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Energy-oriented joint optimization of machine maintenance and tool replacement in sustainable manufacturing

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ABSTRACT

With the increasing attention on sustainable manufacturing, operation and maintenance (O&M) management focuses on not only budget limit, but also energy saving. For modern CNC systems, besides the energy consumption to operate and maintain the machine, a majority of energy consumption generated from tool wear should be considered. It means both machine degradation and tool wear are required to be modelled for the global saving energy. Thus, this paper proposes an energy-oriented joint optimization of machine maintenance and tool replacement (EJMR) policy by integrating energy consumption mechanisms and joint maintenance opportunities in a machine-tool system. The key issue is to combine the preventive maintenance (PM) scheduling of the machine and the polish/preventive replacement (PR) optimization of sequential tools to form energy-effective schemes. Therefore, joint maintenance opportunities of PM actions are utilized to perform tool polish/PR based on energy consumption mechanisms. Four successive procedures (energy consumption analysis, energy-oriented PM scheduling, machine-tool PR model and integrated decision-making process) are developed. Thereby optimal intervals of machine PM and tool polish/PR are obtained to save energy. The case study illustrates that compared with conventional maintenance policies, this proposed EJMR policy can significantly reduce the total non-value-added energy consumption (TNVE) in sustainable manufacturing.

1. Introduction

In recent years, energy consumption optimization in modern manufacturing industry has received increasing attention along with the energy crisis and greater environmental concerns [1,2]. It is estimated that the manufacturing sector accounts for 52% energy consumption worldwide and is one of the main drivers of the growth of energy consumption [3,4]. In order to deal with the continuously rising energy demand and promote energy saving, governments have implemented policies like time-of-use pricing [5,6], carbon tax [7,8] and energy consumption allowance [9]. The increasing attention on energy issues urges manufacturing enterprises to pursue a sustainable manufacturing paradigm [10–12]. In the course of promoting energy saving in manufacturing, researchers have discovered that nearly 85% of the energy consumption has nothing to do with the value-added production process, while a majority of energy is wasted due to non-sense idle or breakdown caused by the lack of proper decision-making on operation and maintenance (O&M) management [13,14]. Therefore, it is urgent to develop an effective maintenance policy to assure both of machine availability and energy saving for sustainable manufacturing.

The traditional maintenance policies mainly focus on the cost optimization [15–17]. Ghaleb et al. [18] aimed to minimizing the total costs by integrating production and maintenance scheduling for a single machine and modeling the degrading process as a Markov chain. Dong et al. [19] integrated a Bayesian updating prognostic model using senser-based degradation information and opportunistic maintenance policy to realize the notable cost reduction. In addition, Si et al. [20] and Xia et al. [21] also utilized the opportunistic maintenance policy model to reduce the total costs in O&M process for leasehold service network and mass customization respectively. Similarly, Chang et al. [22] constructed penalty costs and grouping service costs to find out the optimal short-term maintenance plan where the average costs savings and relative availability improvement degree were regarded as the optimization objectives.

However, the maintenance scheduling in sustainable manufacturing requires not only low cost-rate but also high energy-efficiency [23]. It can be noted that identifying the optimal maintenance intervals is essential for energy consumption optimization. Overlong intervals lead

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to frequent machine failure along with production and energy loss, while short intervals mean frequent maintenance actions with corresponding extra energy consumption [24,25]. Thus, it is important to dynamically form optimal maintenance schemes from the perspective of energy consumption optimization. There have been some studies on maintenance policy optimization in relation to energy consumption. In these studies, the energy rate, the maintenance cost rate and the machine availability are integrated into a multi-objective model, then the optimal interval is obtained by minimizing the multi-objective model [26]. For the purpose of maximizing the energy efficiency of buffered serial production systems, the "energy-saving opportunity window" is applied and regarded as opportunities for the preventive maintenance [27]. However, to our best knowledge, existing maintenance policies normally analyze the energy consumption of the machine and tools separately in O&M process, while energy consumption mechanisms and joint maintenance opportunities have not been considered comprehensively.

