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Dynamic Acquisition and Real-Time Distribution of Carbon Emission for Machining Through Mining Energy Data

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ABSTRACT The acquisition and distribution of carbon emission in manufacturing process are usually regarded as a precondition for management and decision making of carbon emission reduction in mechanical manufacturing industry. Current researches regarding acquisition of carbon emission for mechanical manufacture mainly derive from static statistics and are insufficient to reflect interactive influence of running statues and production processes on carbon emission in mechanical processing. This paper proposed a dynamic acquisition of carbon emission for mechanical manufacture, especially for machining process, which contributes to carbon emission monitoring and management in manufacturing process and overcomes existing deficiencies in static statistic methods. Furthermore, a dynamic monitoring system, consisting of single-machine and multi-machine levels, is developed to verify the feasibility of the proposed method, and is applied in a machining workshop. Case study shows that the proposed method is valid to obtain dynamic variation and distribution of carbon emission, to determine influence of running statues or production processes on emission carbon and to explore potential emission reduction strategies.

INDEX TERMS Carbon emission, mechanical manufacture, dynamic acquisition, emission reduction strategy.

I. INTRODUCTION

Climate change [1], low-carbon economy [2] and carbon trading [3] have attracted increasing attentions from international organizations, industries, and scholars over 100 years. Numerous researches about carbon emission have been applied in forest [4], transports[5], fossil fuel [6], residence [7], among others. In recent years, study on carbon emission has aroused extensive interest in energy-intensive industries, especially mechanical manufacture due to its wide distribution and considerable emission [8]. For example, CO_2 emission of a numerical control machine tool with main shaft power in 22 kW operating one year sometimes is equivalent to that of 61 SUV cars operating in 19,320 km for a one-year period [9]. Therefore, carbon emission retrofitting in mechanical manufacture is a valid field for reducing energy consumption and carbon emission in industry and is achieving increasing importance worldwide.

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A newly-developing approach for this goal is Low carbon manufacturing (LCM), which are required as the process emitting low carbon dioxide intensity from the system sources and during the manufacturing process [10]. Five characterizations of the LCM were discussed by Tridech and Cheng [11] in the 6th international conference on manufacturing research. They pointed out that reducing energy consumption and carbon emission from emission-sources such as machines or equipment is the most helpful measurement for the LCM. Xu *et al.* [12] analyzed the impact of efficiency, investment, and competition on the LCM by studying two rival manufacturers' optimal pricing and emission reduction decisions with different market power structures, indicating that the attribute of low carbon has become a key influential aspect for customers.

The above studies mainly presented the completion, theoretical characterization, and carbon emission management in manufacture process, and pointed out that the obtainment and distribution of carbon emission were a precondition for management and decision making of carbon emission reduction in the LCM.

For mechanical processing, the obtainment of carbon emission, especially dynamic acquisition, has two contributions. On one hand, the power or energy demand in machining process are changeful and various [13]. The cutting parameters affecting carbon emission in machining process, usually depend on operators' experience and are various as well [14]. Take turning [15] or laser sintering [16] for example, there would be thousands of parameters, even for the same task. So, carbon emission in machining process is hard to be estimated exactly in real time. Oppositely, dynamic acquisition is valid way to reveal its dynamic performance and can provide more accurate data for carbon emission calculation online [17]. On the other hand, existing study [18] has demonstrated that real-time running statues of machine tools are indirectly related to carbon emission. Dynamic acquisition of carbon emission can provide running statues monitoring of machine tools indirectly, helping operators to manage devices and avoid some inappropriate long-standby or long-idling process. For instance, Liu *et al.* [19] proposed a method to identify and manage cutting status though real-time emission source. Lin *et al.* [20] analyzed the relationship between carbon emissions (i.e., use of cutting fluids, deposition of worn tools and material consumption) and turning operations, and presented a approach to determine operation time of lathe. The research by Hu *et al.* [21] on spindle power in operating state also shown that running statues of machine tools can be acquired though carbon emissions as power consumption is the main carbon source for a machine tool.

Efforts to measure and acquire carbon emission have been made since the 19th century to obtain the distribution of atmospheric CO_2 and to explore emission reduction strategies. Initially, carbon dioxide was measured through collecting air samples in flask or other container and analyzing the air later in the laboratory [22]. Later, a laser-based absorption spectroscopy technique, called cavity ring-down spectroscopy (CRDS), was developed to monitor CO_2 and had an extensive application as a consequence of its high sensitivity of the method [23]. For example, an established series of devices for measurements of greenhouse gas (GHG) are the Trace Gas Analyzers manufactured by Picarro, Inc [24]. The device has a good stability and been used at many sites of the international GHG monitoring network [25]. However, these direct tests based on air sample or greenhouse gas analyzers are difficult to be applied into dynamic acquisition of carbon-dioxide in machining process because carbon emissions from manufacturing process are indirect-emission process caused by energy consumption, i.e., there is no produced CO_2 on site.

Several studies [26], [27] have reported carbon emission acquisition methods related to manufacturing industry or mechanical processing. For example, Zhang *et al.* [28] presented a carbon flow model to quantify CO_2 emission and analyze CO_2 emission-affecting factors in iron and steel manufacturing. Adopting the similar computing process, a GHG emission calculation method was proposed by Lei *et al.* [29] for forging machine at its manufacturing stage, and a calculation model for carbon emission of product in mechanical processing stage was established [30]. Moreover, Ren *et al.* [31] established a model of CO_2 emissions based on IPCC to acquire and analyze the decoupling of carbon dioxide emissions in China's manufacturing industry.

These mentioned methods, which in nature are static acquisitions, have two obvious characteristics. On one hand, it shows essentially simple numerical values interpreted as a relationship between one production equipment (or produced object) and a numerical value of carbon emission. Therefore, it can be easily understood by consumers. However, on the one hand, actual real-time emission value and distribution (or footprint) are impossible to be reflected in static carbon-emission acquisitions due to variation and uncertainty of dynamic data such as real-time power and production tasks. Meanwhile, influence of machine tools or process parameters on carbon emission in mechanical processing are not emerged in static carbon-emission acquisitions, which makes it difficult for manager, technologist, and operator of machine tool to perform carbon emission management and reduce carbon emission of mechanical manufacture. For example, Carbon Emission Signature (CES^{TM}) for a single part only presented the total emission [30]. The footprint of carbon emission at any manufacturing process, which may support optimization at accurate position, is not afforded.

This paper proposes a dynamic acquisition of carbon emission (DACE) by mining the related dynamic data in manufacturing process to implement the real-time acquisition of carbon emission and obtain distribution of carbon emission online in mechanical processing. The rest of this paper is structured as follows: Section II describes scope of study and system boundary and Section III presents detail process of the DACE method. Section IV shows the development of dynamic monitoring system of carbon emission based the proposed method and Section V describes test results and related discussions.

