International Journal of Precision Engineering and Manufacturing-Green Technology (2020) 7:205–218
https://doi.org/10.1007/s40684-019-00137-x

Online ISSN 2198-0810
Print ISSN 2288-6206

REGULAR PAPER

Task-Oriented Energy Benchmark of Machining Systems for Energy-Efficient Production

Wei Cai[1] · Li Li[1] · Shun Jia[2] · Conghu Liu[3] · Jun Xie[4] · Luoke Hu[5]

Received: 16 April 2018 / Revised: 2 July 2019 / Accepted: 8 July 2019 / Published online: 19 July 2019

Abstract
The energy benchmark has been recognised as an effective analytical methodology and management tool that help to improve the efficiency and performance of energy utilisation. With a wide distribution and large amount of energy consumption at a low efficiency, machining systems have considerable energy-saving potential. This paper proposes a task-oriented energy benchmark in machining systems, and illustrates the concept of the task-oriented energy benchmark and indicators. A method for developing the task-oriented energy benchmark considering the certainty production task and the uncertainty production task is proposed, which lays a solid foundation for studying the energy benchmark, benchmark rating system and energy certification. Furthermore, a case study of the task-oriented energy benchmark not only verifies the reliability but the effectiveness for energy-efficient production.

Keywords Energy benchmark · Task-oriented · Machining system · Energy efficiency

1 Introduction

Facing significant natural resource consumption, environmental degradation, and resulting climate warming, national administration heightened attention on ecological modernization, green growth, and low carbon development, with a national sustainability strategy [1–4]. Manufacturing industry is as an important pillar industry in the national economy [5]. Yet, it brings vast amounts of natural resource consumption and energy consumption at a low efficiency [6, 7], which makes the manufacturing industry pay more attention to energy conservation [8]. The mechanical manufacturing industry that has widely distributed and consumes large amounts of energy [9–11] is a type of typical manufacturing industry. The Energy Yearbook published by the United States Energy Information Administration showed that electricity use of the mechanical manufacturing industry was striking, accounted for 75% of electricity use for manufacturing [12]. Besides, much of the research have shown that the energy efficiency of machining processes was intensely low [13], generally less than 30%. Therefore, decreasing energy consumption and improving energy efficiency are urgent issue for machining systems.

Currently, the International Organization for Standardization (ISO) is developing the ISO 14955 series about machine tools for energy efficiency improvement [14]. The European Commission issued some critical directives to decrease the energy consumption [15]. The Japanese Standards Association presented some relevant studies to implement the energy-efficient machine tools and machining [16]. Besides, many scholars have devoted to efficient energy use for machining systems to investigate the magnitude of the energy efficiency and to improve the energy efficiency [17, 18]. As an example, Gutowski constructed an exergy framework for manufacturing systems to estimate the theoretical energy requirement for producing one unit of product [19]. Kara presented the unit process energy consumption models for material removal processes to characterize the energy

✉ Wei Cai
weicai@swu.edu.cn

[1] College of Engineering and Technology, Southwest University, Chongqing 400715, China

[2] Department of Industrial Engineering, Shandong University of Science and Technology, Qingdao 266590, China

[3] Sino-US Global Logistics Institute, Shanghai Jiao Tong University, Shanghai 200030, China

[4] College of Mechanical Engineering, Chongqing Technology and Business University, Chongqing 400050, China

[5] Key Laboratory of Advanced Manufacturing Technology of Zhejiang Province, Zhejiang University, Hangzhou 310027, China

efficiency of unit processes [20]. Oh studied the machining characteristics and energy efficiency of Ti-6Al-4V in laser-assisted trochoidal milling [21]. Jackson established an energy consumption model for additive subtractive manufacturing processes [22]. Jia proposed a new energy modeling method of machine-operator system for sustainable machining [23]. Balogun proposed a new mathematical model and logic for predicting direct electrical energy requirements in machining toolpaths, realizing the visibility and process dependence of the energy and carbon footprint [24]. Zhou presented an energy consumption model of a workpiece contributing to establishing the energy consumption benchmark in a machining system [25]. Zheng introduced a non-pulsed energy modeling based on energy consumption subunits in wire electrical discharge machining (WEDM) process [26].

To perform the energy management and energy efficiency improvement in machining systems, this paper proposes a task-oriented energy benchmark as a new method, contribute to promoting the energy-efficient production. This paper is organized as follows. In Sect. 2, the theoretical background for the task-oriented energy benchmark is introduced from the different perspectives. Definition of task-oriented energy benchmark is described in Sect. 3. Section 4 introduces the method of establishing the benchmark. Finally, a case study and application analysis are illustrated in a real machining workshop.

2 Theoretical Background

There are some effective measures to improve the environmental performance in machining systems, including the process selection, capacity optimization of the machine tool, more efficient machine tool components, change of technology, electrical energy and material recovery, energy and material cascading, integrated versus central peripherals, selective actuation of subunits, reduction of standby energy [27]. In this paper, some measures to improve the environmental performance can be illustrated briefly from perspectives of energy efficient machining, energy efficient machine tools and energy benchmarking for machining systems.

2.1 Energy Efficient Machining

Currently, the improved machining technology and process optimization are basically two options available for realizing energy efficient machining [28]. While the first option mainly aims to reduce the energy using the advanced machining technology, the second approach focuses on reducing machining time.

Electric energy in machining which can easily be provided is the most crucial source of energy. The main drivers for energy consumption in machining systems are machine tools. Other sources of energy, like transloading equipment (i.e. cranes, forklifts, electro mobiles) and auxiliary equipment of workshops (i.e. lights, air-conditions, compressors, fans), need to be in most cases provided by using the electric energy. Besides, the electric energy consumption caused by machining processes also results in the total environmental footprint. For example, Kellens studied the environmental impact modeling in selective laser sintering processes laying an important basis of helping to identify and quantify measures for significant impact reduction of both involved products and the supporting machine tools [29]. Jia proposed a prediction models for feeding power and material drilling power to support sustainable machining [30]. Mathew considered the environment factor in the work material during drilling [31]. Therefore, to evaluate the environmental and energy performance in machining systems, it is reasonable for electric energy as a parameter for energy efficiency of machining processes. Since the desired outcomes of machining processes are workpieces, a promising key performance indicator (KPI) for energy efficiency of machining processes is the specific energy consumption per workpiece (SEC) [32].

For one workpiece to be machined, different machining technologies and machining plans that involve different machine tools (including parameters, tools, etc.) may lead to a great number of differences in energy consumption. The workpiece to be machined by advanced machine tools (i.e. the high-speed dry-cutting hobbing machine such as YE3120CNC7) consumes less energy consumption with high energy efficiency in comparison to the common or backward machining technology (i.e. the common hobbing machine and hobbing machine such as YKB3120M, YKS3120A) due to the reduction of machining time and energy per time [33]. Therewith, it can be assured that the KPI is comparing the desired outcome (the workpiece) with the entire amount of used energy per workpiece. Obviously, the technological level of machine tools used for the production has a significant impact on machining performance and energy efficiency.

Besides the machining technology aspect, the machine tool operator also is a crucial factor for machining processes. The operator aims to effectively achieve the machining process of workpieces and to avoid the waste of energy such as long running time of machine tools without machining and other inappropriate practices.

2.2 Energy Efficient Machine Tools

In machining processes, selection of machine tools has a huge impact on the total amount of energy demand, and influences of machine tools can be derived from two aspects: the design of machine tools and the use of machine tools.

