in the back cutting depth, feed per tooth, and cutting width, the energy consumption of numerical control machine tools also increases. Especially, when the cutting width is increased to 9 mm, the back cutting depth is increased to 1.8 mm, and when the feed per tooth is 0.6 mm/r, the energy consumption expansion rate is significantly increased from 1.8 J to about 4.5 J. This shows that setting different machine parameters will have a greater impact on the energy consumption of the machine tools, and selecting relatively small parameters without affecting the cutting process can achieve the purpose of saving energy.

### 5 CONCLUSION

In recent years, environmental problems have been the focus of the world’s attention. The impact of energy suppliers such as coal and oil on the environment should not be underestimated. The emission of CO₂ and other harmful substances has seriously affected our ecological environment. Therefore, reducing energy consumption is one of the effective means to control pollution. Machine tools, as the mother of industry, consume a huge amount of energy every year and emit immeasurable harmful gases. Therefore, research on saving energy of numerical control machine tools should be strengthened to ensure the development of heavy industry in China, so that the machinery manufacturing industry can develop sustainably without damaging the environment. The numerical control machine tool is composed of several parts, and the energy consumption of each part is quite different due to the different functions of each part. However, the calculation of energy consumption of the power processing system is relatively complex. After the energy consumption is converted into a mathematical equation, it is found that the main energy consumption is determined by the relevant parameters. Then, the model is used to further analyse the relevant parameters. When the cutting parameters, feed per tooth, and back cutting depth increase, the energy consumption of the machine increases, which shows that the purpose of saving energy can be achieved by controlling the parameters of the machine tool.

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**REFERENCES**

1. Li, B., et al.: Research on modal analysis method of CNC machine tool based on operational impact excitation. Int. J. Adv. Manuf. Technol. 103(1), 1–20 (2019)
2. Zhou, L.R., et al.: Energy consumption model and energy efficiency of machine tools: a comprehensive literature review. J. Clean. Prod. 112 (2015). [https://doi.org/10.1016/j.jclepro.2015.05.093](https://doi.org/10.1016/j.jclepro.2015.05.093)
3. Ping, J., et al.: Energy consumption model and energy efficiency evaluation for CNC continuous generating grinding machine tools. Int. J. Sustain. Eng. 10(3), 1–7 (2017)
4. Jiung, Z., et al.: Electrical energy consumption of CNC machine tools based on empirical modelling. Int. J. Adv. Manuf. Technol. 100(1), 2255–2267 (2019)
5. Sihag, N., Sangwan, K.S., Pundir, S.: Development of a structured algorithm to identify the status of a machine tool to improve energy and time efficiencies. Procedia. CIRP. 69, 294–299 (2018)
6. Ritchie, H.: Energy (2014). Published online at OurWorldInData.org. [https://ourworldindata.org/energy.](https://ourworldindata.org/energy.) [Online Resource]
7. Faizrakhmanov, R.A., et al.: Optimization of the energy consumption of a CNC machine cutting tool with hard-to-formalise restrictions. Russ. Electr. Eng. 88(11), 701–705 (2017)
8. Jintong, X.U., et al.: An energy consumption model and experimental research of numerical control machine tools. J. Cent. South Univ. 48(8), 2024–2033 (2017)
9. Shabir, L., Weber, J., Weber, J.: Analysis of the energy consumption of fluidic systems in machine tools. Procedia. CIRP. 63, 573–579 (2017)
10. Ronan, Ye: CNC Machining Industry Trends, (2019). [https://www.3erp.com/blog/cnc-machining-industry-trends-2019/](https://www.3erp.com/blog/cnc-machining-industry-trends-2019/)
11. Tao, J., Liu, F., Liu, P.: Key performance indicators for assessing inherent energy performance of machine tools in industries. Int. J. Prod. Res. 57(9), 1–14 (2018)
12. Msukwa, M.R., Uchiyama, N.: Design and experimental verification of adaptive sliding mode control for precision motion and energy saving in feed drive systems. IEEE Access. 7, 1–1 (2019)
13. Wang, H., Zhang, C., Liu, R.: Estimation method of CNC machining energy consumption based on step-NC. Comput. Integr. Manuf. Syst. 23(3), 498–506 (2017)
14. Li, H., Sun, L.: Design of testing period for reliability assessment of numerical control machine tools considering working conditions. Math. Probl. Eng. 2018, 1–8 (2018)
15. Ji, Q., et al.: Structural design optimization of moving component in CNC machine tool for energy saving. J. Clean. Prod. 246, 118976 (2020)
16. Zhao, G., et al.: Prediction model of machine tool energy consumption in hard-to-process materials turning. Int. J. Adv. Manuf. Technol. 106(9), 4499–4508 (2020)
17. Li, B., et al.: Exergy-based energy efficiency evaluation model for machine tools considering thermal stability. Int. J. Precis. Eng.
18. Hu, L., et al.: Optimisation of cutting parameters for improving energy efficiency in machining process. Robot. Comput. Integr. Manuf. 59, 406–416 (2019)
19. Bilga, P.S., Singh, S., Kumar, R.: Optimization of energy consumption response parameters for turning operation using Taguchi method. J. Clean. Prod. 137, 1406–1417 (2016)
20. Wang, B., et al.: Proper selection of cutting parameters and cutting tool angle to lower the specific cutting energy during high speed machining of 7050-T7451 aluminum alloy. J. Clean. Prod. 129, 292–304 (2016)
21. Gupta, M.K., Sood, P.K., Sharma, V.S.: Optimization of machining parameters and cutting fluids during nano-fluid based minimum quantity lubrication turning of titanium alloy by using evolutionary techniques. J. Clean. Prod. 135, 1276–1288 (2016)
22. Li, L., et al.: Influence factors and operational strategies for energy efficiency improvement of CNC machining. J. Clean Prod. (2017). https://doi.org/10.1016/j.jclepro.2017.05.084
23. Mull, J-E, et al.: A new tailored solution to predict blow efficiency and energy consumption of hammer-forging machines. Int. J. Adv. Manuf. Technol. 111, 1941–1954 (2020). https://doi.org/10.1007/s00170-020-06237-2
24. Su, Y., et al.: Prediction models for specific energy consumption of machine tools and surface roughness based on cutting parameters and tool wear. Proc. IME B. J. Eng. Manufact. (2020) 0954405420971064
25. Jia, S., Qinghe, Y.U.A.N.: Method of accurately predicting energy consumption of automatic tool change for multi-position rotary tool holder of numerical control machine. U.S. Patent No. 10,691,098 (2020)
26. Lv, Y., et al.: Towards lightweight spindle of CNC lathe using structural optimization design for energy saving. In: 2020 IEEE 16th International Conference on Automation Science and Engineering (CASE). IEEE (2020)
27. Zhao, G., et al.: Specific energy consumption prediction model of CNC machine tools based on tool wear. Int. J. Comput. Integr. Manuf. 33(2), 159–168 (2020)
28. Himeur, Y., et al.: Building power consumption datasets: Survey, taxonomy and future directions. Energy Build, 110404 (2020)
29. Farazjou, F., Mahmoudi Zarandi, M.: The necessity of parametric system design optimization building physics treats based on the amount of energy consumption in residential buildings. Eurasian Journal of Biosciences. 14(2), 5543–5553 (2020)

How to cite this article: Qiang H, Ikbal MA, Khanna S. Prediction of energy consumption of numerical control machine tools and analysis of key energy-saving technologies. IET Collab. Intell. Manuf. 2021;1–9. https://doi.org/10.1049/cim2.12001