A comprehensive energy-oriented maintenance policy should aim to fill the gap between the preventive maintenance (PM) scheduling of the machine and the polish/preventive replacement (PR) optimization of sequential tools. To develop such a complex decision-making process, energy consumption mechanisms and joint maintenance opportunities are essential issues. In industry, most CNC systems (a typical machine-tool system) work with high energy consumption and low productivity, due to the lack of energy-efficient models [28,29]. Researchers have noted that energy consumption modeling is one of the most important prerequisites for energy-oriented optimization [30]. On the one hand, the traditional energy consumption models are developed by machining process, cutting conditions, different energy consumption states and so on [31,32]. Aramcharoen and Mativenga [33] developed an energy model from the perspective of different energy consumption states, which is composed of basic energy, tool change energy, spindle energy, cutting energy, feed energy and cutting fluid delivery energy. On the other hand, some researchers also pointed that the inevitable tool wear effects should also be considered to build a comprehensive energy consumption model for a machine-tool system [34,35]. For an instance, Liu et al. [36] investigated the effect of process parameters and tool wear progression on energy consumption at machine level, spindle level and process level respectively. The tool wear progression is analyzed concretely to evaluate the sustainability of hard milling process [37]. Here, it should be noted that the experiment shows the tool wear progression influence the cutting energy at the process level, while the effect of tool wear on the energy consumption at the spindle is relatively small. Therefore, the energy consumption for a machine-tool system should be divided into two parts. One part is the energy consumption for the machine O&M, and the other is the increasing energy consumption generated by the continuous tool wear progression. However, as one of the key components in the machining process, there are few studies on energy consumption mechanisms for the tool maintenance [38,39], let alone integrating joint maintenance opportunities for a machine-tool system in sustainable manufacturing.

In conclusion, as for the maintenance policy optimization, most of the references focus on the cost optimization and a few of them have studied the energy consumption in the O&M process. Besides, tool wear is inevitable to generate considerable energy consumption in the machining process and the corresponding mechanism has been broadly studied. However, the research about joint maintenance for a machine-tool system considering energy optimization is still a research gap. Referring the study of Lotfi et al. [40–42], Table 1 summarizes the literature dedicated to the maintenance policy optimization and energy consumption analysis.

This paper proposes an energy-oriented joint optimization of machine maintenance and tool replacement (EJMR) policy considering energy consumption mechanisms and joint maintenance opportunities in a machine-tool system. Four successive procedures are developed to obtain the optimal maintenance and replacement intervals based on machine health deterioration and tool wear mechanism. Generally, the machining includes the processes of energy input (materials, electricity, labor force et al), energy transformation and product or semi product output [43]. Among them, the energy consumed due to maintenance activities and tool wear progression is defined as the non-value-added energy consumption (NVE), since it has no direct contribution to the transformation of production. Focusing on this important indicator, the procedures of energy consumption analysis, energy-oriented PM scheduling, machine-tool PR model and integrated decision-making process are illustrated to constitute the EJMR policy. The aim is to form energy-effective schemes by combining PM scheduling of the machine and the tool polish/PR optimization of sequential tools. Thus, performing energy-oriented O&M becomes more interesting, because it is likely to benefit from utilizing joint maintenance opportunities of PM actions to perform tool polish/PR based on energy consumption mechanisms.

Table 1
Classification of the literature.