This paper makes two main contributions. A dynamic acquisition of carbon emission is proposed through mining energy data, not only highlighting actual carbon emission distribution or carbon footprint for the production object or equipment in mechanical processing but also providing a real-time data foundation for analyzing and revealing interactive influence of running statues and production processes on carbon emission in mechanical processing. And a dynamic monitoring system based on the proposed method is developed and applied into a machining workshop, proving the rationality and feasibility, and showing influence of different running statues and production processes on carbon emission.

NOMENCLATURE

$CE(CO_2)$	Carbon emission
CEM_{sb}	Standby emission
CEM_{id}	Idling emission
CEM_c	Cutting emission
CEM_T	Total emission
CEM_i	Carbon emission of the i-th machine tool
CEL	Production-line emission

CEU	Production-unit emission
CES	Workshop-floor emission
CEW_{ms}	Machining-step emission
$CEW_{w,s}$	Standby emission for a machining step,
$CEW_{w,id}$	Idling emission for a machining step
$CEW_{w,c}$	Cutting emission for a machining step
CEW_{mp}	Manufacturing-procedure emission
CEW	Work piece emission.
P	Power demand
$SECe$	Electric energy consumed
t	Time
t_{sb}	Standby time
t_{id}	Idling time
t_c	Cutting time
T	Total time
U, L, S	Total number of machine tools in the corresponding production unit, production line, and workshop
V_{cr}	Emission rate
δ_{e-c}	Emission factor for industrial electricity

II. SCOPE OF STUDY AND SYSTEM BOUNDARY

Mechanical manufacture is generally an industry sector which engages in product manufacturing of various mechanical products, including design and planning of production, workblank manufacturing, mechanical processing of work piece, assembly, etc. The proposed DACE method is mainly used to monitor the dynamic variation of carbon emission in mechanical processing, with the consideration that the energy consumption and carbon emission in mechanical processing are changeful and complicated.

Mechanical processing is a production process of converting workblanks (or semi-products) into work pieces by employing machining methods such as turning, milling, grinding, boring, drilling, etc. [32], as shown Figure 1. The corresponding energy consumption and carbon emission in mechanical processing are various and complicated, reflected in the following aspects. The mechanical or electrical equipment causing carbon emission is numerous, including lathe, milling machine, drilling machine and other production equipment. For a certain machine tool or production unit, there usually are hundreds of different tasks or operations. Furthermore, processing parameters, even for a same task, are various and inconstant. All these factors have a non-ignorable impact on energy consumption and carbon emission of machining process [33].

FIGURE 1. Schematic diagram of mechanical processing in mechanical manufacture.

Regarding system boundary, although carbon emission is caused by both production equipment (i.e., machine tools) and auxiliary equipment (such as light system and transportation system, etc.) in machining industry, auxiliary equipment is neglected in this study due to its lower variability and quantity.

III. THE DYNAMIC ACQUISITION OF CARBON EMISSION THROUGH MINING ENERGY DATA

From the perspective of operator and manager, machine tools and work pieces are two major subjects in manufacturing process. The dynamic acquisition objectives would center on carbon emission at machine tool level which mainly consists of real-time acquisition of both carbon emission and emission rate, and that at work piece level such as carbon emission from complete manufacturing process of a work piece and its compositions (e.g., manufacturing-procedures and machining-steps). To reach these goals, the DACE method is proposed. The corresponding framework is established as presented in Figure 2, which involves the following four steps: 1) Select acquisition models of carbon emission for mechanical manufacture; 2) Collect data related carbon emission, including energy data and production data; 3) Process data as required by employing software technology and communication protocol; 4) visual monitoring for carbon emission by employing human machine interface.

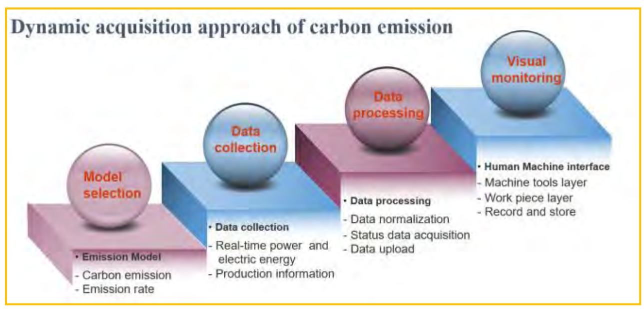


FIGURE 2. Framework of dynamic acquisition approach of carbon emission in mechanical manufacture.

A. CARBON EMISSION MODEL SELECTION

Carbon emissions in mechanical manufacture are caused indirectly by energy consuming in manufacture process. The collected data (e.g., real-time power and electric energy) need to be standardized and converted into carbon emission data before calculating and sending to upper management system. According to the *Guidance for Voluntary Greenhouse Gas Reporting* [34], the Eq. (1) is employed as the main calculating model of carbon emission for mechanical manufacturing process in this study.

$$CE(CO_2) = SECe * \delta_{e-c} \tag{1}$$

To ensure instantaneity and precision, emission rate which describes the instantaneous characteristics of carbon emission is also employed as another model for carbon emission. It can be established by taking a derivative of carbon emission in Eq. (1). The result of derivation is presented in Eq. (2), which shows the relationship between emission rate and power.

$$V_{cr} = \frac{\partial CE(CO_2)}{\partial t} = \frac{\partial SEC_e * \delta_{e-c}}{\partial t} = P * \partial_{e-c} \quad (2)$$

B. DYNAMIC DATA COLLECTION

The collected dynamic data involve real-time power of machine tools, electric energy of machine tools, and production information, as shown in Table 1.

TABLE 1. The composition of dynamic data.

Data	Detail	Purpose or Function
Power	Real-time power of total input for machine tools, real-time power for spindle of machine tools.	State recognition of machine tool, obtainment of emission rate.
Electric energy	Energy consumption at a transfer time interval (usually less than 5 second).	Obtainment of carbon emission.
Production information	Composition of production-unit, production-line, workshop-floor; Cutting parameters; Process schemes; Tools; Workpieces, etc.	Carbon emission calculation on different level.

In this study, real-time power and electric energy data usually are collected by employing power sensors and electric energy meters. For production information, it could be obtained from information management systems such as Manufacturing Execution System [35] and Enterprise Resource Planning systems [36], using computer communication technology in modern manufacturing plants. In ordinary workshop, production information can be obtained by human machine interface.

C. DATA PROCESSING

Data processing is composed of three parts, i.e., data normalization, running statuses acquisition, and data upload. Data normalization refers to the process of translating original energy data into carbon emission data by employing conversion models Eqs. (1) and (2).

