Energy Engineering
DOI:10.32604/EE.2020.010706
Article

An Energy Efficiency Improvement Method for Manufacturing Process Based on ECRSR

Haiming Sun[1,3], Quande Dong[2,*], Cuixia Zhang[2] and Jianqing Chen[3,4]

[1]School of Mechanical Engineering, Hubei University of Automotive Technology, Shiyan, 442002, China
[2]School of Information Engineering, Suzhou University, Suzhou, 234000, China
[3]School of Mechanical Engineering, Hefei University of Technology, Hefei, 30009, China
[4]School of Engineering, Huzhou University, Huzhou, 313000, China
*Corresponding Author: Quande Dong. Email: szxydqd@163.com
Received: 22 March 2020; Accepted: 09 June 2020

Abstract: The improvement of energy efficiency is considered as one of the keys to the sustainable development of manufacturing enterprises. This paper proposes an energy efficiency improvement method for the manufacturing process. Based on the analysis of the characteristics of energy consumption in the manufacturing process, a necessary energy consumption model, an assistant energy consumption model and an ineffective energy consumption model are constructed for identifying the energy consumption attributes of the manufacturing process. Then, the relationship model of energy consumption is built, and the energy efficiency improvement method for the manufacturing process is proposed based on ECRSR (Elimination, Combination, Rearrangement, Simplification and Recovery). Finally, an injection molding machine in a workshop is studied as a case. The results show that the average hourly power-saving rate of a single machine is 37.3%, and the average power-saving rate per piece is 30.9%. This paper provides a feasible method for improving energy efficiency of the manufacturing process from the perspective of IE (Industrial Engineering), and provides both theoretical and methodological support for the sustainable development of the manufacturing industry.

Keywords: Energy efficiency; manufacturing process; improvement; sustainability

1 Introduction

The manufacturing industry is regarded as the pillar industry to create human wealth [1]. However, in the process of transforming manufacturing resources into products, the manufacturing industry consumes energy, which is also one of the main causes of the current serious global environmental problems [2]. The energy consumption of the manufacturing process across the world accounts for 75% of the energy consumption of the manufacturing industry [3]. The energy efficiency of the manufacturing process is very low. The average energy efficiency is less than 30% [4]. At the same time, emissions caused by energy consumption in the manufacturing process have a huge impact on the environment. Gutowski found that the emission of CO_2, SO_2 and NOx caused by the energy consumption of a machine tool running for one year is equivalent to that of 61, 248 and 34 SUVs (Sport Utility Vehicles) respectively [5]. The energy consumption and environmental problems in the manufacturing industry have attracted extensive attention [6,7].

Many experts have studied energy efficiency of the manufacturing process. A virtual machine tool to optimize machining to reduce energy consumption during machining was proposed by Lee et al. [8], and the total energy consumption of the machining process was reduced to 13%. Compared to empirical parameters, the processing time and the specific energy consumption can decline to 19.6% and 15.2% respectively through the method integrating Taguchi, RSM (response surface method) and MOPSO (multi-objective particle swarm optimization algorithm) with CNC (Computerized Numerical Control) machining parameters optimization [9]. An energy-efficient multi-objective optimization for the flexible job-shop scheduling problem is proposed by Mokhtari et al. [10], and the results revealed the importance of the total energy cost as an important objective function in the scheduling of production. The multi-objective optimization model for the machining process is proposed by Deng et al. [11], aiming at improving the energy efficiency and reducing carbon emissions in the machining process. Sangwan's research [12] showed that the reduction of energy consumption during the machining phase is extremely important for improving the environmental performance over the entire life cycle, and an optimization of machining parameters for improving energy efficiency with the response surface methodology and the genetic algorithm approach is studied. A comparison of the actual power consumption during machining with an energetic model of the load-free condition enables the calculation of energetic efficiency and primary processing time for an approach to determine relevant energy efficiency and productivity Key Performance Indicators (KPIs) of machining processes [13]. A considerable amount of energy is consumed by machine tools during run-time operation, such as tool change and tool path. The method of energy efficiency optimization based on tool replacement and tool path is studied by Hu et al. [14]. A novel approach for energy modeling and machining cycle optimization is introduced by Wójcicki et al. [15] for efficiency management in multi-machine manufacturing systems. An optimization-based control strategy for energy efficiency of discrete manufacturing systems is proposed to reduce the global energy consumption and avoid highest power peaks during operation of manufacturing systems by Diaz et al. [16], and reductions of nearly 7% could be achieved, allowing improvements in energy efficiency. Improving energy efficiency in manufacturing using peer benchmarking to influence machine design innovation is studied by Sheppard et al. [17]. Manufacturing companies are faced with the challenge of reducing energy consumption whilst maintaining or increasing profits and productivity, and then the development of modeling tools to improve energy efficiency in manufacturing processes and systems is studied by Mawson et al. [18]. A variety of effective energy management methods are put forward and developed, among which reducing energy consumption through reasonable energy production scheduling technology is a promising method [19]. Based on a sample of 236 German manufacturing companies, Schulze' research results proved that the extent of energy management control system implementation positively relates to firms' energy efficiency [20]. There are also some studies on improving the energy efficiency of the production process through equipment maintenance [21,22] and personnel [23]. Moreover, a novel methodology for energy audit developed and implemented by a large manufacturing company to overcome internal barriers to industrial energy efficiency is presented and discussed by Chiaroni et al. [24]. Industrial practices in some regions also show that energy efficiency of the manufacturing process is beneficial to the sustainable development of enterprises, such as California [25], China [26], Malaysia [27] Chile [28], Italy [29] and some developing countries [30].

