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A framework for characterising energy consumption of machining manufacturing systems

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Energy consumption in machining manufacturing systems is increasingly of interest due to concern for global climate change and manufacturing sustainability. To utilise energy more effectively, it is paramount to understand and characterise the energy consumption of machining manufacturing systems. To this end, a framework to analyse energy consumption characteristics in machining manufacturing systems from a holistic point of view is proposed in this paper. Taking into account the complexity of energy consumption in machining manufacturing systems, energy flow is described in terms of three layers of machining manufacturing systems including machine tool layer, task layer and auxiliary production layer. Furthermore, the energy consumption of machining manufacturing systems is modelled in the spatial and temporal dimensions, respectively, in order to quantitatively characterise the energy flow. The application of the proposed modelling framework is demonstrated by employing a comprehensive analysis of energy consumption for a real-world machining workshop. The characteristics of energy consumption for machine tool layer, task layer and auxiliary production layer are, respectively, obtained using quantitative models in the spatial and temporal dimensions, which provides a valuable insight into energy consumption to support the exploration of energy-saving potentials for the machining manufacturing systems.

Keywords: energy consumption; machining manufacturing systems; energy flow; machining workshop

1. Introduction

Machining is a material removal process that typically involves the cutting of metals using various cutting tools. This is wasteful and energy intensive (Dahmus and Gutowski 2004). As a result of climate change conventions, stringent regulations to reduce carbon dioxide emissions have been imposed globally, which have become an important influential factor in the manufacturing industry for energy reduction (particularly electric energy) (Park et al. 2009). And also, the standards of environmental impact metrics such as eco-labels are widely applied to estimate different manufactured products, in order to establish a sustainable manufacturing environment (Chun and Bidanda 2013). Hence, reducing the energy consumed by machining is identified as one of the strategies to improve sustainability in manufacturing (Pusavec, Krajnik, and Kopac 2010).

The first step towards energy consumption reduction in machining manufacturing systems, which is conceived as manufacturing workshops that were composed of several computerised numerical control (CNC) machines for the manufacturing of a batch of production tasks, is to devise methods to understand and characterise their energy consumption (Herrmann et al. 2007). A survey of recent literature shows that most current research has focused on energy consumption models for machine tool components or machining processes. For the former, the energy consumption was studied based on the analyses of energy demands from individual machine tool components; Kordnowy and Gutowski broke down the energy consumption of machine tools according to energy-consuming components such as computers and fans, servos, coolant pump, spindle, tool changer, etc. (Kordonowy 2002; Dahmus and Gutowski 2004; Gutowski, Dahmus, and Thiriez 2006). Avarm and Xirouchakis (2011) addressed the specific power characteristics of the spindle and feed axes to estimate the variable energy requirements of a machine tool system for part machining. He et al. (2012) discussed the correlation of energy consumption between machine tools and numerical control (NC) codes for the estimation of energy consumed by NC machining. For the latter, attention is paid to the energy consumption of a specific machining process under varied cutting conditions such as material removal rate. For milling machining, one of the early studies carried out by Draganescu, Gheorghe, and Doicin (2003) who presented a statistic modelling of specific consumed energy by means of response surface methodology with experimental data for milling. Diaz, Redelsheimer,

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*Corresponding author. Email: heyan@cqu.edu.cn and Dornfeld (2011) also modelled the specific energy consumption of milling machine tools as a function of process rate. The energy consumption of other machining processes such as turning or drilling has also been widely researched. For example, Mori et al. (2011) addressed energy consumption characteristics under varied cutting conditions for both milling and drilling processes. An energy consumption model was proposed for a turning process based on power measurements under various cutting conditions (Li and Kara 2011). Rajemi, Mativenga, and Aramcharoen (2010) concentrated on the energy footprint requirement of turning processes under various processing conditions.

Although a good understanding of the energy consumption developed, which is targeted at the specific problems in machining manufacturing system, there is still a lack of comprehensive analyses of energy consumption of the machining manufacturing system at an overall system level. To this end, some specific methods considering the energy consumption of machining production systems have been developed. For example, the statistical discrete event formulation was applied to model the energy consumption behaviours of plants (Dietmair and Ver 2009), and the mathematic programming model was proposed to optimise the total energy consumption (Mouzon, Yildirim, and Twomey 2007), and the information infrastructures were provided for transparency the non-productive energy consumption in manufacturing industry (Lees, Evans, and Mareels 2012). Although these methods tried to model energy consumptions at the system level, these were still limited to a partial instead of an overall system level. Systematic approaches are suitable to analyse comprehensive energy consumption of holistic manufacturing systems, which have been concerned by some researchers. For example, Herrmann and Thede (2009), Thiede et al. (2013), Seow and Rahimifard (2011), Seow, Rahimifard, and Woolley (2013) and Weinert, Chiotellis, and Seliger (2011) have used the systematic approaches to model energy consumption in manufacturing systems. For the first two research groups, they both proposed the systematic approaches based on product viewpoint to model energy at the plant and process levels. The approaches can enable energy consumption in manufacturing systems to be decomposed into energy consumed by each process step of products. For the last researcher group, the proposed approach has extended the energy transparency for each process step into the energy transparency for operating states of production equipment at each process step.