Running status acquisition is a precondition to determine the influence of running statuses on carbon emission of machine tools [37]. For some CNC machine tools, running statuses can be obtained from CNC systems though computer communication technology if its communication protocol is open. For most ordinary machine tools with no CNC systems or whose CNC system is hard to access, running statuses consisting of standby status, idling status, etc., can be judged by analyzing real-time power and power-variability of machine tools as follows:

- Start of standby. Two cases are involved in start of standby: one is from stop to standby, and the other is from idling status to standby. The start moment for the former case is considered as the time at which the real-time obtained power increases from zero to nonzero. While for the latter case, it is considered as the time at which the real-time power decreases sharply and then remains near the standby power.
- Start of idling status. The moment when real-time power of spindle changes from zero to nonzero in standby process is usually taken as the start of idling status. And during cutting process, start time of idling state is considered as the time at which real-time obtained power of spindle decreases and then remains near the idling power.
- Start of machining status. During idling status, if real-time power of spindle increases and exceeds the fluctuation range of idling power, the changing moment will be judged as a start time of machining.
- off. If input power of machine tools changes from nonzero to zero, the changing time will be considered as a start of off status.

Both carbon emission data and the obtained status data need to be uploaded to upper layer for centralized management. For a single machine tool, data upload can be carried out though local communication technique if data processing and visual monitoring modules are in the same platform. For multi-machine system such as production line and workshop, data upload is performed by Internet communication technology because data acquisition, data conversion, and running statuses acquisition modules run in a computer but visual monitoring module runs in another hardware, e.g., server.

D. VISUAL MONITORING

Machine tools and work pieces, two major compositions in a mechanical manufacturing process, are taken as two objectives of visual monitoring in this study, as shown in Table 2. The visual monitoring on machine tool level is mainly employed to demonstrate interaction between carbon emission of machine tools and operational processes, which are divided into two parts: single machine and multi-machine. The visual monitoring on work piece level shows the interaction between carbon emissions and process conditions such as cutting parameters, materials, tools, etc., which helps to explore cutting parameters and schedule optimization for emission reduction. It includes carbon emission related to a work piece, a manufacturing procedure, and a machining step.

To reach above objectives in Table 2, an indicator system is established for visual monitoring, as presented in Table 3. Indexes on machine tool level involve that for a single machine tool and multiple machine tools. The former consists of real-time emission rate, standby emission, idling emission, cutting emission, and total emission. The latter involves production-unit emission, production-line emission, workshop-floor emission, and the corresponding emission rate such as production-unit emission rate, production-line emission rate, and workshop-floor emission rate.

Regarding indexes on single-machine level, emission rate is defined as the carbon emission per unit time, usually accurate to a second. its calculation model is presented in

TABLE 2. The objectives of visual monitoring for mechanical processing.

Scope		Objective
Machine tool level	Single machine	Emission rate to demonstrate dynamic variability of carbon emission. Carbon emission of different running statuses to explore interaction between running status and carbon emission. Daily or weekly emission to provide data for carbon emission management.
	Multi-machine	Real-time acquirement of carbon emission in production unit, production line and workshop to provide data for emission reduction management.
Work piece level	Work piece	Carbon emission of a work piece to provide base data for carbon emission benchmark or simple Carbon Emission Signature.
	Manufacturing procedure	The carbon emission of manufacturing procedure to analyze characteristic of schedule.
	Machining step	The carbon emission of machining step to analyze the influence of cutting parameters on carbon emission and to conduct cutting parameters optimizing for emission reduction.

TABLE 3. The indexes of visual monitoring.

Scope	Indexes
Single machine	Real-time emission rate, standby emission, idling emission, cutting emission, and total emission.
Multi-machine	Production-unit emission, production-line emission, workshop-floor emission, and the corresponding emission rate.
Work piece	Work-piece emission, Manufacturing-procedure emission, Machining-step emission.

in Eq. (2). Standby emission refers to the carbon emission from standby process of machine tools and is obtained by integrating emission rate from start time of standby to end time of the standby, as shown in Eq. (3). Similarly, idling emission and cutting emission are defined as the carbon emission from idling and cutting process, respectively, and the corresponding calculation models are presented in Eqs. (4) and (5). Moreover, total emission is defined as the total carbon emission from the start-up of machine tool to current moment. The computing model could be either Eq. (6) integrating emission rate from the start-up time to current time, or the Eq. (7) which sums carbon emission in standby, idling, and cutting processes. These equations are shown as follows.

$$CEM_{sb} = \int_{t_{sb}} V_{cr} dt \tag{3}$$

$$CEM_{id} = \int_{t_{id}} V_{cr} dt \tag{4}$$

$$CEM_{c} = \int_{t_{c}} V_{cr} dt \tag{5}$$

$$CEM_{T} = \int_{T} V_{cr} dt \tag{6}$$

$$CEM_{T} = CEM_{sb} + CEM_{id} + CEM_{c} \tag{7}$$

With respect to indexes on multi-machine level, production-unit emission, production-line emission generally refers to the carbon emission caused by machine tool groups in a production unit and a production line, respectively. Their calculation models are shown in Eqs. (8) and (9). Workshop-floor emission is defined as the carbon emission from a machining workshop. It can be obtained through Eq. (10). Moreover, production-unit emission rate, production-line emission rate, and workshop-floor emission rate are generally defined as the total carbon emission rate caused by equipment in the corresponding production unit, production line, and workshop, respectively. Their acquirements could be obtained through Eq. (2) or a sum of emission rate of each equipment in corresponding area. Related models' information is illustrated as follows.

$$CEU = \sum\nolimits_{U} CEM_i \tag{8}$$

$$CEL = \sum\nolimits_{L} CEM_i \tag{9}$$

$$CES = \sum\nolimits_{S} CEM_i \tag{10}$$

Furthermore, indexes for a work piece involves machining-step emission, manufacturing-procedure emission, and work-piece emission. Machining-step emission is defined as the carbon emission for accomplishing a machining-step. Its value is a sum of the standby emission, idling emission, and cutting emission in that machining-step, as shown in Eq. (11), because a typical machining-step generally is composed of three type of processes, i.e., standby process, idling process, and cutting process. As for manufacturing-procedure emission defined the total carbon emission for accomplishing a manufacturing-procedure, the calculation model is shown in Eq. (12), namely, sum of machining-step emissions. This is because the manufacturing-procedure consists of a series of machining-steps. Similarly, work-piece emission, which refers to the carbon emission for a finished workpiece, can be calculated by summing manufacturing-procedure emission, as shown in Eq. (13). Detailed equations are illustrated as follows.

$$CEW_{ms} = CEM_{w,s} + CEM_{w,id} + CEM_{w,c} \tag{11}$$

$$CEW_{mp} = \sum CEW_{ms} \tag{12}$$

$$CEW = \sum CEW_{mp} \tag{13}$$

IV. DEVELOPMENT OF DYNAMIC MONITORING SYSTEM

To verify the feasibility, a monitoring system based on the proposed method is developed to implement the carbon emission monitoring and management in a machining workshop. The development of monitoring system includes the following three steps. Firstly, Data, including energy data and production information, are collected from machine tools and handlers by using power sensor and Table-PC in Table 4. Secondly, the collected data are processed by the software in Table-PC and then be sent to local Table-PC for single-machine monitoring system and server for multi-machine monitoring through wireless transmission, as shown

TABLE 4. Technical features of the related hardware.