Based on the analysis of the above-mentioned research results [31–33], the research status and limitations in this field are as follows:

- The existing research mainly focuses on the modeling, evaluation, optimization and energy-saving scheduling of the machining manufacturing system. Although a lot of achievements have been made, there is still a lack of research on the definition and recognition of energy consumption attributes in the manufacturing process.

- For optimal control of the mechanical manufacturing system, the main objectives of the existing research are energy efficiency, work piece quality and so on, and there is less research on comprehensive energy efficiency of the manufacturing process.

In the manufacturing process, the actual energy efficiency in product manufacturing is about 30%, and even lower in some manufacturing processes. Part of the energy is wasted in the process of energy conversion and transmission, which can be reduced or recovered through manufacturing process improvement. On the other hand, with the increasing pressure from energy and environmental protection, energy consumption has become an important factor affecting production costs, and has become the object of ecological policy pressure, affecting normal operation of enterprises. Therefore, it is of great theoretical and practical significance for the sustainable development of the manufacturing industry to re-examine the manufacturing process from the perspective of energy efficiency so as to cope with the increasingly serious energy crisis and environmental pollution.

In view of this, an energy efficiency improvement method for the manufacturing process is proposed in this paper. It both makes the theoretical contribution and has practical significance. The theoretical contribution is that the necessary energy consumption model, the assistant energy consumption model and the ineffective energy consumption model for manufacturing process energy are constructed. An energy consumption characteristic model of the manufacturing process is established to identify the process energy consumption attributes. Therefore, the degree of energy consumption in the manufacturing process is accurately quantified, and the energy efficiency improvement for the manufacturing process is designed. The practical value is that it can accurately tell the managers the status of energy consumption in each manufacturing process, provide quantitative data for the horizontal and vertical comparison of each process, and then provide guidance for the managers to identify where the energy efficiency is improved, and give the improvement guidance scheme. It provides practical method support for manufacturing enterprises to cope with the increasingly serious energy crisis and environmental pollution.

To achieve above-mentioned research goals, Section 2 describes the improvement method for energy efficiency for the manufacturing process. In Section 3, the method is verified by a case study, and the results show that the method can effectively improve energy efficiency and reduce energy consumption. Section 4 presents the conclusions.

2 Method

This section mainly discusses the methods, including (i) modeling of energy consumption in the manufacturing process, (ii) evaluation of process energy consumption and (iii) energy efficiency improvement method for the manufacturing process based on ECRSR.

2.1 Modeling of Energy Consumption in the Manufacturing Process

The manufacturing process refers to the combination of elements in the production process from raw materials to products. From the perspective of energy, the manufacturing process uses energy to make raw materials into products. Some of these energy sources are necessary for production, some are used to assist production, and the others are ineffective.

(1) Necessary energy consumption: from the perspective of product manufacturing, necessary energy consumption is the minimum energy in physical theory to ensure product manufacturing, independent of the manufacturing environment. For example, when the machine tool is being processed, the four stages are start-up, standby, no-load and processing, and only the processing stage is the effective energy consumption stage.

The calculation formula is:

$$En_F = \sum_{i=1}^{I} \int_0^t [\Delta s_i \times e(\Delta s_i)] \tag{1}$$

where Δs_i is the processing quantity of the work piece, such as the cutting thickness dimension and the milling depth dimension. $e(\Delta s_i)$ is the energy consumed in processing the Δs_i of the work piece.