In this paper, a modelling framework to characterise the energy consumption of machining manufacturing system from a holistic point of view is proposed. It is a system-wide approach to conduct a comprehensive analysis for energy consumption of machining manufacturing systems. The primary objective of the proposed framework is to answer questions, such as how much energy is required and how it is distributed in relation to time and place, and further extends energy transparency into the level of energy consumers under different operating states during processes steps. The energy transparency for overall machining systems including the detailed energy consumers can provide more valuable insights to support decision-making with respect to the energy-saving potential from the holistic perspective, as well as to support some specific decision-making on using energy efficient consumers and controlling energy consumers' operation in machining manufacturing systems.

This paper is organised as follows. Firstly, the holistic energy flow of machining manufacturing systems is presented to hierarchically describe the multilayer structure of energy consumption characteristics from machine tool layer, task layer and auxiliary production layer. Secondly, the energy consumption of the machining manufacturing system is modelled on the spatial and temporal dimensions, respectively. Thirdly, the application of the proposed modelling framework is demonstrated by employing a comprehensive analysis of energy consumption for a real-world machining workshop.

2. Hierarchical description of the holistic energy flow

Energy consumption in machining manufacturing systems is required not only by material removal processes, but also by machining-related devices such as auxiliary devices of machine tools, and the production-related equipment such as material transportation devices. The energy consumption is dynamically affected by the task variety of production processes. Consequently, taking into account the complexity of energy consumption in machining manufacturing system, the energy flow of machining manufacturing systems is presented to hierarchically describe the multilayer structure of energy consumption characteristics in terms of machine tool layer, task layer and auxiliary production layer as shown in Figure 1.

2.1 *Machine tool layer*

Machine tools are the primary elements of manufacturing system, which consume a significant amount of energy for machining production tasks. The energy flow at this layer is primarily analysed by considering energy characteristics of energy-consuming components of machine tools. Although machine tools have various purposes and capabilities, the power demand of energy consumers particularly composing of machine tools (namely energy-consuming components)

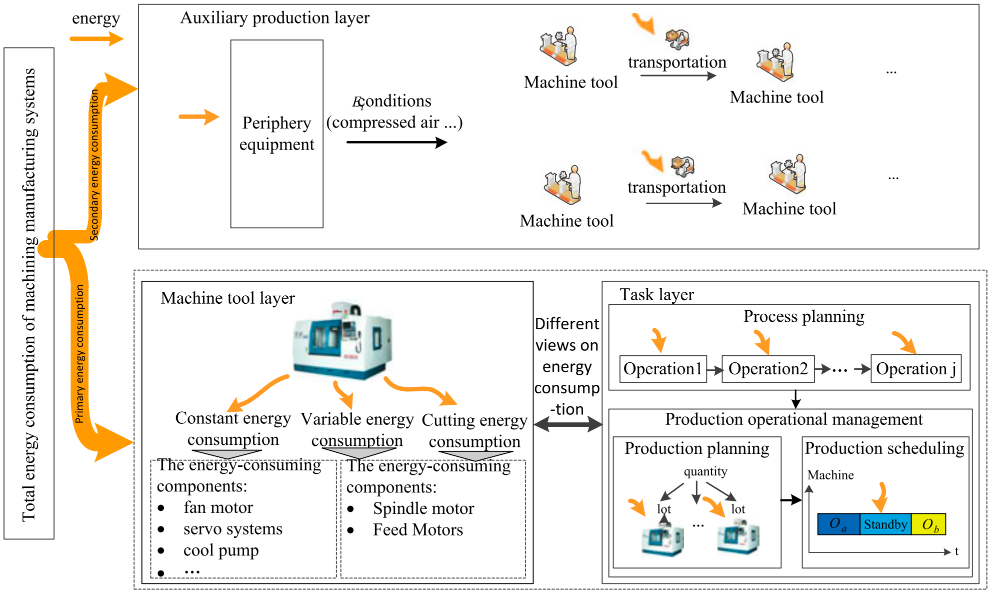


Figure 1. Hierarchical description of holistic energy flow in machining manufacturing systems.