Device	Function	Type	Measuring range	Accuracy	Sample period
Power sensor	Collection of Main power and spindle power	HC-33C3	0-13KW	0.5% FS	50ms
USB-RS485 converter	Translate data from power sensor to Table-PC	Z-TEK, ZE533C	Transmission speed: 300–921.6 kbps		----
Wireless access point	Translate data from Table-PC to server	Aruba	----		----
Table-PC	Data process and monitoring visual for a single machine.	HTK	Cycle for data process: 250ms		
Server	Visual monitoring for multi-machine.	HP 778640-AA1	----	----	----

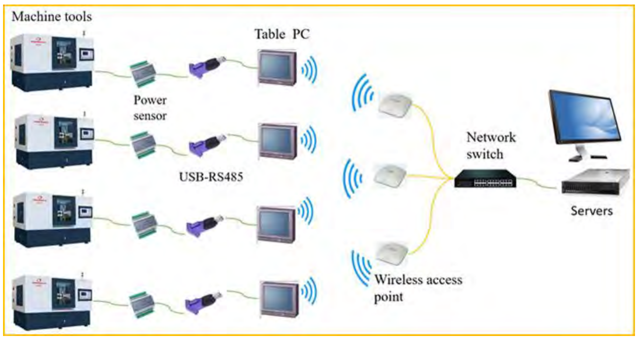


FIGURE 3. The framework of dynamic monitoring system.

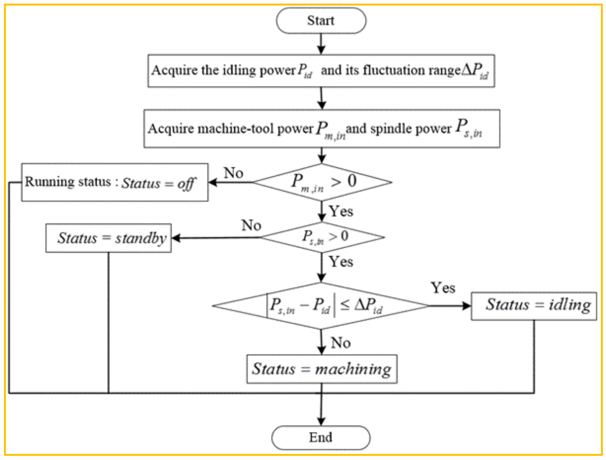


FIGURE 4. Judging procedure of running status of machine tools.

in Figure 3. Finally, Human Machine Interface (HMI) is employed to show the final information, including index parameters in Table 2 and running information of equipment.

As for the first step (i.e., data collection layer), the power data including real-time power and energy of machine tools are collected by power sensors installed in main switch and spindle, whose technical features are shown in Table 4. The simple period is required to be short, usually advised to less than 0.5s because some machining-steps or machining features may cost a very short time. As regards to the latter, production information such as manufacturing procedure and machining step information, is input through Human Machine Interface (HMI).

For the second step, data processing layer of the developed system involves three modules: data conversion, running statuses acquisition, and data upload. They are carried out by the corresponding software installed in Table-PC.

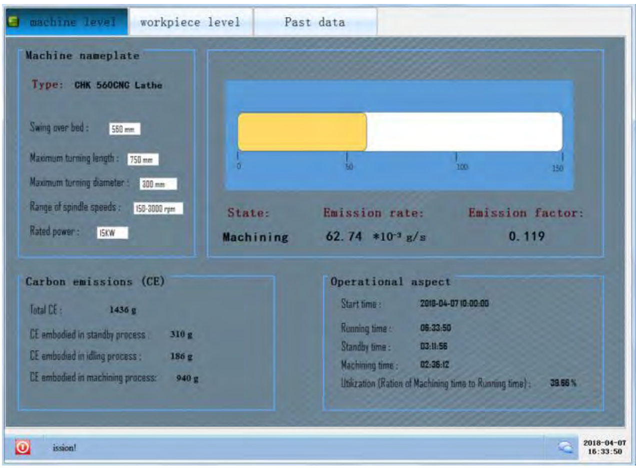
Data conversion refers to data normalization, that is, all energy and power data will be translated into carbon data before upload to visual monitoring layer. For industrial electricity, the conversion process is shown in Eqs. (1) and (2). Moreover, in monitoring system, the emission factor is 0.119, namely, 1 kwh electricity will bring about 0.119 Kg carbon emission [34].

Running status acquisition in this developed system is conducted by analyzing the real-time power and its variety, as illustrated in Figure 4: 1) If power demand at both total input and spindle input are zero, the running status will be considered as off; 2) If the total-input power of machine tool is nonzero but the spindle-input power is zero, the running status will be considered as standby; 3) If both total-input and spindle-input power are nonzero but the spindle power fluctuates in range of the predefined idling power, the running status is judged as idling; 4) If spindle-input power is nonzero and exceeds range of predefined idling power, the running status is judged as machining status.