(2) Assistant energy consumption: the energy consumed by the assistant measures used to realize the necessary energy consumption of product manufacturing, such as preheating, standby and start-up. The calculation formula is:

$$En_A = \sum_{j=1}^{J} \int_0^t [A_j \times e(A_j)] \tag{2}$$

where A_j is the j-th assistant production process, such as start-up and standby of machining processes. $e(A_j)$ is the energy consumed of production process A_j.

(3) Ineffective energy consumption: all ineffective energy consumption and assistant energy consumption are nonfunctional energy consumption, such as heat dissipation, waiting and other energy consumption that is invalid for equipment manufacturing products.

The calculation formula is:

$$En_I = En - En_F - En_A \tag{3}$$

where En_I is ineffective energy consumption, such as waiting and invalid operation during machining.

Formula (3) shows that ineffective energy consumption refers to energy consumption other than necessary energy consumption and assistant energy consumption in the manufacturing process.

The above-mentioned formula defines the energy use of the process and supports the improvement of the manufacturing process.

2.2 Evaluation of Process Energy Consumption

Based on the above-mentioned process energy consumption relationship modeling, the energy consumption is evaluated. The basis of the evaluation is that the input energy of components is En^i, and the output energy is $\{En^i_N,\ En^i_A,\ En^i_I\}$.

(1) Efficiency of Necessary Energy Consumption

The efficiency of necessary energy consumption is the ratio of the necessary energy consumption of the process to the total energy input $En^i$of the i-th manufacturing process.

$$p^i_N = \frac{En^i_N}{En^i} \tag{4}$$

where En^i_A is the necessary energy consumption of the i-th manufacturing process. En^i is the total energy input of the i-th manufacturing process.

(2) Efficiency of Assistant Energy Consumption

Efficiency of assistant energy consumption is the ratio of the assistant energy consumption En^i_A to the total energy input En^i of the i-th manufacturing process.

$$p_A^i = \frac{En_A^i}{En^i} \tag{5}$$

where En_A^i is the assistant energy consumption of the *i*-th manufacturing process.

(3) Efficiency of Ineffective Energy Consumption

Efficiency of ineffective energy consumption is the ratio of the ineffective energy consumption En_I^i to the total energy input En^i of the *i*-th manufacturing process.

$$p_I^i = \frac{En_I^i}{En^i} \tag{6}$$

where En_I^i is the ineffective energy consumption of the *i*-th manufacturing process.

We make the *i*-th manufacturing process have the following properties:

$$D = \left\{En^i, p_N^i, p_A^i, p_I^i\right\} \tag{7}$$

Formula (7) realizes the quantitative evaluation of the energy consumption status of each process.

This model provides support for identifying the energy consumption attributes of the manufacturing process. It clearly represents the necessary energy consumption, the assistant energy consumption and the ineffective energy consumption of the manufacturing process. It provides quantitative reference for horizontal and vertical comparison between processes, and provides evidence and basis for the improvement of process energy efficiency, and affords the decision basis for the energy efficiency of the manufacturing process.

According to Formula (7), we can work out the standard in energy efficiency improvement, that is, the effect of this improvement is better than the original one. The standard in energy efficiency improvement is set as follows:

$$\begin{cases} Improved\left(En^i\right) < Original\left(En^i\right) \\ Improved\left(p_N^i\right) \geq Original\left(p_N^i\right) \\ Improved\left(p_A^i\right) \leq Original\left(p_A^i\right) \\ Improved\left(p_I^i\right) \leq Original\left(p_I^i\right) \end{cases} \tag{8}$$

Formula (8) provides the standard basis for an energy efficiency improvement method for the manufacturing process; it is a direction for ECRSR.

2.3 Energy Efficiency Improvement Method

Based on the energy consumption modeling and the attribute evaluation of the manufacturing process, the energy efficiency improvement method for the manufacturing process based on ECRSR is worked out as follows (Fig. 1). ECRSR is the measures taken to process energy in the manufacturing process, mainly including elimination, combination, rearrangement, simplification and recovery. For ineffective energy consumption, it is necessary to eliminate it as much as possible. If it cannot be cancelled, it should be combined, simplified or recovered. For assistant energy consumption, it should be combined, rearranged, simplified or recovered as much as possible to reduce its use. For necessary energy consumption, it should be combined or rearranged to reduce assistant energy consumption and ineffective energy consumption. These measures can reduce energy consumption in the manufacturing process and optimize energy efficiency.