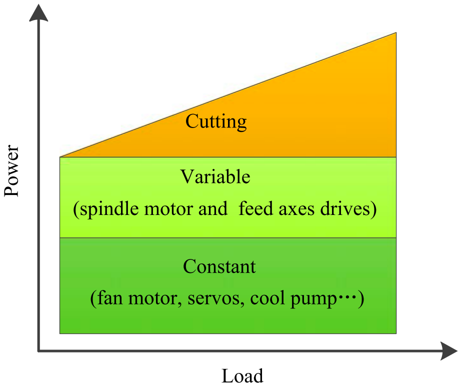


Figure 2. Power demand breakdown for energy-consuming components of machine tool (Diaz et al. 2010).

can be generically classified into three categories: constant, variable and cutting power (see Figure 2) (Dahmus and Gutowski 2004; Diaz et al. 2010). The machine tool components that require constant power consumption independent of material cutting processes include fan motors, servos and cool pump. Spindle motors and feed motors consume both variable power and cutting power. The former is used to maintain the motion of spindle axes and feed axes varied with motion speeds. The latter is specific for cutting material depending on cutting loads.

2.2 *Task layer*

The energy flow described at the task layer is to analyse energy consumption regarding production tasks. Compared to energy flow in machine tool layer, the energy consumption modelling in the task layer addresses how energy is consumed and distributed in the production processes of tasks. In this layer, the energy for production processes of tasks can be categorised into two parts, respectively: energy used during productive time and that during non-productive time. For the first part, energy consumption primarily depends on the process routing or process parameters of tasks, which can be optimised by proper process planning. For the second part, the energy is greatly affected by some factors in production operational management, such as lot size planning, machine tool selection and scheduling.

Since the production processes of tasks are constituted with multiple operations of tasks, the analysis of energy consumption for each operation of tasks can provide some detailed information on energy consumption for the production processes of tasks to explore the energy-saving potential through process planning or production operational management optimisation in machining manufacturing system.

2.3 *Auxiliary production layer*

The energy flow at the auxiliary production layer is explored focusing on production-related equipment such as material transportation devices and periphery equipment. Energy is required to transport tasks from the buffer of one machine tool to another one after finishing the previous task. Additionally, periphery equipments such as illumination devices, air compressor and central coolant lubricant supply system also consume energy during the manufacturing processes.

3. Quantitative energy consumption modelling at system level

In order to further characterise the holistic energy flow of machining manufacturing system, energy consumption of machining manufacturing system is modelled in the spatial and temporal dimensions, respectively, in this section. The energy models in the spatial dimension can be used to analyse how energy is consumed by individual energy consumers distributed in machining manufacturing system, and the energy models in temporal dimension can answer how energy is consumed in varied production operational processes depended on production task variety.

3.1 *Energy models in spatial dimension*

Energy models in spatial dimension are established to quantitatively analyse the energy characteristics of energy consumers. Energy consumers can be described as the elements or members that are allocated in machining manufacturing systems and consume electrical energy, including primary energy consumers like spindle motors in the machine tool layer or secondary energy consumers like compressed air in the auxiliary production layer.

The characteristics of energy consumption greatly depend on the operating states of energy consumers (Dietmair and Ver 2009). Generically, the following three categories of basic models may be used to analyse energy consumed by various energy consumers under various operating states.

3.1.1 *0–1 distribution basic model*

The power of energy consumers under this category can be generally analysed considering two states: fully activated or not activated during the operating states of energy consumers. The power demand P^r_{con} is a constant value when the energy consumer is fully activated, and is zero when not activated. The energy consumption of energy consumers of this category is defined as:

$$E_r = P^r_{\text{con}} t_{\text{act}} \tag{1}$$

where E_r presents the energy consumption of the r^{th} energy consumer and t_{act} is the activated duration of the energy consumer.

The energy consumers that fall into this category include fan motor, cool pump and some secondary energy consumers. For instance, the power demand of hydraulic pump stands constant throughout the stand-by and processing states, and changes to zero when unclamping the chuck (Li and Kara 2011).

3.1.2 *Discrete distribution basic model*

In this category, energy consumers are characterised by the power being constant during the time interval of an operating state, and may change to another constant if the operating state changes. Consequently, the power of these energy consumers may have a series of discrete values, and the energy consumption of the energy consumers in this category is formulated as:

$$E_r = \sum_{v} P^v_r t^v_r \tag{2}$$

where P^v_r is the power of the r^{th} energy consumer under the v^{th} operating state, and t^v_r is the duration time of the r^{th} energy consumer under the v^{th} operating state.

A typical example of this category is the energy consumed by the spindle motor under air cutting which is used for maintaining the motion of the spindle components during no material removal period. The power of spindle motor is a constant until the operating state changes with the spindle speed which is normally kept at several fixed speeds for air cutting. Therefore, the energy consumption of the spindle motor under air cutting is calculated using Equation (2) whilst the value of P_r^v may be obtained by experiments.