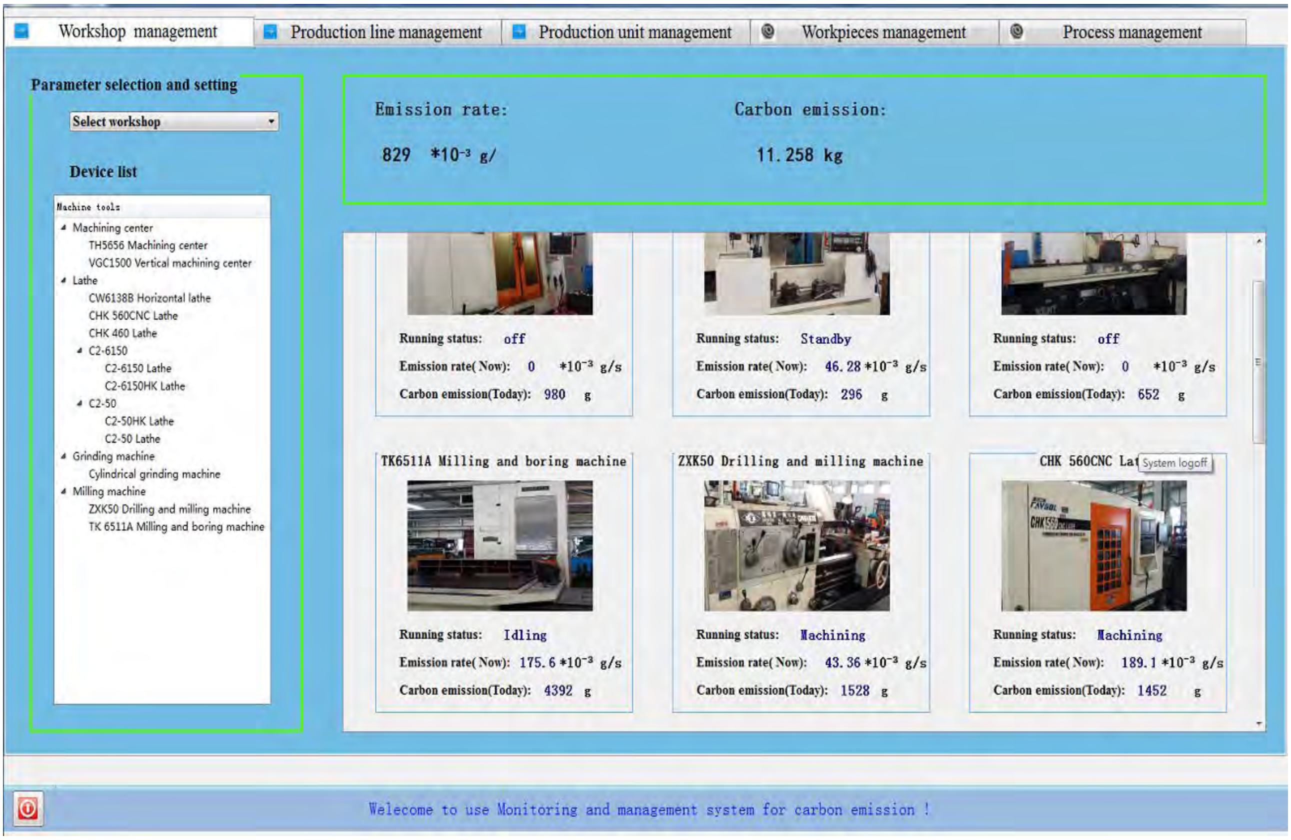
Data upload in the developed system involves two aspects. On one hand, the carbon emission and running status information is uploaded to server for multi-machine management by the wireless access point in Table 4. The upload period which should be bigger than the simple period of data collection is advised to be configurable. The default time of upload period in this developed monitoring system is one second. On the other hand, carbon emission and running status information are uploaded to local Table-PC for single-machine management by making use of the local communication technique. The upload period is the same to that for multi-machine management.

Regarding the third step, the visual monitoring layer of carbon emission for machining workshop consists of two aspects: single-machine system and multi-machine system.

The developed single-machine visual monitoring system, as shown in Figure 5 (a), involves machine tool level and work piece level. The detailed visual information on machine tool level involves the emission rate, carbon emission of different running statuses, and real-time running information related to carbon emission such as running time, equipment utilization. The visual information on work piece level includes carbon emission of any machining-step or manufacturing-process. Besides, to find the influence of process parameters on carbon emission in manufacturing process, the corresponding production information are also been shown in visual monitoring layer on work piece level.



(a)



(b)

FIGURE 5. (a) Single-machine visual monitoring. (b) Multi-machine visual monitoring.

The multi-machine monitoring visual system employed to manage multi-machine section, manufacturing procedure section, and work piece section in Table 2, is composed of five modules: workshop management, production line management, production unit management, workpiece management, and process management. The first three modules are responsible for carbon emission monitoring and management of machine tools in workshop, production line and production unit. The latter two modules, namely workpiece management and process management modules, are established to monitor and manage the carbon emission of manufactured work pieces, manufacturing-process emission and machining-step emission. The specific monitoring interface is shown in Figure 5 (b).

V. DISTRIBUTION OF CARBON EMISSION IN MACHINING PROCESS AND DISCUSSION

To verify the feasibility of the proposed method and the developed system, the developed system was applied in a machining workshop, as shown in Figure 6 (a) and (b).

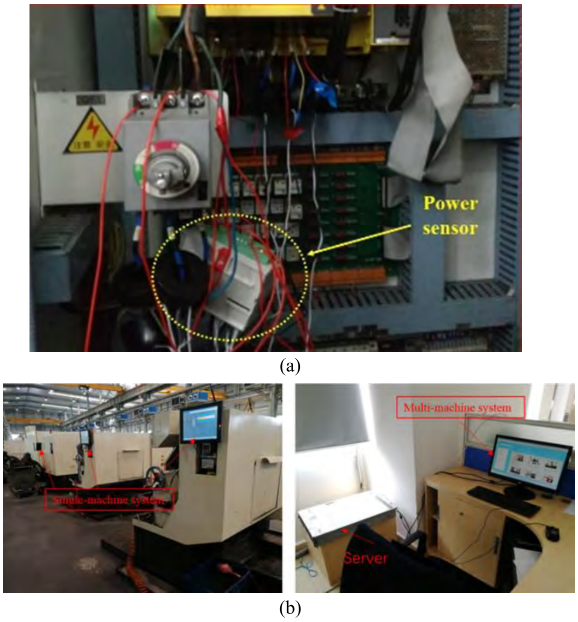


FIGURE 6. (a) Sensor installation. (b) Real-time monitoring on-site.

The power sensor in the developed system was installed in the electric cabinet and the Table-PC was installed next to the corresponding machine tool. Moreover, according to manufacturers' requirement, server and multi-machine system were installed in manager's office.

A. CARBON EMISSION DISTRIBUTION ON MACHINE TOOL LEVEL

The general carbon emission distribution on machine tool level is illustrated in Figure 7 and 8, which derives from a typical workday (8 hours) and daily manufacture-task. The average total emission of the selected machine tools in application case is approximately 1.626 Kg/day. The daily emission for each machine tool is shown in Figure 7, where different colors represent different quantitative values. Moreover, to find the corresponding machine tool fast, the position of each machine tool in the figure is in accordance with site location of that in workshop.

In this application case, only emission rate of a single machine tool is taken into consideration because emission rate for multi-machine system is just a sum of value for the single one. From the viewpoint of running processes and statuses of machine tools, the emission rate can be divided into three classes: emission rate in standby, idling, and machining process, respectively. Emission rate in standby, idling are shown in Figure 9 and 10. As emission rate in machining process is changeable and irregular, which brings little practicability in industrial application, the emission rate in machining process is not discussed in this section.