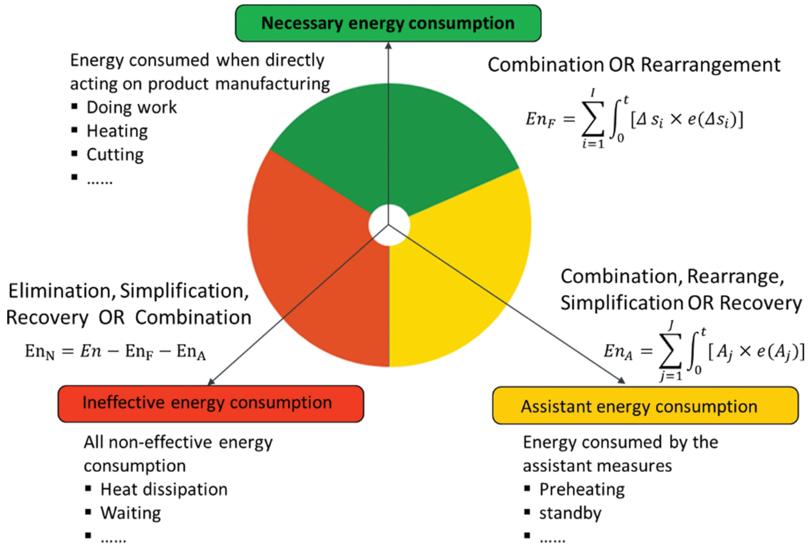

Figure 1: Energy efficiency improvement method

3 Case Study

3.1 Background

The injection molding machine in a workshop adopts hydraulic transmission and electro-hydraulic proportional control technology. The process of installing the hydraulic system of the quantitative pump is generally divided into mold locking, injection, dissolved colloid, pressure maintaining, cooling, mold opening, ejection and standby process stages (Fig. 2).

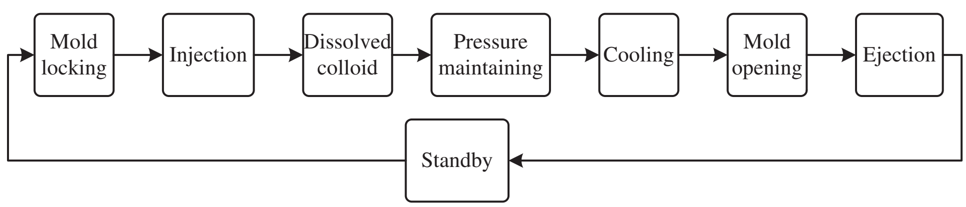

Figure 2: Process stages of installing the hydraulic system of the quantitative pump

Each stage needs different pressure and flow, so each process needs a different current. In addition to the high-pressure mold locking, injection and dissolved colloid, the pressure required by other processes is very small. Their pressure and flow are regulated by pressure proportional valves and flow proportional valves. In the hydraulic system of the positioning pump, the oil pump provides a constant current, and the redundant hydraulic oil flows back to the oil tank through the overflow valve. This process is a high-pressure throttling process. After testing, it is found that the electric energy loss is up to 50% (Tab. 1). In the production process, the constant hydraulic pressure can be reasonably combined through the control of the solenoid valve, and distributed to the flow and pressure required by each action, so as to achieve the injection molding purpose. Injection molding machine loads are a wide range of variable loads. The flow and pressure required for each process is very different. The motor efficiency is not only very low, but also wastes a lot of electric energy.

3.2 Results

In view of the working state and process design of an injection molding machine, it is difficult to achieve ideal stability and energy-saving effect by using ordinary energy-saving devices. About the criteria for the

Table 1: Process properties

Process properties	Mold locking	Injection	Dissolved colloid	Pressure maintaining	Cooling	Mold opening	Ejection	Standby
p_N^i	48%	55%	57%	17%	14%	11%	15%	5%
p_A^i	28%	24%	15%	25%	25%	20%	31%	13%
p_I^i	24%	21%	28%	58%	61%	69%	54%	82%

Table 2: Improvement mode for process stages

Processes	Improvement mode
Mold locking	Rearrangement and simplification
Injection	Rearrangement and simplification
Dissolved colloid	Rearrangement and simplification
Pressure maintaining	Combination and simplification
Cooling	Combination and simplification
Mold opening	Combination and simplification
Ejection	Combination and simplification
Standby	Elimination and recovery

use of the five energy management measures of a process, mainly a specific method of measuring the process energy consumption attributes is developed, and the measures in each stage are mainly determined by engineers according to the characteristics and data of the specific process. Based on the analysis of ECRSR, the pressure and current of each process are optimized by using an energy saver.