For the design of machine tools, which improve the energy efficiency or energy utilization [34], it is focusing on reducing the idling rate and the load loss power, and improving the load rate of the cutting that involves the design of machine tools, at times. The specific methods or measures as followed:

- *Reasonable selection of motor capacity of machine tools*: On the one hand, it can reduce energy loss of motor to improve energy utilization. On the other hand, providing the enough cutting power also indirectly leads to the improvement of energy utilization. Assuming that the motor capacity is bigger, the idling power is bigger resulting in the reduction of energy utilization. In contrast, assuming that the motor capacity is less, the energy loss of motor is increased and it is unable to provide enough cutting power, which also reduces the energy utilization.
- *Structure design of machine tools*: To reduce the idling power and load loss power, it is worth notice in selecting reasonably the lubrication system and lubricating oil, selecting the reasonable accuracy of transmissions and determining reasonable requirement of assembly technology.
- *Improving the load rate of the cutting*: Improving performance indicators of machine tools including the rigid indicator and speed changing indicator (i.e. reasonable common ratio or stepless speed changing) is a crucial measure for increasing the cutting parameters and choosing optimal cutting parameters to increase the energy utilization.
- *Reducing the idling rate or idling time*: The effective measures comprise improving the transmission structure, reducing the time of speed changing, improving clamp and reducing the time of tool changing and clamping.

For the use of machine tools, there are a slice of the measures of energy efficiency, and they are focusing on machining parameters. Machining parameters mainly include the cutting speed, feed and the depth of cut, which are closely related to the production efficient, cost, energy demand, etc. Selection of the reasonable machining parameters plays a significant role in production efficient, cost, energy demand.

To evaluate the energy efficiency level of the machining process, measures of improving energy efficiency can be performed according to the analysis on energy efficient machining and machine tools. This paper proposes an energy benchmark concept that can evaluate the energy efficiency level of machining processes.

2.3 Energy Benchmark of Machining Systems

Developing energy benchmark is an effective analytical methodology and management tool that help to promote the energy efficiency and performance [35, 36]. A multitude of approaches to energy benchmarking have been applied in the petrochemical industry [37], steel and cement industry [38] and coal mining industry [39]. Studying energy benchmark has aroused extensive interest in recent years [40].

However, current research regarding the use of energy benchmark for machining systems is insufficient due to complexity and variety of energy consumption processes used in these systems, which indicates that machining systems offer considerable energy-saving potential. Developing the energy benchmark in machining systems has significant effects:

- Top management by e.g. setting institution of rewards and punishments on energy usage.
- Energy managers by e.g. performing energy audit and energy measure.
- Workshop managers by e.g. conducting energy monitoring, management and improving energy efficiency in production processes.
- Machine operators by e.g. strengthening awareness of the energy conservation and normalized operation.

Currently, in the mechanical manufacturing industry, studying the energy benchmark has become an important strategy of carrying out sustainable machining. Quite a few scholars have proposed important research achievements related to energy benchmark of machining systems. For example, Liu analyzed the complexity of product energy consumption allowance (PECA) in discrete manufacturing industry and proposed some strategies for establishing the PECA [6]. Zhou presented a concept of the energy-consumption-step (ECS) to uniformly describe various types of energy consumption in the whole machining process of a workpiece, established the architecture of the ECS and proposed an energy-consumption model for establishing energy-consumption allowance of a workpiece in a machining system [25]. El-Maraghy performed the energy use analysis of manufacturing lines and addressed a method for energy benchmarking to improve energy efficiency [41]. Cai made systematic studies for the energy benchmarking in machining systems including the energy benchmarking directions, concepts, flamework, methods, et al., laying an important foundation for the energy benchmarking research [42, 43]. These studies have offered effective methods for developing the energy benchmark in machining systems. However, study on task-oriented energy benchmark of machining systems has not been resolved, so that there is absence of a method for promoting energy-efficient production.

2.4 Contributions

With regards to the analysis of energy efficient machining and machine tools, the energy benchmark can provide a support for energy efficient machining and machine tools. To date, previous studies are significant for the energy benchmark study, but are far from sufficient to satisfy the demand for establishing a reasonable energy benchmark in machining. Deficiencies of previous studies focus mainly on the following two aspects:

- For establishment of the energy benchmark in machining, types of the production task from the perspectives of production scales, production amount, production plans and others have been not considered.
- The complexity and variety of the energy consumption processes result in difficulty of establishing the energy benchmark because of the lack of an effective method.

In this paper, we presented the use of the task-oriented energy benchmark to reduce energy consumption and to improve energy efficiency in machining systems. This study illustrated concept and connotation of the task-oriented energy benchmark and proposed indexes of the benchmark. On this basis, a method for developing the energy benchmark of machining systems is presented, which lays a solid foundation for studying the energy benchmark, benchmark rating system and energy certification, etc.

3 Definition of Task-Oriented Energy Benchmark

Task-oriented energy benchmark plays a role in the energy management, monitoring and energy efficiency improvement for the actual production tasks. Realistically, although there are some methods for energy benchmarking, few studies involve the task-oriented energy benchmark of machining systems, even cannot give a clear definition. Therefore, this section illustrates the concept of the task-oriented energy benchmark in machining systems to develop the benchmark and to further perform the energy-efficient production.

The task-oriented energy benchmark is a metric for the standardised evaluation of the energy consumption and efficiency for the production task in machining systems. In this study, the production task is the machining requirement for the same workpiece. The production task can be regarded as unit workpiece or a batch of workpieces that may be processed through various machining plans including a slice of machine tools, various machine tools and production line. These different machining plans for the production task result in large differences of energy use.

The energy benchmark needs to be established in advance while the production task or production quantity of the workpiece is given. The complex machining environment or machining equipment makes the diversification of machining plans, leading to differences of energy consumption for the same workpiece. If the machining environment (i.e. machining equipment) is onefold, or the assigned processing for the workpiece is in a specific machining plan, in other words, the production task is certainty in machining processes. The certainty production task is the certainty of the production quantity, production plan and other process information for the product to be manufactured. On the contrary, the production task is uncertainty in machining processes. Therefore, the task-oriented energy benchmark comprises the energy benchmark under the certainty production task and the uncertainty production task. Moreover, the energy benchmark under certainty production task includes the energy benchmark with historical machining information and without machining information (namely new workpiece). Realistically, the classification of the certainty production task and uncertainty production task is to simplify the establishment of energy benchmark in terms of real scenarios. For example, in the machining workshop of the Chongqing Machine Tool Works Co., Ltd., a batch of gear needs to be processed with given production quantity, given machining equipment (i.e. high-speed dry-cutting hobbing machines) and machining plans, which makes the production information and machining information clear. The scenario is certainty production task, and its benchmark belongs to the energy benchmark under certainty production task. On the contrary, in this machining workshop, although the production quantity of the workpiece is given, the machining equipment is diversified (i.e. the common hobbing machine, wet-cutting CNC hobbing machines and high-speed dry-cutting hobbing machine) resulting in differences of machining plans. Obviously, their energy consumption is different [34], and it is not clear about how many tasks are assigned of the workpiece in above three types of machine tools. Therefore, this scenario is uncertainty production task, and its benchmark belongs to energy benchmark under uncertainty production task.

Indexes of the task-oriented energy benchmark, as an important metric, can be constructed in terms of the concept and connotation. Indicators for the benchmark comprise the benchmark under certainty production task and the benchmark under uncertainty production task. The benchmark under certainty production task can be described using specific energy consumption per workpiece (SEC), production amount of the workpiece (PA), total energy consumption (TEC) and energy saving coefficient (ESC) to represent the energy usage level of the workpiece. For the benchmark under uncertainty production task, its indicators are more complex and comprise use of a number of different sub indicators to show the energy usage including the integrated SEC under different machining plans, production scale (PS), process correlation coefficient (PCC) and TEC.