B. CARBON EMISSION FOOTPRINT ON WORK PIECE LEVEL

The carbon emission on work piece level includes machining-step emission, manufacturing-procedure emission, and work-piece emission, which are presented in the "process management" and "workpieces management" modules in Figure 5 (b). To determine effects of process parameters on carbon emission of manufactured product and to explore potential energy-saving and emission reduction strategies, five work pieces and their carbon emission are studied and discussed in this application case. Their production information such as manufacturing-procedures, machining-steps, and cutting parameters, is shown in Table 5. And their carbon emission including machining-step emission, manufacturing-procedure emission, and work-piece emission, are presented in Figure 11. The "11301A_1, 11301A_2, ..." in Table 5 and Figure is the step number named according to rule of the selected enterprise.

C. DISCUSSIONS

1) INFLUENCE OF RUNNING STATUES AND PROCESS PARAMETERS ON CARBON EMISSION

It can be concluded from Figure 8 that carbon emission in cutting process is the major source, usually accounting for more than 50 percent. The standby emission is less than idling emission for most cases. Moreover, monitoring results also show that carbon emissions for the same running state of different machine tools usually are different, e.g., idling emissions of TKA 6511 Milling and boring machine, CW 6138B Horizontal lathe and VGC1500 Vertical machining center are 1773g, 530g, and 171g, respectively. Even for the same type of machine tools such as CHK 560CNC Lathe, CHK 460 Lathe, C2-6510 HK Lathe, taking the standby emission as an example, the results are different as well.

From the viewpoint of emission rate, the monitoring results suggest that emission rate in both standby process and idling process at a certain revolving speed are constant. The Figure 9 illustrates that emission rate of different machine tools in standby usually are different, ranging from 6 to 148 *10-3 g/s, and some differ sharply. With respect to emission rate in idling process, the Figure 10 presenting the relationship between spindle revolving speeds and emission rate in idling process shows that emission rate in idling process increases with the rising revolving speeds. Some can be fitted as linear function with revolving speed as a variable, such as VGC 1500 Vertical machining center, C2-6510 Lathe, and ZXK50 Drilling and milling machine, and some can be fitted as quadratic function such as TK 6511A Milling and boring machine.

Regarding influences of process parameters on carbon emission, three aspects, i.e., work piece emission, manufacturing-procedure emission, and machining-step emission are discussed. The results in Figure 11 show that work-piece emissions for different work pieces usually are different. For example, the emissions of nut, shaft sleeve, cylindrical gear are 115.43g, 97.58g, 275.97g, respectively. Even for the same work piece, taking support shaft as an example, the results may also be different if the employed machine tools and cutting parameters are not same.

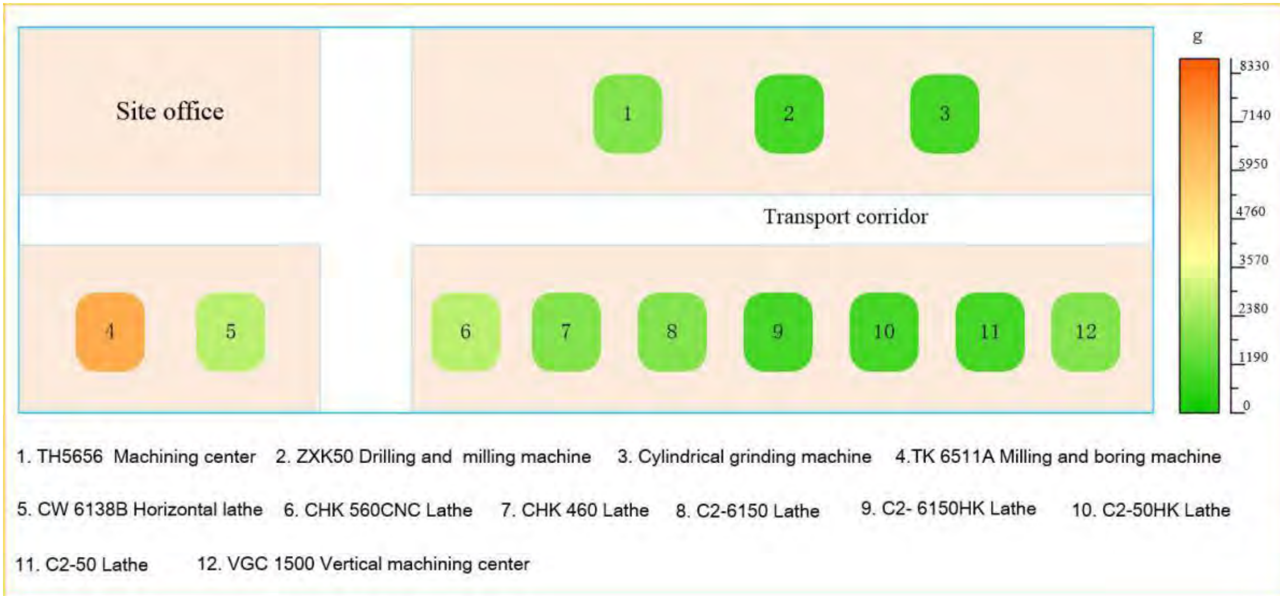


FIGURE 7. Distribution of carbon emission of workshop.

These two inferences are also suitable for machining-step emission and manufacturing-procedure emission, namely, different machining-steps and manufacturing-procedures will cause different carbon emission, and that even for the same type of machining-steps (i.e., 11301A_1 and 11301B_1) and manufacturing-procedures (i.e., 11301A_3 and 11301B_3), the carbon emission may also be different. In addition, carbon emission of a complicated machine-step may be more than that for a short manufacturing-procedure. An example is that the machining-step emission of 11306A_3 in Figure 11 is bigger than the manufacturing-procedure emission consisting of 11306A_1 and 11306A_2.

2) EMISSION REDUCTION STRATEGIES AT MACHINING WORKSHOP FLOOR

The above results have shown that both process parameters and machine tools have an influence on carbon emission in mechanical processing. Therefore, emission reduction strategies at machining workshop floor can be divided into the following aspects.

The carbon emission can be reduced by taking actions from the perspective of machine tools. The results in Figure 9 and Figure10 have suggested that even the type of machine tools (such as C2-6510 Lathe and C2-6510 HK Lathe) are same, emission characteristics can be different as well. Therefore, selecting a low-emission machine tool is a useful approach to reduce emission in case that quality requirements are satisfied. For example, decision making in procurement stage introduced by Liu *et al.* [17] for higher energy efficiency is a valid way to reduce emission in entire service stage of machine tools. Similarly, the approach proposed by He *et al.* [38] about machine tool selection and operation sequence in flexible machining job shops is a good choice.

In addition, machining process may be a main studying direction for emission reduction because carbon emission of machine tools mainly derive from machining process, usually accounting more than 50%. The measures reducing energy in machining process, such as adopting a knowledge-driven [15] or integrating Taguchi, RSM and MOPSO [39], are effective ways to reduce emissions. Regarding non-cutting process, the reduction can be conducted toward to decrease emission in both standby and idling process. An easy way to decrease emission rate in idling process is selecting a low revolving speed since the results in Figure 10 have shown that emission rate increases with the rising revolving speeds. A strategy using shut-down and stand-by modes to increase the energy efficiency of an already balanced production line [40] is also a significant reference.