Therefore, an asynchronous servo energy saver is used to achieve efficient and stable control. The asynchronous servo energy saver is industrial energy-saving equipment, the specification is TD6000-1kw, and Suzhou Tengdayuan Electric Co., Ltd., is the manufacturer. The asynchronous servo economizer adopts multiple terminal signals. The proportional flow and pressure signals of an injection molding machine are the main feedback input signals of the energy saver. The proportional flow and pressure signals are used as the auxiliary input signals of the energy saver for fine-tuning to ensure the accurate and stable operation of the injection molding machine (Fig. 3).

X1: it is the negative end (V−) of the switch power supply on the injection molding machine controller. It is used as the operation signal of the energy saver. It can clearly indicate the state of energy saving.

X2: it is taken from the mold opening/locking signal on the controller of the injection molding machine to fine-tune the frequency of the economizer. It supports combination, rearrangement and simplification of this process.

X3: it is the injection signal from the controller of the injection molding machine to fine-tune the frequency of the economizer. It supports combination, rearrangement and recovery of this process.

X4: it is from the sol signal on the controller of the injection molding machine to fine-tune the frequency of the economizer. It supports combination, rearrangement, simplification and recovery of this process.

X5: it is from the mold opening signal on the controller of the injection molding machine to fine-tune the frequency of the economizer. It supports elimination, combination, and recovery of this process.

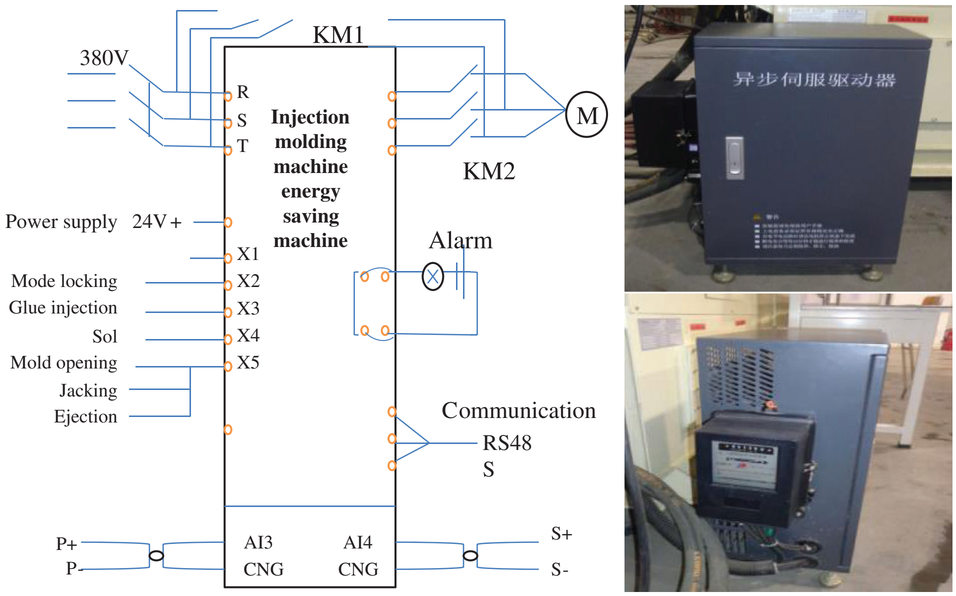

Figure 3: Improvement structure of asynchronous servo energy saver

According to the process identification and judgment, they adjust the frequency of the asynchronous servo energy saver to realize elimination, combination, rearrangement, simplification and recovery of each link in the process.

Our test method is to record the power consumption of a working procedure after installing an asynchronous servo energy saver. First, record the power consumption of a single machine and the production module in a short time (2 hours), and compare them with the normal mode to confirm whether they save power and the power-saving ratio; then record the node status of this machine for five consecutive days to compare whether the power-saving ratio follows a steady trend.

After installing the energy saver, it is found that the energy consumption of a single machine is reduced from 90.35 to 38.57 kWh, and the energy-saving ratio is more than 30% (Fig. 4). It can be seen that the energy-saving effect of the converter is stable and the energy-saving amplitude is large.