4 Development of the Task-Oriented Energy Benchmark

This study aims at developing an task-oriented energy benchmark in machining systems for energy-efficient production, and the method is constructed in the following five steps: (i) goal and scope definition, (ii) establishment of the database, (iii) acquisition of energy-consumption data and determination of the benchmark under the certainty production task, (iv) acquisition of energy-consumption data and determination of the benchmark under the uncertainty production task, and (v) development of the index systems using the benchmark.

4.1 Goal and Scope Definition

The goal of this study is to develop a reasonable task-oriented energy benchmark in machining systems. The machining systems are composed of various machine tools and do not involve other machining equipment and auxiliary equipment of the workshop. The energy consumption of the use phase of the involved machine tools is taken into account, and the manufacturing and maintenance of machine tools and tooling are not considered. Machining systems are in units of the firm and are integrated with machine tools by one or more workshops, but do not involve the integration among the firms. The functional unit considered is one workpiece that is a typical machining product. The benchmark can play a role in guiding the production under the certainty task and uncertainty task. Regarding the system boundary, the machining cycle of one workpiece is, in principle, a cradle-to-grave exercise. However, in some cases, cradle-to-gate, gate-to-gate, gate-to-cradle, and, more recently, cradle-to-cradle approaches are possible [44, 45]. Considering the benchmark of the workpiece, the approach can only be gate-to-gate, as there can be an ocean of different applications later. Therefore, the whole of gate-to-gate processes within the system boundary include the whole machining processes that may be production lines, single machine tool and multiple machine tools in the machining workshop from the raw material to the qualified workpiece. Energy consumption of the unit workpiece is the sum of energy consumption in machining processes involved in machining systems.

4.2 Establishment of the Database

As shown in Table 1, the database needs to be established in advance, which comprises three parts: (i) energy-related data, (ii) energy-unrelated data and (iii) production data. This information can be used to acquire energy consumption data and to determine the benchmark.

Firstly, for the energy-related data including the standby power, starting energy consumption, idling power and load loss coefficient, methods for developing these databases are as followed.

- Standby power is collected from the standby power database that can be established by measuring the standby power of each machine tool beforehand [46, 47].
- Starting energy consumption is collected from the starting energy consumption database, and it can be measured with speed as a variable beforehand [48].
- Idling power is collected from the idling power database, also the idling power can be determined by measuring the power at several selected speeds beforehand [6, 46].
- Load loss coefficient is a complex parameter, generally, the value of load loss coefficient is 0.15–0.25 [48, 49]. To acquire more accurate load loss coefficient, establishing the database by measuring or calculating the load loss coefficient for each machine tool is indispensable [50].

Secondly, this study needs collect energy-unrelated data that includes machining parameters, standby time and idling time. The standby time is the universal waiting time for the spindle stop, and the time comprises a variety of scenarios like the manual clamping time for the workpiece, manual tool changing time, rest time for the machine tool and debugging time. The idling time is the time of spindle running for offering the cutting preparation, and the time involve a variety of scenarios like automatic tool changing time, air cutting time, and loading and unloading time. These data of standby time and idling time can be acquired through the established databases in advance, and methods

Table 1 Basic information affecting the benchmark

Main classification	Sub classification
Energy-related data	Standby power
	Starting energy consumption
	Idling power
	Load loss coefficient
Energy-unrelated data	Machining parameters
	Standby time
	Idling time
Production data	Production amount
	Production scale

for establishing the databases has been illustrated in the previous study [46].

4.3 Determining the Energy Benchmark Under Certainty Production Task

Acquiring the energy-consumption data and the benchmark under certainty production task is a crucial basis for determining the benchmark under uncertainty production task. The benchmark under certainty production task is the benchmark of the workpiece for each machining plan in the machining workshop, and the machining plan is certainty. Actually, the workpiece may involve various machining workshops, thus the workpiece has multiple benchmarks.

To acquire the energy consumption of the workpiece under various machining plans, an energy consumption model is established [6, 46]:

$$E = E_{SB} + E_{ST} + E_{ID} + E_{CM} \tag{1}$$

where, E is the energy consumption of one workpiece during the whole of machining processes under a machining plan,E_{SB}, E_{ST}, E_{ID} and E_{CM} are the total energy consumption in the standby, starting, idling and cutting material processes, respectively.

Therefore, the SEC can be acquired based on the Eq. (1)

$$SEC = \sum_{i=1}^{m} \left(\sum_{j=1}^{n_{sb}} E_{sb_{ij}} + \sum_{j=1}^{n_{st}} E_{st_{ij}} + \sum_{j=1}^{n_{id}} E_{id_{ij}} + \sum_{j=1}^{n_{cm}} E_{cm_{ij}} \right) \tag{2}$$

where SEC is regarded as the energy benchmark of unit workpiece under a machining plan, n_{sb} is the number of standby processes in ith machine tool, n_{st} is the number of starting processes in ith machine tool, n_{id} is the number of idling processes in ith machine tool, and n_{cm} is the number of cutting material processes in ith machine tool.

$$E_{sb} = P_{sb} \times t_{sb}$$

$$E_{id} = P_{id} \times t_{id}$$

$$E_{cm} = \left\{ P_{id} + [1 + \varphi(n)] \times P_c \right\} \times t_{cm}$$

where P_{sb} and P_{id} are the standby power and idling power, P_c is the cutting power of the tool in the cutting material processes.t_{sb}, t_{id} and t_{cm} are the standby, idling and cutting material time, respectively, and $\varphi(n)$ is the load loss coefficient of the machine tool [49].

The Eq. (2) provides an important support for determining the benchmark. In the machining workshop, the machining plan is certainty for the production task, the status of workpiece to be machined that has been processed or unprocessed should be considered. The benchmark under certainty production task comprises two kinds of scenarios: the workpiece with and without historical machining information. Therefore, these benchmarks for two kinds of circumstances should be considered respectively.

4.3.1 Benchmark with Historical Machining Information

The historical machining information (HMI) involve machining plans, machining parameters and the number of the workpiece under each machining route. Given that the processed workpiece comprises 1th, 2th, 3th,…, ith machining routes resulting in the various machining plans (P_1, P_2, P_3,…, P_i), the corresponding SEC under each machining plan can be described: $SEC_{P_i} = f\left(P_i\right)$.

Given that the amount of the processed workpiece under each machining plan are Z_1, Z_2, Z_3,…, Z_i, respectively, the corresponding scrap of the workpiece are W_1, W_2, W_3,…, W_i. The scrap consumes a lot of energy, and their energy consumption should be shared with all the qualified workpieces. Therefore, the SEC of the workpiece is as follows

$$SEC_{HMI} = \frac{\sum_{i=1}^{n} SEC_{P_i} \times Z_i}{\sum_{i=1}^{n} \left(Z_i - W_i\right)} \tag{3}$$

where SEC_{HMI} is the energy benchmark with historical machining information under the certainty production task, n is the number of the machining plan.

4.3.2 Benchmark Without Historical Machining Information

Since lack of historical machining information for the workpiece (i.e. the number of processed workpiece and scrap), it is difficult to determine the benchmark using the Eq. (3) through the determined machining plan and parameters. Therefore, for the specific scenario, on basis of obtaining the SEC using Eq. (2), it is necessary to evaluate its machining plan and energy consumption from the perspectives of (i) reasonability of machining plan and energy consumption and (ii) reasonability of uncertainty time in machining to determine a reasonable benchmark of the workpiece.

- *Evaluating reasonability of the machining plan and energy consumption*: The reasonability of machining plan is an important basis for establishing the energy benchmark. Whether the machining plan is reasonable should be evaluated via benchmarking staffs, process planners, operators and workshop managers from perspectives of the energy consumption, process performance, experience in machining and production management. For example, while meeting production requirements, selecting the low speed and the large depth of cut for the machining is better than selecting the high speed and the small depth of cut, and the energy consumption of the former is less compared with the latter. Under the same allowance for machining, reducing the machining time can decrease energy consumption. Based on the principle of the minimum energy consumption, the machining plan and energy consumption of the workpiece can be determined.