3.1.3 *Continuous distribution basic model*

The energy consumers of this category include the spindle motors and feed motors, the power of which varies continuously during the material removal processes for production tasks. This is the most complicated power characteristics which are dynamically affected by task-related parameters such as process parameters or task assignments. The energy consumption of the energy consumers with the continuous characteristic can be modelled as:

$$E_r = \int P_r(t)dt \tag{3}$$

where $P_r(t)$ is the power of the r^{th} energy consumer over the t period including the cutting power and the power for maintaining the r^{th} energy consumers running. Note that both the power in this basic model and the one in Equation (2) for the discrete distribution basic model can be used to denote the power for the same energy consumers such as spindle motors. But the difference between them is that the former describes the power consumption under the air-cutting state and the latter represents the power consumption under the material-removal operating state.

In summary, since energy characteristics of consumers depend on power characteristics during operating processes, power changing regularity of consumers can be used to determine which basic model is suitable to model the energy of consumers. If the power of consumers keeps constant during the operating processes, '0–1' distribution basic model is used to model this kind of consumers. If the power of consumers keeps constant during the time interval of an operating state, but may change to another constant value if the operating state changes, the discrete distribution basic model is suitable to model this kind of consumers. If the power of consumers varies continuously during the operating processes, this changing regularity obeys the continuous distribution characteristic and the continuous distribution basic model is used for modelling the consumers. These power changing characteristics can be easily derived from some simple power measurements or operating principles of consumers.

Based on the above three basic models describing the energy consumption characteristics of energy consumers, the general process to model energy consumption of an energy consumer is shown in Figure 3. The operating states are identified, and the energy characteristic of each operating state for energy consumers were, respectively, analysed and modelled using the corresponding energy models.

3.2 *Energy model in temporal dimension*

The energy model in temporal dimension is to quantitatively analyse the energy consumption as time passes in machining manufacturing systems. The energy consumption in the temporal dimension is varied, while production tasks are changed such as adding new tasks or finishing tasks. Therefore, the production cycle, which is defined with the

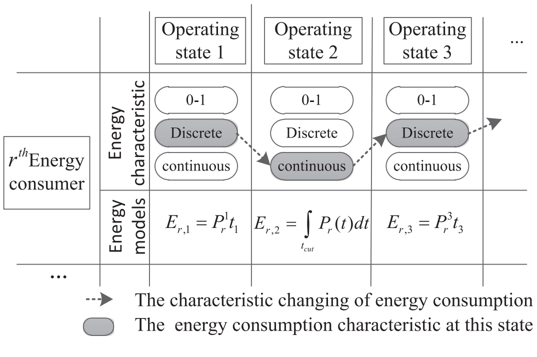


Figure 3. The energy consumption of an energy consumer of machine tool.

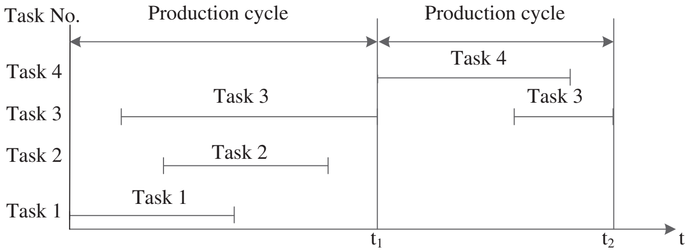


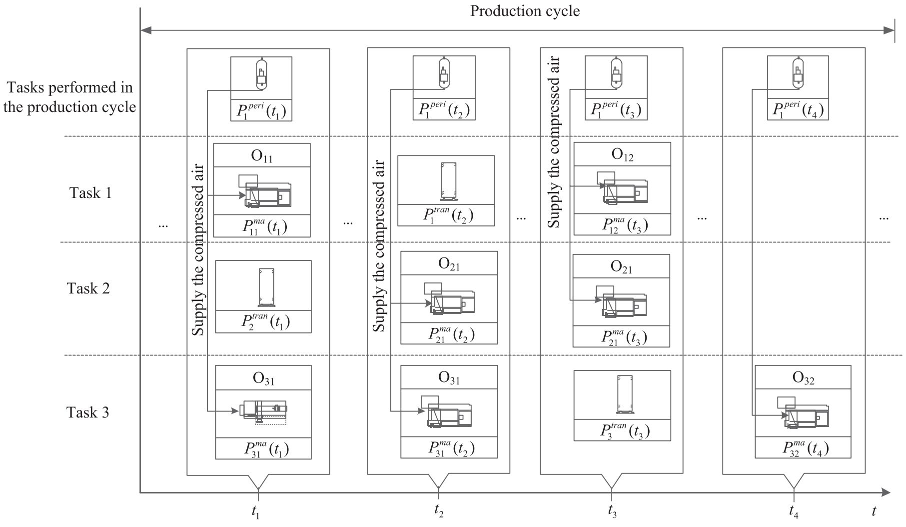
Figure 4. An example of production cycles in the machining manufacturing systems.

completion time of a batch of production tasks for several parts and several machines shown in Figure 4, is considered as the timescale to characterise energy consumption in temporal dimension.