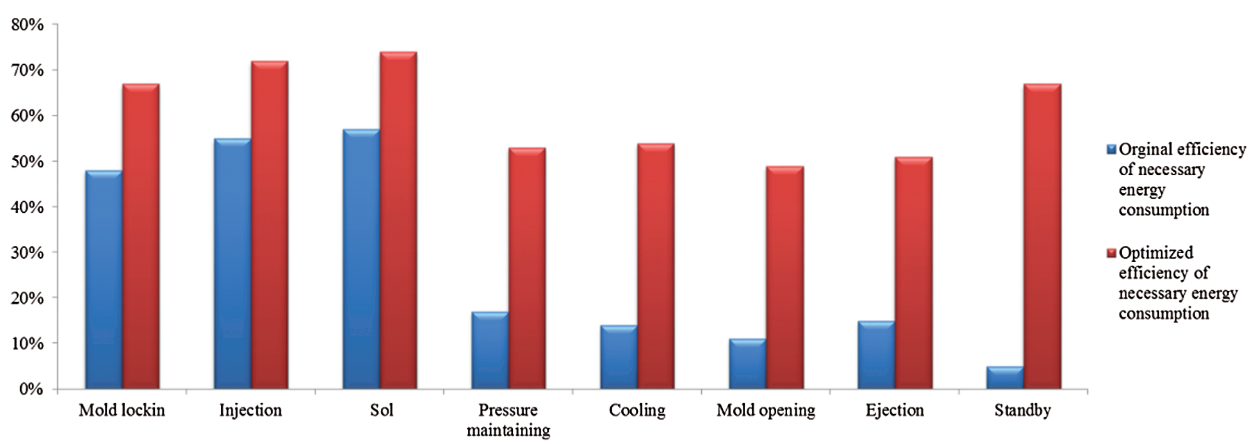

Figure 4: Energy saving ratio of process stages

3.3 Discussion

The energy efficiency improvement method for the manufacturing process is used in the workshop, and has achieved good results. In the manufacturing process, the average hourly power-saving rate of a single machine is 37.3%, and the average power-savings rate per piece is 30.9%. The energy efficiency improvement is obvious.

For energy consumption of enterprises, the energy consumption of the molding machine before the improvement is 9.03 kWh/h, and the energy consumption of a single machine after the improvement is 4.52 kWh/h. The annual energy saved is 563,000 kWh/year, and the annual energy-saving cost is 372,000 RMB. The energy-saving effect is immediate. The implementation results show that this method has the following advantages: this method can tell the managers to optimize the allocation of processing resources from the perspective of effective energy consumption, assistant energy consumption and ineffective energy consumption, and provide guidance for the production personnel to standardize the operation of energy conservation and emission reduction. It can also reduce the total energy consumption and improve energy efficiency for the manufacturing process, and then realize the optimal configuration of the manufacturing process and the rapid improvement of the manufacturing efficiency. Moreover, this method can provide the original power for energy conservation and emission reduction, realize green upgrading of the manufacturing process, reduce energy consumption, and enhance the core competitiveness of enterprises. It can also support the sustainable development of the manufacturing industry.

Based on the above-mentioned research process and conclusions, the following three implications can be realized:

Firstly, to promote energy conservation and emission reduction in the manufacturing process, the characteristics and endowment of energy consumption, as well as the impact of the previous and subsequent stage and the process, need to be comprehensively considered. It is necessary to comprehensively identify and judge the energy use of the total manufacturing system, so as to provide effective support for the improvement of energy efficiency.

Secondly, the improvement of energy efficiency in the manufacturing process is a complex system, which involves equipment, materials, personnel, process and environment. Any one of these factors will affect the energy efficiency of the manufacturing process. Therefore, the improvement of energy efficiency for the manufacturing process should define the way of energy consumption, and combine technology and management to achieve the improvement of energy efficiency in the manufacturing process.

Thirdly, improving the energy efficiency of the manufacturing process plays a greater role in promoting corporate social responsibility, which is of significance to enhancing the core competitiveness of enterprises and promoting the sustainable development of enterprises.

4 Conclusions

Improving energy efficiency is the key problem to be solved for energy saving and emission reduction of the manufacturing industry. It has become a major strategic issue for the sustainable development of the manufacturing industry in various countries. To solve this problem, an energy efficiency improvement method for the manufacturing process is proposed based on energy consumption characteristics from the perspective of IE. The main innovations of this method are as follows: (i) the necessary energy consumption model, the assistant energy consumption model and the ineffective energy consumption model are constructed for identifying the process energy consumption attributes of the manufacturing process; (ii) the relationship model of energy consumption is studied for evaluation of process energy consumption; and (iii) the energy efficiency improvement method for the manufacturing process based on ECRSR is proposed. The method was applied in a workshop and the results show that it is feasible and effective. This is beneficial for enterprises to cope with the current resource crisis and environmental pollution pressure, and provides a driving force for their sustainable development.

For future research, it will be interesting to study the integrated application of measurement standard, management benchmark and neural network of this method considering the energy relationship between manufacturing processes and energy efficiency, which is necessary and has broad prospects for exploiting the potential of energy conservation and emission reduction of manufacturing systems.