- *Evaluating reasonability of uncertainty time in machining*: The energy consumption in machining is affected by uncertainty time such as standby time, idling time of machine tools. For example, if the standby time is much too long, the energy is wasted; if the standby time is much too short, it is difficult for operators to clamp the workpiece and follow-up. Thus, the standby time depends on the operator level and further keeps allowance to ensure that the most machining processes can be completed, normally. Determining the idling time is similar to the standby time. If the uncertainty time is changed, the corresponding energy consumption should be adjusted.

On basis of the machining plan and energy consumption evaluation, the benchmark is related to energy-saving level of firms. Therefore, the SEC of the workpiece is as follows

$$SEC_{No-HMI} = \kappa \times SEC \tag{4}$$

where SEC_{No-HMI} is energy benchmark without historical machining information under the certainty production task, κ is an energy saving coefficient. The larger the κ, the lower the energy saving level of the firm is. κ is slightly less than 1.0 or slightly greater than 1.0. Determination of the κ has various methods that include workshop historical information-based evaluation method and scoring method of the expert decision-making. The evaluation method of the workshop historical information-based depends on current energy consumption level of the machining workshop. The κ can be estimated through statistics and analysis of a period of energy consumption for all workpieces. Scoring method of expert decision-making is a subjective behavior for determining the κ by several experts of energy managers and production managers according the energy saving level. Actually, determination of the κ is very complicated, and the specific method will be introduced in subsequent study in detail because of space limitations.

According to the certainty production task, the TEC_i can be determined in terms of PA_i of the workpiece under *ith* machining plan:

$$TEC_i = SEC_i \times PA_i. \tag{5}$$

Therewith, the TECs under various machining plans can be determined. Therefore, the energy benchmark of the workpiece under various machining plans is acquired, this benchmark of the workpiece is regarded as a product energy benchmark with the certainty production (PEB_c):

$$PEB_c = f\left(TEC_1,\ TEC_2, \ldots,\ TEC_n\right) \tag{6}$$

where,$TEC_1, TEC_2,$ and TEC_n are the TEC under the 1th, 2th and *n*th machining plan, respectively, $f(\cdot)$ is the function about the TEC. The PEB_c is determined using the statistical analysis with the detail illustration in the case study.

4.4 Determining the Energy Benchmark Under Uncertainty Production Task

Acquiring energy-consumption data and determining the benchmark for the workpiece under the uncertainty production task are arduous compared with the certainty production task. The reasons are that there are various machining plans and process parameters for the workpiece, and it is an unawareness of production amount for the workpiece under each machining plan, which results in the uncertainty for production task and the difficulty in determining the benchmark.

4.4.1 Process Correlation Coefficient

Specific machining plan and the production amount for the workpiece to be produced are not easily identifiable certain due to perplexity in assigning production tasks. The uncertainty production task has an uncertainty of machining plans and the production amount. Therefore, to solve this problem, this paper proposes a new concept of process correlation coefficient (PCC), and the PCC is the correlation for the production scale under different machining plans and the production amount. As an example, given that there are *n* machining plans for the workpiece, the TEC can be determined:

$$TEC_T = SEC_1 \times PA_1 + SEC_2 \times PA_2 + \cdots + SEC_n \times PA_n \tag{7}$$

where, TEC_T is the total energy consumption for the workpiece under all machining plans. Actually, the TEC_T cannot be acquired in terms of the Eq. (7) because $PA_1, PA_2, \ldots, PA_n$ are unknown due to uncertainty of machining plans. Thus, the Eq. (7) is difficult to determine the TEC_T. On this basis, the following Eqs. (8) and (9) can solve this problem using the PCC:

$$TEC_T = PEB_u \times PA_t \tag{8}$$

$$PEB_u = \omega_1 \times SEC_1 + \omega_2 \times SEC_2 + \cdots + \omega_n \times SEC_n \tag{9}$$

where, PEB_u is a product energy benchmark with the under the uncertainty production task, PA_t is the production amounts of the workpiece ($PA_t = PA_1 + PA_2 + \cdots + PA_n$), $\omega_1, \omega, \ldots, \omega_n$ are PCWs under different machining plans.

4.4.2 Determining the Benchmark Using the Process Correlation Coefficient

Although the Eq. (9) introduces a general method based on the PCW, the acquisition of the PEB_u and TEC_T are formidable due to the uncertainty of the production task. Therefore, for the uncertainty production task, the PEB_u can be estimated in terms of the PS that can be divided into three categories including the mass production, medium production and small production for the workpiece. The Eq. (9) can be further described using the Eq. (10)

$$PEB_u = \omega_{mass} \times SEC_{mass} + \omega_{medium} \times SEC_{medium} + \omega_{small} \times SEC_{small}. \tag{10}$$

Given that there are n machining plans for the workpiece, the SEC of each machining plan that comprises machine tools or systems can be acquired. Therefore, SEC_{mass}, SEC_{medium} and SEC_{small} can be determined in terms of production capacity of machine tools or machining systems. Realistically, these production plans, whatever the workpiece is produced in the form of the mass production, medium production and small production, can happen in parallel.

$$SEC_{mass} = \frac{SEC_1 + SEC_2 + \cdots + SEC_i}{i} \tag{11}$$

$$SEC_{medium} = \frac{SEC_{i+1} + SEC_{i+2} + \cdots + SEC_{i+j}}{j} \tag{12}$$

$$SEC_{small} = \frac{SEC_{i+j+1} + SEC_{i+j+2} + \cdots + SEC_{i+j+k}}{k} \tag{13}$$

where, i, j and k are the number of SEC_{mass}, SEC_{medium} and SEC_{small}, $i + j + k = n$.

Moreover, for the ω_{mass}, ω_{medium} and ω_{small}, the production amount of the workpiece as the mass, medium and small production can be estimated to be n_{mass}, n_{medium} and n_{small}. The ω_{mass}, ω_{medium} and ω_{small} are:

$$\omega_{mass} = \frac{n_{mass}}{n_{mass} + n_{medium} + n_{small}} \tag{14}$$

$$\omega_{medium} = \frac{n_{medium}}{n_{mass} + n_{medium} + n_{small}} \tag{15}$$

$$\omega_{small} = \frac{n_{small}}{n_{mass} + n_{medium} + n_{small}} \tag{16}$$

Acquiring PCCs (ω_{mass}, ω_{medium} and ω_{small}) is simple but imprecise, and they are exceedingly dependent on the high expertise for decision-makers.

4.5 Development of the Index System Using the Benchmark

This paper proposes the index system using the benchmark aiming to implement the benchmark in a direct way at the respective objects. The index system could be applied to the energy management or energy audit for the energy sector in the workshop, which is available for the energy efficiency improvement in the real machining process. The index system can be extended to an energy card, and it comprise quite a few key information. If the production task is certainty, the indexes systems include PEB_c, TEC_i, SEC_i and PA_i; if the production task is uncertainty, the index system includes PEB_u, TEC_T, PA_t, SEC_{mass}, SEC_{medium}, SEC_{small}, ω_{mass}, ω_{medium} and ω_{small}. Furthermore, the index system also consists of other basic information besides the benchmark information. Therefore, the information for the index systems is as following in Table 2, the specific development of indexes systems is introduced in the case study.

5 Case Study

This case illustrates the process of developing the task-oriented energy benchmark in machining systems considering two kinds of scenarios (the certainty production task and uncertainty production task) and analyzes its practicability of the benchmark in a real production process. The case study includes three aspects: (i) certainty production task, (ii) uncertainty production task, and (iii) discussion.