For each production cycle, energy consumption can be generically modelled by the integral of the varied power over time, which is determined by the varied production processes of tasks. The energy consumption of the machining manufacturing system involves one production cycle that can be divided into the energy requirements for performing the tasks and the energy requirements for assisting the production. The energy model in the temporal can be formulated as below:

$$E_w = \int_0^{T_w} P_w(t)dt = \sum_i \sum_j \int_{t_{ij}} P_{ij}^{\text{ma}} dt + \sum_o \int_{T_w} P_o^{\text{peri}} dt + \sum_i \int_{T_w} n_i P_i^{\text{tran}} dt \tag{4}$$

where E_w presents the energy consumption of the machining manufacturing systems at the w^{th} production cycle, P_w is the varied power of the machining manufacturing systems at the w^{th} production cycle, T_w is the duration of the w^{th} production cycle, P_{ij}^{ma} presents the power of the j^{th} operation of Task i, t_{ij} is the machining time of j^{th} operation of Task, P_o^{peri} is the power of the o^{th} periphery equipment and P_i^{tran} is the power consumed to transport Task i to assist the production, and n_i is the transportation times of Task i.



	Time t_1	Time t_2	Time t_3	Time t_4
$P(t)$	$P(t_1) = P_1^{peri}(t_1) + P_{11}^{ma}(t_1) + P_2^{tran}(t_1) + P_{31}^{ma}(t_1)$	$P(t_2) = P_1^{peri}(t_2) + P_1^{tran}(t_2) + P_{21}^{ma}(t_2) + P_{31}^{ma}(t_2)$	$P(t_3) = P_1^{peri}(t_3) + P_{12}^{ma}(t_3) + P_{21}^{ma}(t_3) + P_3^{tran}(t_3)$	$P(t_3) = P_1^{peri}(t_4) + P_{32}^{ma}(t_4)$

$P(t)$: Total power of the machining manufacturing system at time t
$P_{ij}^{ma}(t)$: Machining power of the j$^{\text{th}}$ operation of Task i at time t
$P_1^{peri}(t)$: Power of air compressor at time t
$P_i^{tran}(t)$: Power consumed to transport Task i at time t

Figure 5. Breakdown of the power of the machining manufacturing systems.

Table 1. Detailed information for the three production tasks.

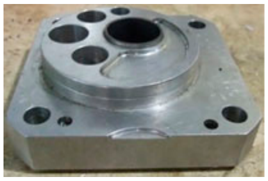
Task no.	Finish task	Process operation		Machine tool	Time (min)
Task 1		O_{11}	Rough milling	PL700	18
		O_{12}	Rough milling	HASS VF5/50	10
		O_{13}	Finish milling	PL700	30
		O_{14}	Turning	C2-6136HK	10
		O_{15}	Turning	C2-6136HK	3
		O_{16}	Drill	PL700	2
Task 2		O_{21}	Turning	CD6140A	120
		O_{22}	Grinding	HAAS VF5/50	32
		O_{23}	Milling	PL700	33
		O_{24}	Milling	PL700	25
		O_{25}	Boring	HAAS VF5/50	120
		O_{26}	Milling	HAAS VF5/50	70
Task 3		O_{31}	Rough milling	PL700	15
		O_{32}	Boring	PL700	40
		O_{33}	Rough milling	HAAS VF5/50	10
		O_{34}	Boring	HAAS VF5/50	20
		O_{35}	Drill	CD6140A	10

Figure 5 shows an example of the varied power of the machining manufacturing systems for one production cycle. At time *t*1, the power of the machining manufacturing system consists of power consumed by performing Task 1 and 3 in the machine tools, transporting Task 2 and supplying the compressed air to the machine tools, similarly, at time *t*2, the power of the machining manufacturing system consists of the power consumed by performing Task 2 and 3 in the machine tools, transporting Task 1 and supplying the compressed air by periphery equipment to the machine tools at time *t*2. In this way, the power of the machining manufacturing system varies with the production processes of tasks.

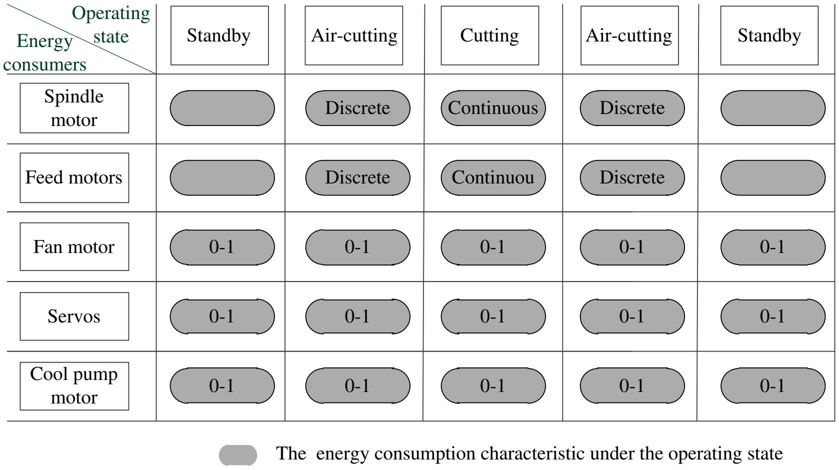
If the cycle time is very different between Task 1 and 3, for example, at the time *t*2, operation O11 of Task 1 has been finished and is transported to the next machine tool while operation O31 of Task 3 is not done, and the power changes from P(*t*1) to P(*t*2). The former includes the power for operation O11 of Task 1 and the power for operation O31 of Task 3 while the latter still includes the power for operation O31 of Task 3 but excludes the power for operation O11.