Funding Statement: This research is supported by the key projects of natural science research in Anhui Universities (KJ2019A0673), Anhui Science and Technology Innovation Strategy and Soft Science Research Project (No. 201806a02020041), and major science and technology projects of Anhui Province (18030901023).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Liu, C., Cai, W., Jia, S., Zhang, M., Guo, H. et al. (2018). Emergy-based evaluation and improvement for sustainable manufacturing systems considering resource efficiency and environment performance. *Energy Conversion and Management, 177,* 176–189. DOI 10.1016/j.enconman.2018.09.039.
2. Cai, W., Liu, C., Zhang, C., Ma, M., Rao, W. et al. (2018). Developing the ecological compensation criterion of industrial solid waste based on emergy for sustainable development. *Energy, 157,* 940–948. DOI 10.1016/j.energy.2018.05.207.
3. Wang, H., Jiang, Z. G., Wang, Y., Zhang, H., Wang, Y. H. (2018). A two-stage optimization method for energy-saving flexible job-shop scheduling based on energy dynamic characterization. *Journal of Cleaner Production, 188,* 575–588.
4. Schudeleit, T., Zust, S., Weiss, L., Wegener, K. (2016). The total energy efficiency index for machine tools. *Energy, 102,* 682–693. DOI 10.1016/j.energy.2016.02.126.
5. Jia, S., Yuan, Q., Cai, W., Li, M., Li, Z. (2018). Energy modeling method of machine-operator system for sustainable machining. *Energy Conversion and Management, 172,* 265–276. DOI 10.1016/j.enconman.2018.07.030.
6. Liu, C., Zhu, Q., Wei, F., Rao, W., Liu, J. et al. (2020). An integrated optimization control method for remanufacturing assembly system. *Journal of Cleaner Production, 248,* 119261. DOI 10.1016/j.jclepro.2019.119261.
7. Liu, C., Cai, W., Jia, S., Zhang, M., Guo, H. et al. (2018). Emergy-based evaluation and improvement for sustainable manufacturing systems considering resource efficiency and environment performance. *Energy Conversion and Management, 177,* 176–189. DOI 10.1016/j.enconman.2018.09.039.
8. Lee, W., Kim, S. H., Park, J., Min, B. K. (2017). Simulation-based machining condition optimization for machine tool energy consumption reduction. *Journal of Cleaner Production, 150,* 352–360. DOI 10.1016/j.jclepro.2017.02.178.
9. Li, C., Xiao, Q., Tang, Y., Li, L. (2016). A method integrating Taguchi, RSM and MOPSO to CNC machining parameters optimization for energy saving. *Journal of Cleaner Production, 135,* 263–275. DOI 10.1016/j.jclepro.2016.06.097.
10. Mokhtari, H., Hasani, A. (2017). An energy-efficient multi-objective optimization for flexible job-shop scheduling problem. *Computers & Chemical Engineering, 104,* 339–352. DOI 10.1016/j.compchemeng.2017.05.004.
11. Deng, Z., Lv, L., Huang, W., Shi, Y. (2019). A high efficiency and low carbon oriented machining process route optimization model and its application. *International Journal of Precision Engineering and Manufacturing-Green Technology, 6(1),* 23–41. DOI 10.1007/s40684-019-00029-0.
12. Sangwan, K. S., Kant, G. (2017). Optimization of machining parameters for improving energy efficiency using integrated response surface methodology and genetic algorithm approach. *Procedia CIRP, 61(1),* 517–522. DOI 10.1016/j.procir.2016.11.162.