Table 2 The index system of the benchmark

<table>
<tr><td rowspan="2">Basic information</td><td colspan="3">Workpiece</td><td colspan="3">Workpiece number</td><td colspan="3">Material</td><td colspan="3">Figure of product</td></tr>
<tr><td colspan="3">※</td><td colspan="3">※</td><td colspan="3">※</td><td colspan="3">※</td></tr>
<tr><td rowspan="19">Energy information</td><td colspan="12">If it is certainty production task</td></tr>
<tr><td colspan="3">Machining plan 1</td><td colspan="3">Machining plan 2</td><td colspan="3">Machining plan i</td><td colspan="3">Machining plan n</td></tr>
<tr><td colspan="3">SEC_1</td><td colspan="3">SEC_2</td><td colspan="3">SEC_i</td><td colspan="3">SEC_n</td></tr>
<tr><td colspan="3">※</td><td colspan="3">※</td><td colspan="3">※</td><td colspan="3">※</td></tr>
<tr><td colspan="3">PA_1</td><td colspan="3">PA_2</td><td colspan="3">PA_i</td><td colspan="3">PA_n</td></tr>
<tr><td colspan="3">※</td><td colspan="3">※</td><td colspan="3">※</td><td colspan="3">※</td></tr>
<tr><td colspan="4">PEB_c</td><td colspan="4">PA_t</td><td colspan="4">TEC_T</td></tr>
<tr><td colspan="4">※</td><td colspan="4">※</td><td colspan="4">※</td></tr>
<tr><td colspan="12">If it is uncertainty production task</td></tr>
<tr><td colspan="12">Production scale</td></tr>
<tr><td colspan="4">Mass production</td><td colspan="4">Medium production</td><td colspan="4">Small production</td></tr>
<tr><td colspan="4">SEC_{mass}</td><td colspan="4">SEC_{medium}</td><td colspan="4">SEC_{small}</td></tr>
<tr><td colspan="4">※</td><td colspan="4">※</td><td colspan="4">※</td></tr>
<tr><td colspan="4">n_{mass}</td><td colspan="4">n_{medium}</td><td colspan="4">n_{small}</td></tr>
<tr><td colspan="4">※</td><td colspan="4">※</td><td colspan="4">※</td></tr>
<tr><td colspan="4">ω_{mass}</td><td colspan="4">ω_{medium}</td><td colspan="4">ω_{small}</td></tr>
<tr><td colspan="4">※</td><td colspan="4">※</td><td colspan="4">※</td></tr>
<tr><td colspan="4">PEB_u</td><td colspan="4">PA_t</td><td colspan="4">TEC_T</td></tr>
<tr><td colspan="4">※</td><td colspan="4">※</td><td colspan="4">※</td></tr>
</table>

5.1 Certainty Production Task

This case is to establish an energy benchmark in the Chongqing Machine Tool Works Co., Ltd., China: an energy benchmark of a cylindrical gear under the certainty production task. For the cylindrical gear under certainty production task, each of machining plans comprises two machine tools including the CNC lathe (CHK560CNC) and hobbing machine (Y3150E). Parameters of the cylindrical gear include the material (45 steel), tooth number (60), modulus (5), profile angle (20°) and cross teeth (7). The machining environment is as follows in Fig. 1.

According to the method analysis, these databases (i.e. the standby power, starting energy consumption, idling power and load loss coefficient databases for the CHK560CNC and Y3150E) can be established in advance. The energy-unrelated data such as the standby power, starting energy consumption, idling power and load loss coefficient can be acquired by these databases. The specific establishment processes for these databases can be found in the previous study [47], thus, these processes are omitted in this paper. Besides, the energy-unrelated data including machining parameters, the standby time and the idling time can be collected from the technologist and calculation in terms of the machining parameters. The machining parameters are as follows in Table 3.

Therefore, the benchmark of the cylindrical gear under the certainty production task can be obtained in terms of its machining plan, as follows

$$SEC^{c}_{cylindricalgear} = \sum_{i=1}^{m} \left(\sum_{j=1}^{n_{sb}} sb_{ij} + \sum_{j=1}^{n_{st}} E_{st_{ij}} + \sum_{j=1}^{n_{id}} E_{id_{ij}} + \sum_{j=1}^{n_{cm}} E_{cm_{ij}} \right)$$
$$= 3.86\ kWh.$$

In addition, according to the machining plan and production task, the production amount of the cylindrical gear ($PA_{cylindricalgear}$) is 30. Therefore, the total energy consumption of the cylindrical gear ($TEC_{cylindricalgear}$) can be determined as 115.8 kWh.

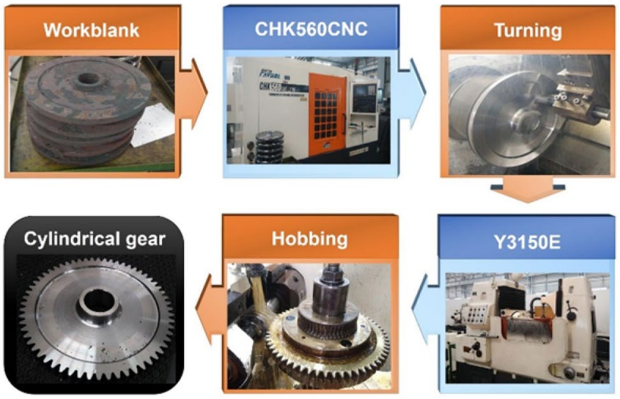


Fig. 1 Machining environment of the cylindrical gear

5.2 Uncertainty Production Task

This case is to establish an energy benchmark in the Chongqing Machine Tool Works Co., Ltd., China: an energy benchmark of the gear blank. The gear blank is an important component for the gearbox. Due to the nondeterminacy of the amount of the gear blank production for each machining plan and the nondeterminacy of the selected machining equipment, the gear blank can be produced with the characteristic of the uncertainty production. The gear to be machined and parameters are as follows in Fig. 2.

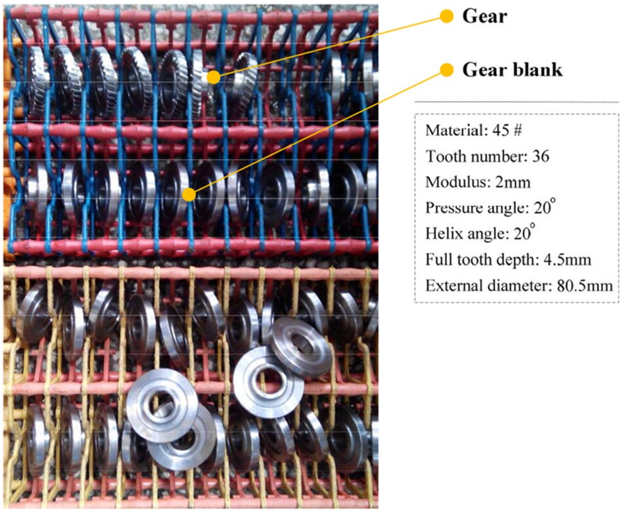
Regarding the total production requirements or production amount that is 300 gears, the production scale can be divided into two categories: mass production and small production, considering the production capacity of machine tools or machining systems in this machining workshop in the Chongqing Machine Tool Works Co., Ltd., China. For these gears to be produced, production amount of the mass production and small production can be roughly estimated as 260 gears ($n_{mass} = 260$) and 40 gears ($n_{small} = 40$), respectively, in terms of the experience of the technician. The *SEC* of each machining plan can be estimated based on the previous energy model and basic data (energy-related data and energy-unrelated data). In this case, for the mass production and small production, the specific machining plan and the number of the machining plan can be determined synthetically considering the manufacturing equipment (machine tools) and quantity. The number of the machining plan for the mass production is two types, and the manufacturing equipment are the machine tool (CHK560CNC lathe) and the machine tool (GSK980TDb). The number of the machining plan for the small production is one type, and the manufacturing equipment are the machine tool (CD6140A).