Category	Optimization objective		Object of study			Main Contribution	Reference
	Cost	Energy	Tool	Single machine	Multiple machine		
Maintenance Policy Optimization	1			1		Integrate production and maintenance scheduling	[18]
	1				1	Integrate Bayesian updating model and opportunistic maintenance	[19]
	1				1	Opportunistic maintenance for leasehold service network	[20]
	1				1	Opportunistic maintenance for mass customization	[21]
		1			1	Schedule short-term maintenance plan	[22]
	1		1			Production sequences requiring tool replacements	[38]
	1		1			Performance forecast model focusing on wear and maintenance process	[39]
Energy Consumption Analysis		1		1		Optimize process parameters and tip radius in dry milling	[28]
		1		1		Spindle power data for tool wear prediction.	[30]
		1		1	1	Hierarchical energy model of machine tool production cycle	[32]
		1	1	1		Comprehensive information on energy intensity in machining process	[33]
			1			Method based on shape mapping to predict off-line tool wear	[34]
			1			Cutting parameters and tool geometry on tool wear	[35]
		1	1	1		Energy including tool wear at the machine, spindle, and process levels	[36]
		1	1	1		Energy consumption model considering tool wear	[37]
Summary	6	7	7	7	5		
Present study	1	1	1	1		Joint maintenance for machine-tool system considering energy and cost optimization	

The novelty and contributions of this paper can be summarized as follows:

(i) We provide a novel analysis of energy consumption as the prerequisite of energy optimization. Unlike most approaches in the literature focusing on machining process or cutting conditions, the energy consumed in a machine-tool system is divided into NVE and value-added energy (VE) considering the effectiveness of energy transformation, and minimizing NVE is the primary optimization objection in this paper. Particularly, we modeled the increasing energy consumption of tool wear progression in different stages, since the server tool wear stage can result in considerable NVE.

(ii) We unprecedentedly consider a joint maintenance model for a machine-tool system from the perspective of energy optimization. The existing research objects on maintenance models are generally single-machine level and multi-machine level, while the research objective is cost optimization mostly. In the EJMR policy, the machine and its sequential tools are modeled jointly to schedule maintenance intervals to avoid frequent breakdown of the system. To realize energy optimization, the NVE consumed in a machine-tool system is integrated to obtain the maintenance intervals dynamically.

(iii) We present a PR model for sequential tools that considers the trade-off between economy and energy consumption. The energy-oriented model (EOM) and cost-oriented model (COM) are proposed to form the comprehensive PR model. Compared to other conventional maintenance policies like periodic preventive maintenance (PPM) policy and energy-oriented preventive maintenance (EPM) policy, the proposed EJMR policy significantly reduces the total non-value-added energy consumption (TNVE) in sustainable manufacturing.

The remainder of this paper is organized as follows. Section 2 "Problem statement" describes the O&M problem for machine-tool systems and provides the framework of the EJMR policy. Section 3 "Energy consumption analysis" presents the mechanism analysis for energy consumption considering the tool wear progression. Section 4 "EJMR decision-making" proposes energy-oriented models and EJMR decision-making process to acquire optimal intervals of machine PM, tool PR and tool polish cycle by cycle. Section 5 "Numerical example and discussion" illustrates the EJMR policy with CNC examples. Comparison experiments are given to identify the validity of its energy-effectiveness. Finally, Section 6 "Conclusion" provides concluding remarks and future works.

2. Problem statement

2.1. System description

This paper proposes an energy-oriented joint optimization of machine maintenance and tool replacement (EJMR) policy. The aim is to realize the sustainable maintenance management for machine-tool systems, such as modern CNC systems. The key approach is to analyze energy consumption mechanisms and utilize joint maintenance opportunities. To promote energy saving and the cost saving, the energy is divided into two categories: the value-added energy consumption (VE) and the NVE, while the costs are divided as the value-added cost (VC) and the non-value-added cost (NVC). As shown in Fig. 1, electricity is regarded as the energy consumption form to develop a comprehensive energy model combining the machine O&M actions with the tool wear progression. The PM scheduling of the machine and the polish/PR optimization of sequential tools are combined to form an energy-effective scheme. Thus, joint maintenance opportunities should be exploited to dynamically optimize machine PM actions and tool polish/PR schemes based on energy consumption mechanisms. As two types of different entities, the degradation process of the machine is independent with sequential replaced tools.