13. Hacksteiner, M., Duer, F., Ayatollahi, I., Bleicher, F. (2017). Automatic assessment of machine tool energy efficiency and productivity. *Procedia CIRP, 62,* 317–322. DOI 10.1016/j.procir.2016.06.034.
14. Hu, L., Liu, Y., Peng, C., Tang, W., Tang, R. et al. (2018). Minimising the energy consumption of tool change and tool path of machining by sequencing the features. *Energy, 147,* 390–402. DOI 10.1016/j.energy.2018.01.046.
15. Wójcicki, J., Bianchi, G., Tolio, T. (2018). Hierarchical modelling framework for machine tool energy optimization. *Journal of Cleaner Production, 204,* 1044–1059. DOI 10.1016/j.jclepro.2018.09.030.
16. Diaz, J. L., Bermeo, M., Diaz-Rozo, J., Ocampo-Martinez, C. (2019). An optimization-based control strategy for energy efficiency of discrete manufacturing systems. *ISA Transactions, 93,* 399–409. DOI 10.1016/j.isatra.2019.03.015.
17. Sheppard, P., Rahimifard, S. (2019). Improving energy efficiency in manufacturing using peer benchmarking to influence machine design innovation. *Clean Technologies and Environmental Policy, 21(6),* 1213–1235. DOI 10.1007/s10098-019-01701-4.
18. Mawson, V. J., Hughes, B. R. (2019). The development of modelling tools to improve energy efficiency in manufacturing processes and systems. *Journal of Manufacturing Systems, 51,* 95–105. DOI 10.1016/j.jmsy.2019.04.008.
19. Liu, N., Zhang, Y. F., Lu, W. F. (2019). Improving energy efficiency in discrete parts manufacturing system using an ultra-flexible job shop scheduling algorithm. *International Journal of Precision Engineering and Manufacturing-Green Technology, 6(2),* 349–365. DOI 10.1007/s40684-019-00055-y.
20. Schulze, M., Heidenreich, S., Spieth, P. (2018). The impact of energy management control systems on energy efficiency in the German manufacturing industry. *Journal of Industrial Ecology, 22(4),* 813–826. DOI 10.1111/jiec.12625.
21. Do, P., Hoang, A., Iung, B., Vu, H. C. (2018). Energy efficiency for condition-based maintenance decision-making: application to a manufacturing platform. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 232(4),* 379–388. DOI 10.1177/1748006X18762282.
22. Hoang, A., Do, P., Iung, B. (2017). Energy efficiency performance-based prognostics for aided maintenance decision-making: application to a manufacturing platform. *Journal of Cleaner Production, 142,* 2838–2857. DOI 10.1016/j.jclepro.2016.10.185.
23. Mahapatra, K., Alm, R., Hallgren, R., Bischoff, L., Tuglu, N. et al. (2018). A behavioral change-based approach to energy efficiency in a manufacturing plant. *Energy Efficiency, 11(5),* 1103–1116. DOI 10.1007/s12053-017-9581-9.
24. Chiaroni, D., Chiesa, V., Franzò, S., Frattini, F., Latilla, V. M. (2017). Overcoming internal barriers to industrial energy efficiency through energy audit: a case study of a large manufacturing company in the home appliances industry. *Clean Technologies and Environmental Policy, 19(4),* 1031–1046. DOI 10.1007/s10098-016-1298-5.
25. Uz, D. (2018). Energy efficiency investments in small and medium sized manufacturing firms: the case of California energy crisis. *Energy Economics, 70,* 421–428. DOI 10.1016/j.eneco.2017.12.006.
26. Lin, B., Chen, G. (2018). Energy efficiency and conservation in China's manufacturing industry. *Journal of Cleaner Production, 174,* 492–501. DOI 10.1016/j.jclepro.2017.10.286.
27. Fernando, Y., Hor, W. L. (2017). Impacts of energy management practices on energy efficiency and carbon emissions reduction: a survey of Malaysian manufacturing firms. *Resources, Conservation and Recycling, 126,* 62–73. DOI 10.1016/j.resconrec.2017.07.023.
28. Pérez, K., González-Araya, M. C., Iriarte, A. (2017). Energy and GHG emission efficiency in the Chilean manufacturing industry: sectoral and regional analysis by DEA and Malmquist indexes. *Energy Economics, 66,* 290–302. DOI 10.1016/j.eneco.2017.05.022.
29. Cagno, E., Trianni, A., Spallina, G., Marchesani, F. (2017). Drivers for energy efficiency and their effect on barriers: empirical evidence from Italian manufacturing enterprises. *Energy Efficiency, 10(4),* 855–869. DOI 10.1007/s12053-016-9488-x.
30. Cantore, N. (2017). Factors affecting the adoption of energy efficiency in the manufacturing sector of developing countries. *Energy Efficiency, 10(3),* 743–752. DOI 10.1007/s12053-016-9474-3.

31. Zhai, M. Y., Huang, G. H., Liu, L. R., Bao, Z. Y., Guan, Y. R. (2020). Inter-regional carbon flows embodied in electricity transmission: network simulation for energy-carbon nexus. *Renewable and Sustainable Energy Reviews, 118,* 109511. DOI 10.1016/j.rser.2019.109511.
32. Liu, C., Zhu, Q., Wei, F., Rao, W., Liu, J. et al. (2019). A review on remanufacturing assembly management and technology. *The International Journal of Advanced Manufacturing Technology, 105(11),* 4797–4808. DOI 10.1007/s00170-019-04617-x.
33. Borsato, M. (2017). An energy efficiency focused semantic information model for manufactured assemblies. *Journal of Cleaner Production, 140,* 1626–1643. DOI 10.1016/j.jclepro.2016.09.185.