Similarly, the *SEC* of each machining plan can be acquired using above method, and the number allocation for each machining plan is as follows in Table 4. In terms of the Eqs. (7)–(16), SEC_{mass} and SEC_{small} can be determined as 0.1379 kWh and 0.2031 kWh, and ω_{mass} and ω_{small} also can be determined as 0.867 and 0.133. Therefore, for the gear blank under the uncertainty production task, the PEB_u and TEC_T can be acquired, and PEB_u is 0.1466 kWh, and TEC_T is 43.98 kWh.

On basis of the acquiring the benchmark in machining systems under the certainty production task and the uncertainty production task, it is easy to develop a systematic energy benchmark card to control energy consumption and perform energy efficiency monitoring as shown in Fig. 3. The energy benchmark card comprises more information including product information, production information, energy information and energy suggestion. In real production, the energy benchmark card is uniformly structured with a coloured frame to draw people's attention in the factory hall to provide some necessary information for operators and

Table 3 Machining processes and parameters for the cylindrical gear

Step	Content		Spindle speed (rpm)	Feed (mm/r)	Depth of cut (mm)
	Machining processes	Cutting times for machining			
CHK560CNC					
1	End of turning	Once	220	0.22	0.5
2	Turing(Ø31.4 mm)	Twice	200	0.22	3.5
3			200	0.22	
4	End of turning	Twice	200	0.22	0.5
5			200	0.22	
6	End of turning	Twice	200	0.22	0.5
7			300	0.22	
8	Turing for the central cylindrical and R	Six times	350	0.22	0.4
9			350	0.22	
10			350	0.22	
11			350	0.22	
12			350	0.22	
13			350	0.22	
14	Turing for the central cylindrical	Three times	300	0.15	0.18
15			300	0.15	
16			300	0.15	
17	Turing hole (Ø55.6 mm)	Twice	450	0.22	1.6
18			450	0.22	
19	Turing R	Once	250	0.15	0.1
20	Exchanging plane				
21–40	Repeating the above steps: 1–19				
Y3150E					
41	Hobbing	Three times	120	0.007	6
42			120	0.014	3.5
43			120	0.014	0.5



Material: 45 #
Tooth number: 36
Modulus: 2mm
Pressure angle: 20°
Helix angle: 20°
Full tooth depth: 4.5mm
External diameter: 80.5mm

Fig. 2 The gear blank, gear and parameters

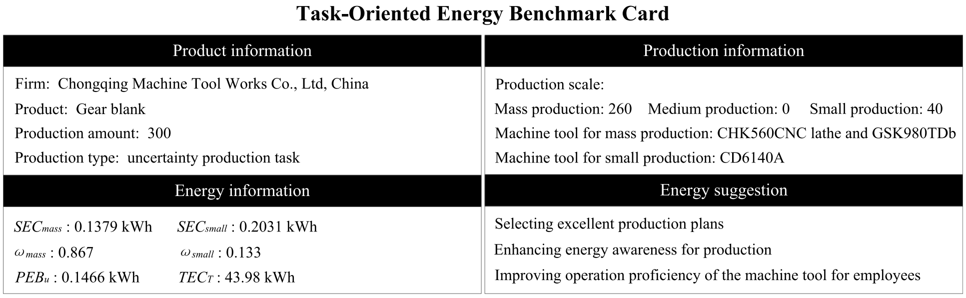
managers. Besides, the energy benchmark card can further be a benchmark compared with the same product among firms, and will become a standard to promote the sustainable production. The benchmark is expected to be a new tool that helps to improve the efficiency and performance of energy utilisation.

6 Discussion

The proposed method is an effective measure to promote product energy management and energy efficiency improvement in machining systems, especially for the energy-efficient production for the batch production. In previous studies, there are few useful methods available for developing the energy benchmark in machining with merely macro framework [6]. Recently, development of the energy benchmark become a focus. Methods for establishing the energy benchmark in machining are illustrated by authors, as shown in Table 5. The proposed method is the forecast method by building energy models. The proposed models, especially for

Table 4 The SEC of each machining plan and number allocation

Production scale	No. of machining plan	Machine tool (s)	SEC (kWh)	Number allocation
Mass production	1th	CHK560CNC lathe	0.1539	130
	2th	GSK980TDb	0.1218	130
Small production	1th	CD6140A	0.2031	40



Task-Oriented Energy Benchmark Card

Product information	Production information
Firm: Chongqing Machine Tool Works Co., Ltd, China Product: Gear blank Production amount: 300 Production type: uncertainty production task	Production scale: Mass production: 260 Medium production: 0 Small production: 40 Machine tool for mass production: CHK560CNC lathe and GSK980TDb Machine tool for small production: CD6140A
Energy information	**Energy suggestion**
SEC_{mass} : 0.1379 kWh SEC_{small} : 0.2031 kWh ω_{mass} : 0.867 ω_{small} : 0.133 PEB_u : 0.1466 kWh TEC_T : 43.98 kWh	Selecting excellent production plans Enhancing energy awareness for production Improving operation proficiency of the machine tool for employees

Fig. 3 Energy benchmark card for the gear blank under uncertainty production task

Table 5 Differences among prediction method, expert decision, and statistical analysis [43]

Methods	Applicability		Data requirements		Model requirements			Reliability		
	New workpieces	Processed workpieces	Low	High	Low	Medium	High	Bad	Good	Excellent
Forecast method	√	√		√			√		√	
Statistical analysis		√		√		√				√
Expert decision	√	√	√		√			√		

the total formula Eq. (2), is reliable. The forecast error for the formula is within 10%. In this case, the forecast error of the energy consumption model is as followed

$$\Delta_{Error} = \frac{\left|SEC_{Fore} - SEC_{Actu}\right|}{SEC_{Actu}} = \frac{\left|\sum_{i=1}^{m}\left(\sum_{j=1}^{n_{sb}} E_{sb_{ij}} + \sum_{j=1}^{n_{st}} E_{st_{ij}} + \sum_{j=1}^{n_{id}} E_{id_{ij}} + \sum_{j=1}^{n_{cm}} E_{cm_{ij}}\right) - SEC_{Actu}\right|}{SEC_{Actu}} = 8.75\%.$$

Realistically, forecast deviation of energy consumption in standby, starting and idling procedures which mainly depends on the accuracy of basic databases by observed measurement is small. In cutting material procedures, the forecast deviation of its energy consumption is higher than standby, starting and idling procedures. However, the average energy consumption of cutting material procedures only occupies less than 30% of total energy consumption of machining processes according to statistical analysis, which has less effect on prediction deviation relatively. Thus, it can be found that the accurate establishment of basic databases is the key to reduce the prediction deviation. Some random factors in machining process also affect the forecast accuracy, which can be accepted to some extent. Actually, the accuracy of proposed method for forecasting energy consumption is generally higher than 90% according to statistical analysis of 24 machining plans in Fig. 4.