In terms of the machine, it suffers from increasing degradation with usage and age as the deterioration process, which usually leads to failures if no maintenance action is taken. Normally, two kinds of maintenance actions are performed: (1) PM and (2) corrective repair (CR). PM utilizes probabilistic methods to find optimal maintenance intervals to avoid unnecessary failures. CR actions are adapted between PM actions to rectify failed machine back to its operation state with unchanged hazard rate [44]. Designed lifetime of the machine is much longer than a tool, thus we consider the PR actions only for sequential tools.

As for the tools, polish and PR actions are performed to avoid the tool breakdowns. In order to reduce the shutdown in the manufacturing process, the tool is generally opportunistically polished when the machine is performed PM actions. Each tool wear procession is considered when describing the degradations of sequential tools. After several machine PM cycles, a tool will be preventively replaced at the end of a certain cycle, which is normally earlier than the designed lifetime of this tool. Apparently, all above PM, CR, polish and PR actions will arise NVE. How to utilize joint maintenance opportunities to reduce the NVE value of the machine-tool system is scheduled by the proposed EJMR programming.

2.2. EJMR framework

In sustainable manufacturing, an interactive process is required to output energy-effective schemes by combining the PM scheduling of the machine and the polish/PR optimization of sequential tools. Thus, the EJMR policy for machine-tool systems is developed with four successive procedures, as illustrated in Fig. 2.

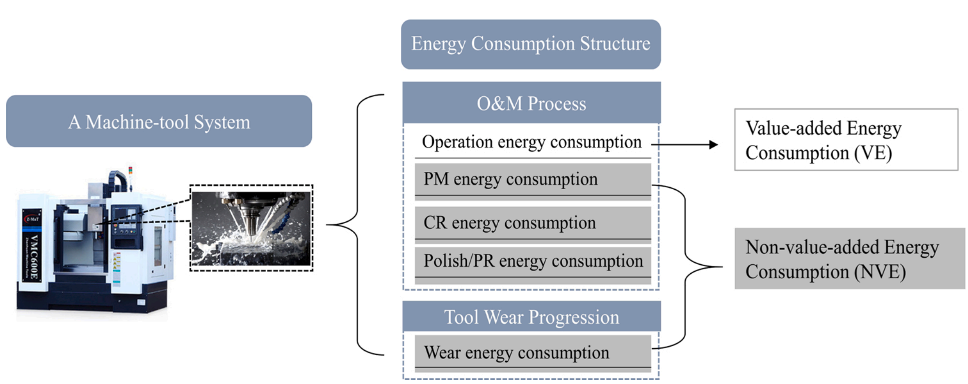

Fig. 1. Energy consumption structure for a machine-tool system.