4. Case study

The application of the proposed framework is demonstrated by conducting a comprehensive analysis of the energy consumption of a real-world small-size machining workshop to support the exploration of energy-saving potential for the holistic machining workshop.

The small-size machining workshop consists of two vertical machining centres HAAS VF5.50 (Made by ReSell CNC Machine Tool of USA) and PL700 (Made by Chengdu Precise CNC Machine Tool of China), one CNC lathe C2-6136HK (Made by Chongqing No. 2 Machine Tool Works of China), one manual lathe CD6140A (Made by Dalian Machine Tool Group of China) and one air compressor (Made by Shanghai Success Engine Compressor of China). The material transportation device is not considered in this case study, since the transportation of production tasks is carried out by manual handling, and this can be easily added to the system if required.

To simplify the case study, only three tasks are taken as a batch of production tasks in this machining workshop. The process operations and the production assignment of machine tools for performing the three tasks are shown in Table 1. The processing time including cutting time and set-up time is obtained by the empirical statistic or the on-site measurement, and the related power data are obtained by machine data available from both relevant literature and



Energy consumers \ Operating state	Standby	Air-cutting	Cutting	Air-cutting	Standby
Spindle motor	▨	Discrete	Continuous	Discrete	▨
Feed motors	▨	Discrete	Continuou	Discrete	▨
Fan motor	0-1	0-1	0-1	0-1	0-1
Servos	0-1	0-1	0-1	0-1	0-1
Cool pump motor	0-1	0-1	0-1	0-1	0-1

▨ The energy consumption characteristic under the operating state

Figure 6. Operating states of PL700 for the operation O_{11}.

catalogues. The related power data in this case exactly include the power for fan motor and servo, spindle motors, feed motors and cool pump motors, which maintain machine tools running; the power for material removal; and the power of air compressor. For the first one, the power data are obtained by measurement. For the second one, the literatures focusing on cutting energy such as Draganescu, Gheorghe, and Doicin (2003) or machining catalogues, presented some approaches to obtain the cutting power, and these approaches can be used to estimate the cutting power data for material removal. For the third one, the power data for air compressor can be obtained by referring to the equipment specification. These power data are the required parameters in the proposed quantitative energy consumption models in order to analyse the energy consumption in machining manufacturing systems.

According to the proposed modelling framework, the energy characteristics for performing the batch of production tasks in the machining workshop are, respectively, analysed from the machine tool layer, task layer and auxiliary production layer by using quantitative models in the spatial and temporal dimensions.

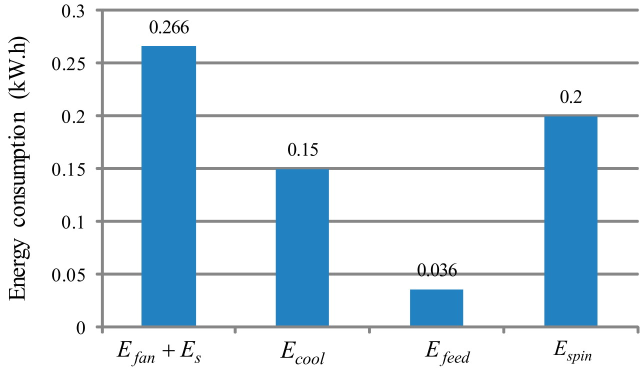
4.1 *Machine tool layer*

Energy analysis at machine tool layer is conducted by the quantitative model in the spatial dimension. The machine tool PL700 for performing the operation O_{11} (rough milling) is taken as an example to analyse energy consumption characteristics. The operating states of PL700 for the operation O_{11} are identified as shown in Figure 6 and the power parameters of energy consumers of PL700 for the operation O_{11} are listed in the Table 2.

Based on the identified segmentation of operating states, the constant energy consumers such as fan motor, servos and cool pump motor are modelled with the 0–1 distribution basic model. The varied energy consumers are modelled with the discrete distribution basic model for the air-cutting operating state and with continuous distribution basic model for the material cutting state. Consequently, the energy consumption of primary energy consumers for PL700 is analysed as shown in Figure 7. Energy consumption of spindle motor E_{spin}, feed motor E_{feed} and the cool pump motor E_{cool} are

Table 2. Power parameters of energy consumers of PL700 for the operation O_{11}.