Besides acceptable forecast accuracy of the proposed method, the method provides an effective solution for performing energy management of batch production, not merely cares for the level of the unit workpiece compared with latest research [36]. Actually, it is more important for the firm and workshop in the task-oriented energy management and energy-efficient production. The use of energy can be measured and quantified for the production task by the current method including the certainty production task

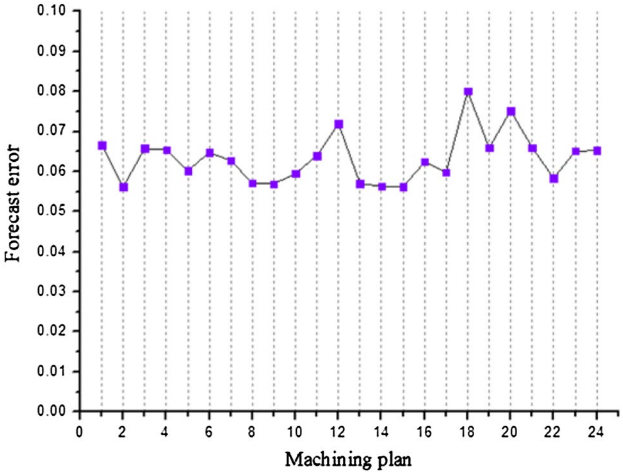


Fig. 4 The forecast error of energy consumption model for this case

and uncertainty production task. On the other hand, energy managers can master the overall energy consumption level of the production task and determine whether it is eligible. The energy benchmark also benefits energy audits, energy statistics, and energy-efficient analysis, aiding the decision making of energy managers.

In the production investigation on machining workshop, the phenomenon in the production workshop, which the majority of operators usually keep machine tools running standby for a long time without machining, is very common. The operation is not adroit in the idling and cutting material processes lacking energy saving consciousness. Through rough estimation and data statistical analysis, the energy consumption of the machining process has more than 20% energy-saving potential in this machining workshop. Implementing the energy benchmark is beneficial to energy management and energy efficiency improvement for production task. Meanwhile, institution of energy consumption restraint and supervision could be established in terms of this benchmark, which carries out a reward and punishment system. The waste of energy caused by a long running time for machine tools and other unreasonable operations also can be avoid for operators and the energy saving consciousness can be enhanced.

7 Conclusions

With a wide distribution and large amount of energy consumption at a low efficiency, machining systems have considerable energy-saving potential. The energy benchmark has been recognised as an effective analytical methodology and management tool that help to improve the efficiency and performance of energy utilisation. In this study, a concept of task-oriented energy benchmark was proposed contributing to promoting the energy-efficient production. The results of the study were summarised as follows.

First, previous studies on energy benchmarks related to machining or production were analysed. We proposed a task-oriented energy benchmark to overcome existing deficiencies. The benchmark synthetically considered two circumstances of production task from the perspective of the certainty production task and uncertainty production task. Second, this paper illustrated the goal and scope definition for the task-oriented energy benchmark and presented a method for developing the task-oriented energy benchmark in machining systems. The database for supporting establishment of the benchmark was described including the energy-related data, energy-unrelated data and production data. For the benchmark under certainty production task, this paper proposed two kinds of benchmarks that included the benchmark with historical machining information and the benchmark without historical machining information, further introduced corresponding benchmark models. For the benchmark under uncertainty production task, an important parameter of process correlation coefficient that describes relations among production task was proposed on basis of obtaining the benchmark under certainty production task. The method for establishing the benchmark under certainty production task using the process correlation coefficient was presented. Finally, the task-oriented energy benchmark was applied to the real machining system showing that the proposed method was feasible for establishing an energy benchmark for the certainty production task and uncertainty production task, which plays a crucial role in strengthening energy management and promoting the energy-efficient production.

Acknowledgements The authors acknowledge the technical support from Chongqing Machine Tool Works Co., Ltd., China. The project is supported by the Fundamental Research Funds for the Central Universities (SWU118068), and National Natural Science Foundation of China (Grant Nos. 51805479, 51875480 and 51705055).

References

1. Müller, J. M., & Voigt, K. I. (2018). Sustainable industrial value creation in SMEs: a comparison between industry 4.0 and made in China 2025. *Int J Precis Eng Manuf Green Technol, 5*(5), 659–670.
2. Li, L., Huang, H., Zhao, F., et al. (2017). An energy-saving method by balancing the load of operations for hydraulic press. *IEEE/ASME Trans Mechatron, 22*(6), 2673–2683.
3. Deng, Z., Lv, L., Huang, W., et al. (2019). A high efficiency and low carbon oriented machining process route optimization model and its application. *Int J Precis Eng Manuf Green Technol, 6*(1), 23–41.