On the other hand, Figure 11 shows that the carbon emission for same work piece (e.g., support shaft) may be different if using different machine tools and manufacturing-procedures. Therefore, designing a low-emission schedule, optimizing manufacturing-procedure and cutting parameters are efficient ways to reduce carbon emission. The related measures using for reference have attracted many scholars and some have been applied in industry. For example, Optimization of cutting parameters to reduce the cutting energy consumption (CEC) within the MEC[41], and systematic approach of process planning and scheduling optimization [42].

3) COMPARISON WITH OTHER METHODS

To analyze and compare the proposed method with the statistics, some descriptive-statistic results for workshop and work piece are given in Table 6, respectively.

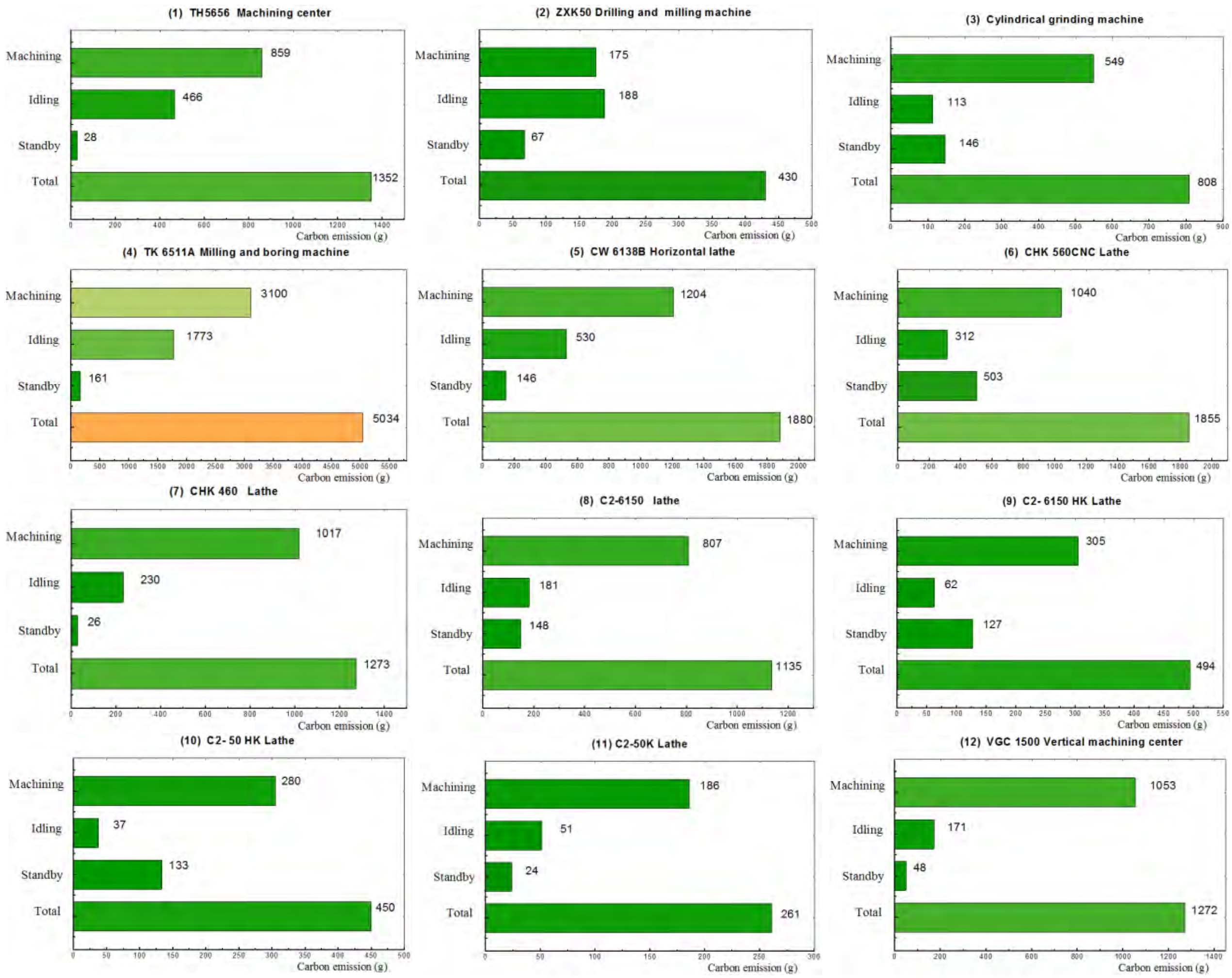


FIGURE 8. The emission distribution in different running statuses of machine tools.

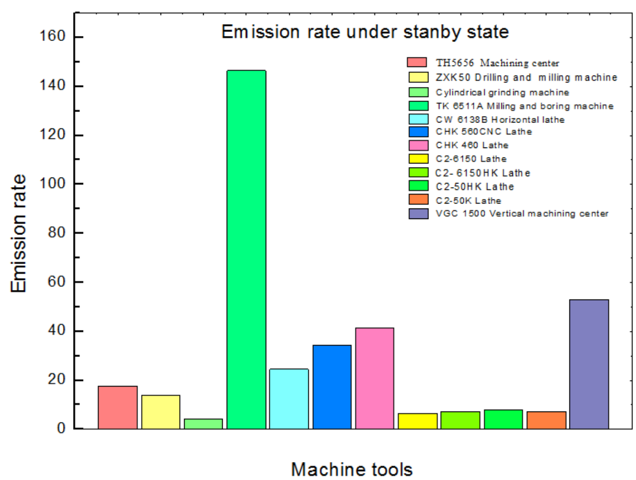


FIGURE 9. Emission rate in standby process of different machine tools.

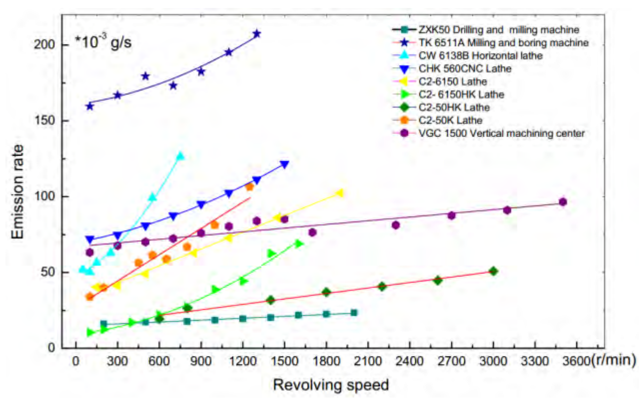


FIGURE 10. Emission rate in idling process of different machine tools.