Component		Power (10^{-3} kW)
Fan motor and servo		601
Cool pump motor		340
Spindle motor	600 rpm	45
	900 rpm	73
	1800 rpm	136
X axis motor	1500 mm/min	10
Y axis motor	1500 mm/min	10
Z axis motor	Rapid movement	770
	100 mm/min	16

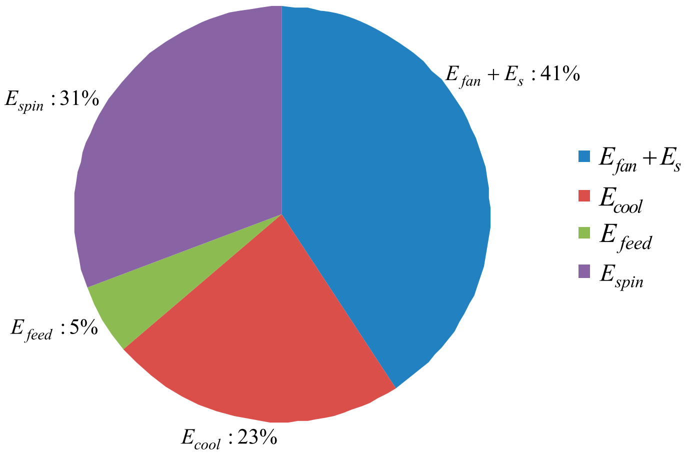


$E_{fan}+E_s$: Energy consumption consumed by fan motor and servos
E_{cool} : Energy consumption consumed by cool pump
E_{feed} : Energy consumption consumed by feed motors
E_{spin} : Energy consumption consumed by spindle motor

Figure 7. Energy consumption of primary energy consumption of PL700.

0.200, 0.036, 0.150 kW h, respectively, and the fixed energy consumption of PL700 including the energy consumption of fan motor and servos is 0.266 kW h. In addition, Figure 8 shows the comparison of energy consumption for the energy consumers of PL700. It is seen that the maximum energy is consumed by constant energy consumers including fan motor, servos and cool pump motor which weighs about 64% of the energy consumption of PL700. Obviously, it indicates that the constant energy consumption is the most important contributing factor to the total energy consumption for the machining operation O_{11}.

Similarly, the energy consumption of machine tools for performing the batch of tasks in this case can be estimated as shown in Figure 9. The largest amount of energy is consumed by the machine tool HAAS VF5/50 due to the required largest power as well as the longest operating time for performing the tasks assigned on this machine tool. Additionally, the second largest amount of energy is consumed by the machine tool PL700. Other machine tools consume much less energy since a fewer number of operations is assigned to the machine tools.



$E_{fan}+E_s$: Energy consumption consumed by fan motor and servos
E_{cool} : Energy consumption consumed by cool pump
E_{feed} : Energy consumption consumed by feed motors
E_{spin} : Energy consumption consumed by spindle motor

Figure 8. Percentage comparison of energy consumption of primary energy consumers of PL700.

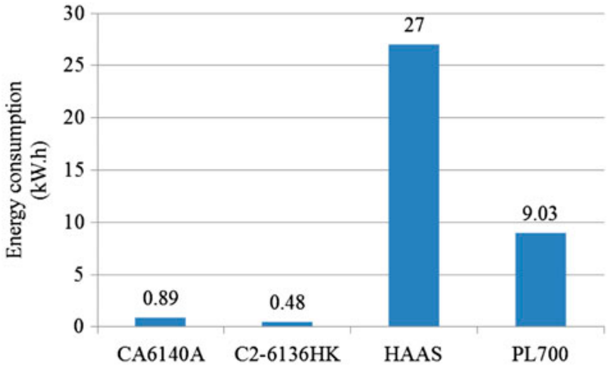


Figure 9. Energy consumption of four machine tools in this machining workshop.

4.2 *Task layer*

Energy consumption at the task layer of this production cycle is characterised by the quantitative model in the temporal dimension, which divides the energy flow of the task layer at this production cycle into energy requirements for performing Task 1, 2 and 3. The distributions of energy consumption at the task layer are shown in Figure 10. In the production cycle, Task 2 consumes the largest amount of energy, since most of the operations of the task were assigned on the machine tool HASS VF5/50 and the processing time for the six operations of Task 2 was the longest.

Furthermore, the energy consumption for Task 2 is analysed in order to obtain detailed energy information for each operation as shown in Figure 11, from which it can be seen that O_{25} boring on HAAS VF5/50 consumed the largest amount of energy accounting for 46%, due to the longest operation time of the machine.