4. Cai, W., Liu, C., Zhang, C., et al. (2018). Developing the ecological compensation criterion of industrial solid waste based on emergy for sustainable development. *Energy, 157,* 940–948.
5. Jiang, Z., Jiang, Y., Wang, Y., et al. (2019). A hybrid approach of rough set and case-based reasoning to remanufacturing process planning. *J Intell Manuf, 30*(1), 19–32.
6. Liu, F., Zhou, X. N., & Cai, W. (2015). The complexity and strategy for establishing product energy consumption allowance in discrete manufacturing industry. *J Mech Eng, 10*(19), 138–145. **(in Chinese)**.
7. 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. *Int J Precis Eng Manuf Green Technol, 6,* 1–17.
8. Cai, W., Liu, C., Lai, K. H., Li, L., Cunha, J., & Hu, L. (2019). Energy performance certification in mechanical manufacturing industry: a review and analysis. *Energy Convers Manag, 186,* 415–432.
9. Cai, W., Lai, K., Liu, C., et al. (2019). Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy. *Sci Total Environ, 665,* 23–32.
10. Zhao, J., Li, L., Wang, Y., et al. (2019). Impact of surface machining complexity on energy consumption and efficiency in CNC milling. *Int J Adv Manuf Technol, 102,* 1–15.
11. Woo, W. S., & Lee, C. M. (2018). A study on the optimum machining conditions and energy efficiency of a laser-assisted fillet milling. *Int J Precis Eng Manuf Green Technol, 5*(5), 593–604.
12. EIA (2011) Annual energy review. 2011. Last visited: March 2015, http://www.eia.gov/totalenergy/data/an-nual/index.cfm.
13. Mori, M., Fujishima, M., Inamasu, Y., et al. (2011). A study on energy efficiency improvement for machine tools. *CIRP Ann Manuf Technol, 60*(1), 145–148.
14. ISO 14955-1:2014. Machine tools—environmental evaluation of machine tools-part 1: design methodology for energy-efficient machine tools. International Organization for Standardization (ISO), 2014.
15. European Commission (EC). Directive 2009/125/EC of the European parliament and of the council of 21 October 2009. http://eurlex.europa.eu/legalcontent/EN/TXT/PDF/?uri¼CELEX:32009L0125&from¼EN. Accessed 29 Apr 2015.
16. JIS TS B 0024-1:2010. Machine tools—test methods for electric power consumption—part 1: machining centres. Japanese Standards Association, 2010.
17. Yoon, H. S., Kim, E. S., Kim, M. S., et al. (2015). Towards greener machine tools—a review on energy saving strategies and technologies. *Renew Sustain Energy Rev, 48,* 870–891.
18. Hu, L., Tang, R., Cai, W., Feng, Y., & Ma, X. (2019). Optimisation of cutting parameters for improving energy efficiency in machining process. *Robot Comput Integr Manuf, 59,* 406–416.
19. Gutowski, T. G., Branham, M. S., Dahmus, J. B., Jones, A. J., Thiriez, A., & Sekulic, D. P. (2009). Thermodynamic analysis of resources used in manufacturing processes. *Environ Sci Technol, 43*(5), 1584–1590.
20. Kara, S., & Li, W. (2011). Unit process energy consumption models for material removal processes. *CIRP Ann Manuf Technol, 60*(1), 37–40.
21. Oh, N. S., Woo, W. S., & Lee, C. M. (2018). A study on the machining characteristics and energy efficiency of Ti-6Al-4V in laser-assisted trochoidal milling. *Int J Precis Eng Manuf Green Technol, 5*(1), 37–45.
22. Jackson, M. A., Van Asten, A., Morrow, J. D., et al. (2018). Energy consumption model for additive-subtractive manufacturing processes with case study. *Int J Precis Eng Manuf Green Technol, 5*(4), 459–466.
23. Jia, S., Yuan, Q., Cai, W., Li, M., & Li, Z. (2018). Energy modeling method of machine-operator system for sustainable machining. *Energy Convers Manag, 172,* 265–276.
24. Balogun, V. A., & Mativenga, P. T. (2013). Modelling of direct energy requirements in mechanical machining processes. *J Clean Prod, 41,* 179–186.
25. Zhou, X., Liu, F., & Cai, W. (2016). An energy-consumption model for establishing energy-consumption allowance of a workpiece in a machining system. *J Clean Prod, 135,* 1580–1590.
26. Zheng, J., Lai, X., Zhou, X., Chen, A., & Zheng, W. (2019). Non-pulsed energy modeling based on energy consumption subunits in wire electrical discharge machining (WEDM) process. *Int J Precis Eng Manuf, 20,* 1–10.
27. Kellens, K., Dewulf, W., Lauwers, B., et al. (2013). Environmental impact reduction in discrete manufacturing: examples for non-conventional processes. *Procedia CIRP, 6,* 27–34.
28. Spiering, T., Kohlitz, S., Sundmaeker, H., et al. (2015). Energy efficiency benchmarking for injection moulding processes. *Robot Comput Integr Manuf, 36,* 45–59.
29. Kellens, K., Renaldi, R., Dewulf, W., et al. (2014). Environmental impact modeling of selective laser sintering processes. *Rapid Prototyp J, 20*(6), 459–470.
30. Jia, S., Yuan, Q., Cai, W., Lv, J., & Hu, L. (2019). Establishing prediction models for feeding power and material drilling power to support sustainable machining. *Int J Adv Manuf Technol, 100*(9–12), 2243–2253.
31. Mathew, N. T., & Vijayaraghavan, L. (2017). Environmentally friendly drilling of intermetallic titanium aluminide at different aspect ratio. *J Clean Prod, 141,* 439–452.
32. Li, W., & Kara, S. (2011). An empirical model for predicting energy consumption of manufacturing processes: a case of turning process. *Proc Inst Mech Eng Part B J Eng Manuf, 225*(9), 1636–1646.
33. Cai, W., Liu, F., & Hu, S. (2018). An analytical investigation on energy efficiency of high-speed dry-cutting CNC hobbing machines. *Int J Sustain Eng, 11*(6), 412–419.
34. Zein, A., Li, W., Herrmann, C., et al. (2011). Energy efficiency measures for the design and operation of machine tools: an axiomatic approach. *Glocalized solutions for sustainability in manufacturing* (pp. 274–279). Berlin, Heidelberg: Springer.
35. Koo, C., & Hong, T. (2015). Development of a dynamic operational rating system in energy performance certificates for existing buildings: geostatistical approach and data-mining technique. *Appl Energy, 154,* 254–270.
36. Cai, W., Liu, F., Xie, J., et al. (2017). An energy management approach for the mechanical manufacturing industry through developing a multi-objective energy benchmark. *Energy Convers Manag, 132,* 361–371.
37. Porzio, G. F., Fornai, B., Amato, A., et al. (2013). Reducing the energy consumption and CO2 emissions of energy intensive industries through decision support systems–an example of application to the steel industry. *Appl Energy, 112,* 818–833.
38. Yang, F., Liu, Y., & Liu, G. (2016). A process simulation based benchmarking approach for evaluating energy consumption of a chemical process system. *J Clean Prod, 112,* 2730–2743.
39. Sahoo, L. K., Bandyopadhyay, S., & Banerjee, R. (2014). Benchmarking energy consumption for dump trucks in mines. *Appl Energy, 113,* 1382–1396.
40. Wang, E., Shen, Z., Alp, N., et al. (2015). Benchmarking energy performance of residential buildings using two-stage multifactor data envelopment analysis with degreeday based simple-normalization approach. *Energy Convers Manag, 106,* 530–542.
41. ElMaraghy, H. A., Youssef, A. M. A., Marzouk, A. M., et al. (2017). Energy use analysis and local benchmarking of manufacturing lines. *J Clean Prod, 163,* 36–48.

42. Cai, W., Liu, F., Zhang, H., et al. (2017). Development of dynamic energy benchmark for mass production in machining systems for energy management and energy-efficiency improvement. *Appl Energy, 202,* 715–725.
43. Cai, W., Liu, F., Xie, J., et al. (2017). A tool for assessing the energy demand and efficiency of machining systems: energy benchmarking. *Energy, 138,* 332–347.
44. Dan, Song, Jin, Yang, & Bin, Chen. (2016). Life-cycle environmental impact analysis of a typical cement production chain. *Appl Energy, 64,* 916–923.
45. Ji, C., & Hong, T. (2016). Comparative analysis of methods for integrating various environmental impacts as a single index in life cycle assessment. *Environ Impact Assess Rev, 57,* 123–133.
46. Cai, W., Liu, F., Zhou, X. N., et al. (2016). Fine energy consumption allowance of workpieces in the mechanical manufacturing industry. *Energy, 114,* 623–633.
47. Liu, F., Xie, J., & Liu, S. (2015). A method for predicting the energy consumption of the main driving system of a machine tool in a machining process. *J Clean Prod, 105,* 171–177.
48. Huang, J., Liu, F., & Xie, J. (2016). A method for determining the energy consumption of machine tools in the spindle start-up process before machining. *Proc Inst Mech Eng Part B J Eng Manuf, 230*(9), 1639–1649.
49. Hu, S. H., Liu, F., He, Y., & Peng, B. (2010). Characteristics of additional load losses of spindle system of machine tools. *J Adv Mech Des Syst, 4*(7), 1221–1233.
50. Liu, P., Liu, F., & Liu, G. (2017). A new approach for calculating the input power of machine tool main transmission systems. *Adv Mech Eng, 9*(9), 1687814017723791.

Wei Cai received Ph.D. degree in mechanical engineering from Chongqing University, China, in 2018. Currently, he is a lecturer at Department of Mechanical Engineering, College of Engineering and Technology, Southwest University, Chongqing, China. His fields of interest are green manufacturing, sustainability evaluation and energy benchmarking.

Li Li received Ph.D. degree from Chongqing University, China, in 2011. Currently, she is a professor at Department of Mechanical Engineering, College of Engineering and Technology, Southwest University, Chongqing, China. Her fields of interest are green manufacturing and intelligent manufacturing.

Shun Jia received Ph.D. degree from Zhejiang University, China, in 2014. Currently, he is an associate professor at the Shandong University of Science and Technology. His fields of interest are sustainable design and manufacturing and low carbon manufacturing and lean production.

Conghu Liu received Ph.D. degree from Hefei University of Technology, China, in 2016. Currently, he is an associate professor of Suzhou University. He is a post-doctoral researcher at Sino-US Global Logistics Institute, Shanghai Jiao Tong University, Shanghai, China. His fields of interest are sustainable production systems, remanufacturing and green supply chains.

Jun Xie received Ph.D. degree from Chongqing University, China, in 2016. Currently, he is an associate professor at the Chongqing technology and Business University. His fields of interest are sustainable manufacturing, low carbon manufacturing and energy optimization.

Luoke Hu (M'18) received the B.Eng. degree in industrial engineering from Zhejiang University of Technology, Hangzhou, China, in 2011, and the Ph.D. degree in industrial engineering from Zhejiang University, Hangzhou, China, in 2017. He was a visiting scholar with the Institute for Manufacturing, Department of Engineering, the University of Cambridge, Cambridge, U.K., from 2014 to 2015. He is currently a research associate with the School of Mechanical Engineering, Zhejiang University, Hangzhou, China. His research interests include sustainable manufacturing, intelligent manufacturing, and energy optimisation.