The value in Table 6 based on static statistics is essentially obtained using difference value of emissions at initial (or before production) and end moments (or after production). It shows that carbon emission of workshop for each day varies from 0.133 to 3.492 Kg/day. The maximum difference is 3.359 Kg/day. But from the table, the source of this variation can't be acquired, which may make it difficult for the manager, technologist, and operator of machine tool to manage carbon emission and explore emission reduction methods. In contrast, the results based on the DACE method, as shown

TABLE 5. The production information of work pieces.

Step number	Machine tool	Process	Cutting length	Cutting width	Cutting depth	Cutting diameter	Raw diameter
Support shaft							
11301A_1	C2-6510 HK lathe	Rough turning	120	----	----	90.6	100
11301A_2	C2-6510 HK lathe	Finish turning	120	-----	-----	90	90.6
11301A_3	ZXK50 Drilling and milling machine	Groove milling	100	24	16	----	----
11301B_1	CHK 460 lathe	Rough turning	120	----	----	90.6	100
11301B_2	CHK 460 lathe	Finish turning	120	-----	-----	90	90.6
11301B_3	VGC 1500 Vertical machining cente	Groove milling	100	24	16	----	----
11301C_1	CHK560CNC lathe	Rough turning	120	----	----	90.6	100
11301C_2	CHK560CNC lathe	Finish turning	120	-----	-----	90	90.6
11301C_3	VGC 1500 Vertical machining cente	Groove milling	100	24	16	----	----
Nut							
321213_1	C2-6510 HK lathe	Turning	20	----	----	54	72
321213_2	C2-6510 HK lathe	Turning	35	----	----	69	72
321213_3	ZXK50 Drilling and milling machine	Hexagonal milling	207	4	----	---	---
Shaft sleeve							
413062_1	CHK560CNC lathe	Rough turning	60	----	----	100	105
413062_2	CHK560CNC lathe	Rough turning	60	----	----	80	70
Cylindrical gear							
11306A_1	CHK 460 Lathe	Rough turning	60	----	----	251.6	260
11306A_2	CHK 460 Lathe	Rough turning	102	----	----	58.4	50
11306A_3	VGC 1500 Vertical machining cente	Milling	220	220	50	--	---
11306A_4	CHK 460 Lathe	Finish turning	60	----	----	251	251.6
11306A_5	CHK 460 Lathe	Finish turning	102	----	----	60	58.4
Shaft							
170308_1	C2-6510 HK lathe	Turning	50	----	----	40	60
170308_2	C2-6510 HK lathe	Turning	50	----	----	30	40
170308_3	ZXK50 Drilling and milling machine	Milling Plane	50	30	15	--	---

in the Figure 8, present the carbon emission distribution of machining workshop, which make it easy to find the source of carbon emission and variation. The source of variation even can accurate to each running state of any machine tool. Moreover, according to the results of a work piece in Table 6, we know that carbon emission of work pieces based on static statistics only shows a simple numerical value such as mean value to interpret the relationship between a product and its carbon emission. The carbon emission of the manufacturing process contributing to analysis and optimize process is not presented. But from results based on DACE method, as shown in Figure 11, the composition of the carbon emission for production process, including manufacturing-procedure emission and machining-step emission, can be easy to know, which helps to process-based optimization for reducing the carbon emission.

In general, the DACE method not only highlights the actual carbon emission distribution of production equipment and carbon footprint for production object, but also provides a data foundation for analyzing and evaluating the influence of running statues and production processes on carbon emission in mechanical processing.

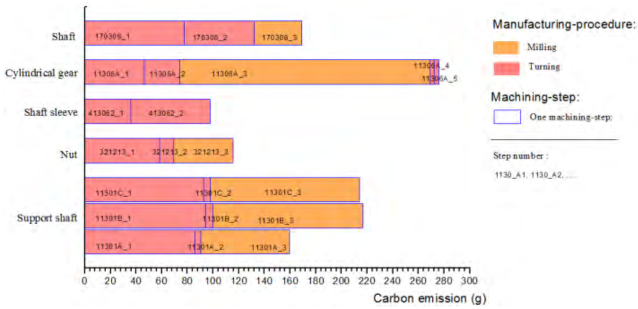


FIGURE 11. The carbon emission of the chosen work pieces.

TABLE 6. Descriptive statistic results.

Carbon emission on workshop layer (Kg/day)			
Statistics		**Daily emission**	
Mean		1.665	
Range		3.359	
Maximum		3.492	
Minimum		0.133	
Valid number		25	
Carbon emission at work piece layer			
Support shaft (Kg)		Cylindrical gear (Kg)	
Statistics	**Emission**	**Statistics**	**Emission**
Mean	0.198	Mean	0.285
Std. deviation	0.095	Std. deviation	0.098
Maximum	2.126	Maximum	0.298
Minimum	0.186	Minimum	0.269
Valid number	30	Valid number	30

VI. CONCLUSION

Global climate change, low-carbon economy, and emissions trading scheme have intensified concerns for greenhouse gas emissions, and thus, have led to creating an international effort to control and decrease GHG emissions in industry, especially in manufacturing industry. Most existing methods regarding the acquisition of carbon emission are static statistics, which is insufficient to reflect real-time variety and distribution of carbon emission in mechanical processing. Therefore, this paper proposes a dynamic acquisition to implement the real-time acquisition of carbon emission and obtain the distribution of carbon emission, to determine influence of running statues and production process on emission carbon, and to explore potential emission-reducing strategies in machining workshop.

The contributions of this work can be categorized into three aspects. Firstly, a dynamic acquisition of carbon emission is proposed through mining energy data, overcoming the limitations that static statistics of carbon emission are insufficient to reflect real-time variety and distribution or footprint of carbon emission in mechanical processing. Secondly, a series of real-time quantitative indexes on machine tool and on work piece level respectively are proposed. The proposed indexes play a crucial role not only in monitoring and management of carbon emission in machining workshop but also in evaluating environment of machine tools to support selection of machine tools and design of low-emission machine tools. Finally, a dynamic monitoring system based on the proposed method is developed and then applied into a machining workshop, proving the rationality and feasibility and the measuring results have revealed the influence of different running statues and production processes on carbon emission. Moreover, some emission reduction recommends on machine tool and work piece level are also proposed by analyzing and discussing the measuring results.

A limitation of this work is that some peripheral carbon-sources are neglected in the developed method and system. To improve the accuracy and completeness, future work will involve methods for acquisition of carbon emission caused by other resource such as lubricating oil and chips. Additionally, some optimizing schedules and parameters would be further detailed to reduce carbon emission in machinery manufacture.

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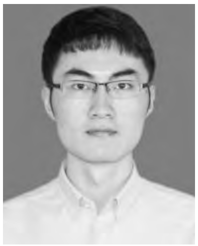

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