4.3 *Auxiliary production layer*

The energy consumption from the auxiliary production layer in this case is consumed only by the air compressor. The energy of the air compressor can be characterised by the 0–1 distribution energy models in the spatial dimension. The operating time of the air compressor is determined by the production cycle for completing this batch of production tasks. In this case, the air compressor consumed 12 kW h energy to supply the compressed air to the machine tools during this production cycle.

Note that for a complex industrial environment, energy flow and energy characteristics are also very sophisticated. It is really difficult to understand and analyse energy consumption for this industrial environment. Modern simulation tools are helpful for solving the difficulties faced by complex industrial environment. Therefore, the simulation tools such as Petri-Net can be used to extend this approach to be more effectively applied in the complex industry environment. On

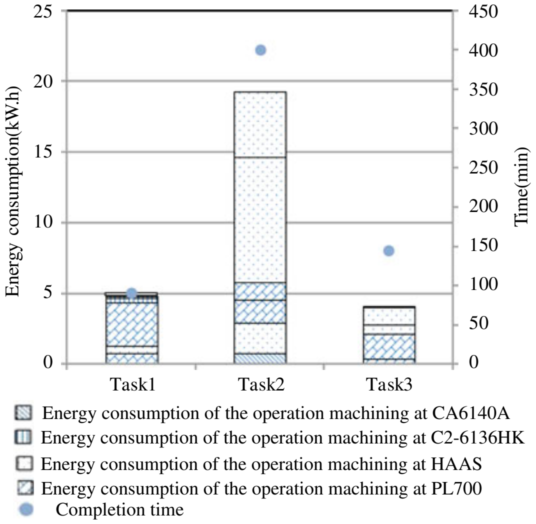
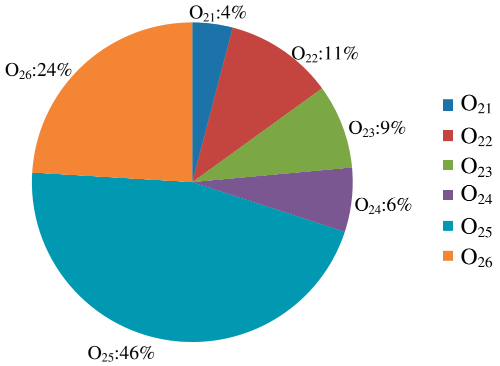


Figure 10. Energy consumption of tasks in machining manufacturing systems.



O_{2j}: Energy consumption of the j$^{\text{th}}$ operation of Task 2

Figure 11. Percentage comparison of energy consumption of operations of the Task 2.

the other hand, since it is heavy work to retrieve these above parameters, some standardised measurements, such as machine tool-test methods for electric power consumption proposed by Japanese Standards Association (2010), can be applied to simplify the parameter measurement.

5. Conclusions and discussions

Comprehensive analysis of energy consumption in machining manufacturing systems essentially contributes to addressing the questions of how energy is required and how distribution takes places at which time and place, and thus supports the exploration with respect to energy-saving potentials for holistic machining manufacturing systems. In this paper, we propose a system-wide approach to characterising the energy consumption of machining manufacturing systems from a holistic point of view. The machining manufacturing systems are decomposed into a three-layer structure for the description of the holistic energy flow. The energy flow of the machine tool layer is primarily analysed by considering the energy characteristics of energy-consuming components of machine tools; the energy flow at the task layer is to analyse energy consumption depending on production tasks; the energy flow of the auxiliary production layer focuses on production-related equipment such as material transportation devices and periphery equipment. Furthermore, the energy consumption of overall machining manufacturing systems is modelled on the spatial dimension and temporal dimensions. The former is to quantitatively analyse the energy characteristics of energy consumers and the latter to deal with the energy consumption of the machining manufacturing systems at production cycles. The application of the proposed modelling framework is demonstrated in order to conduct a comprehensive analysis of energy consumption for a real-world small-size machining workshop.

This comprehensive analysis of energy consumption in machining manufacturing systems supports decision-making with respect to the energy-saving potential for holistic machining manufacturing systems. Some energy-saving scenarios supported by this comprehensive analysis include:

- Determining the priority of energy-saving elements in the holistic machining manufacturing systems based on the energy usage rate used by energy consumers at both the machine tool and auxiliary production layers.
- Reducing the energy consumption in the non-productive period by the production of operational optimisation based on energy usage of tasks in production cycles.
- Reducing the energy consumption of tasks by optimising process planning and parameters based on the energy usage of each operation of tasks.
- Estimating and forecasting energy consumption of the machining manufacturing systems using the historic analysis of energy usage for energy consumers and tasks.

In the next step, the approach needs to be deeply explored from two aspects. One is to use simulation tools to enable the approach more flexible and dynamic. On the other hand, more factors impacting energy efficiency will be considered to improve the approach, such as the components not directly using energy.

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