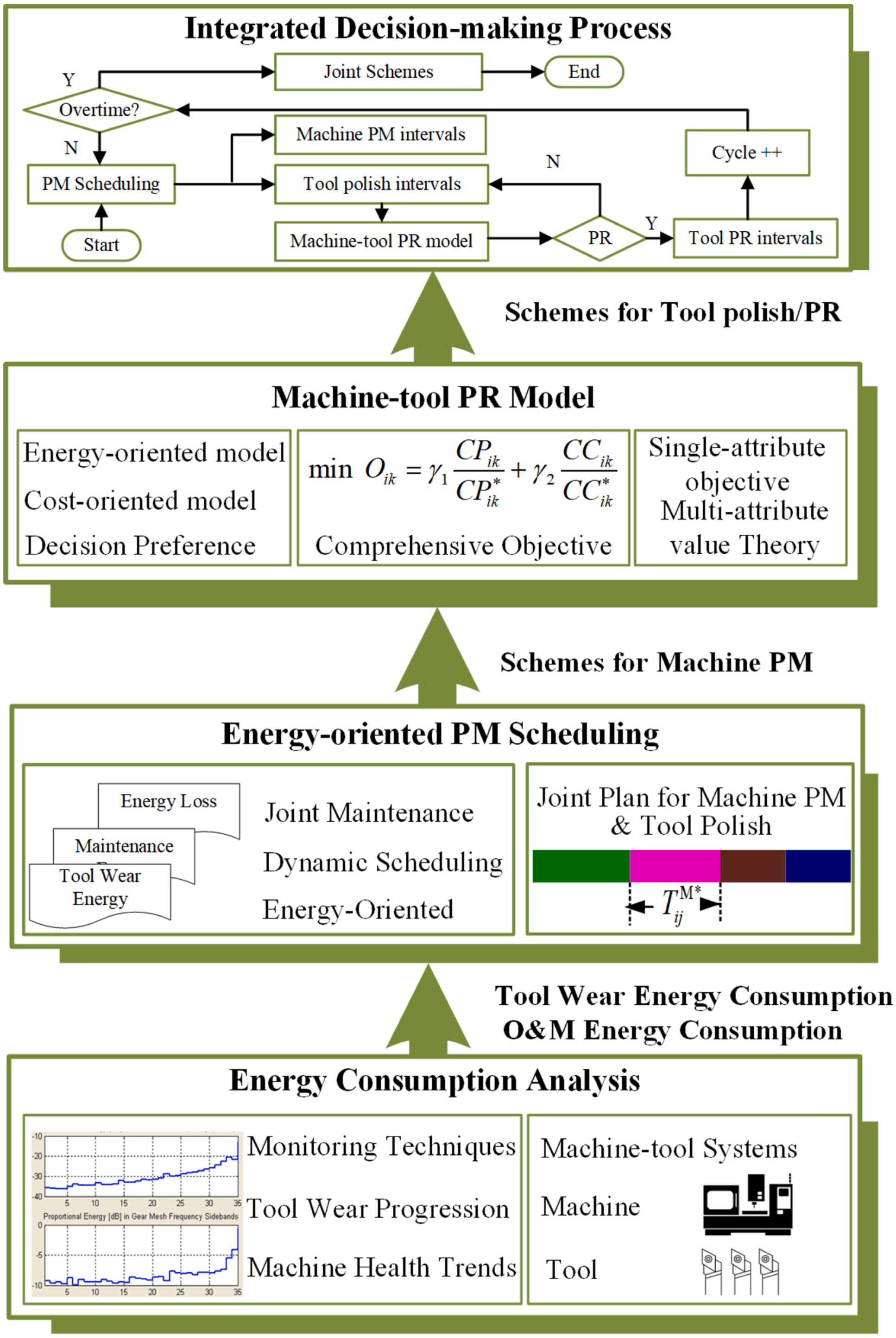

Fig. 2. The framework of the EJMR policy.

2.2.1. *Energy consumption analysis*

The first procedure is to analyze the energy consumption within a machine-tool system. The core issue is to model the effects of the tool wear progression on the evaluation of the total energy consumption. In CNC manufacturing process, the energy loss from the tool wear is regarded as the NVE due to the friction between the contacting parts. It is essential to evaluate the specific wear volume, which can be transferred into the energy consumption by empirical equation. Thereby, the energy consumption of both the machine and each tool can be analyzed as the base for the following decision-making process.

2.2.2. *Energy-oriented PM scheduling*

Based on the energy consumption analysis for the machine-tool system during each PM cycle, energy-oriented PM scheduling considers the NVE to obtain the joint maintenance opportunity. On the one hand, the energy consumed in the tool wear procession is part of the TNVE. On the other hand, the maintenance actions and corresponding energy loss due to the breakdown of the machine-tool system also constitute TNVE from the view of maintenance management. These dynamically outputted PM intervals lead to the joint maintenance opportunities for tool polish or tool PR. However, the energy-oriented model only determines the joint maintenance opportunities for the machine and tool, the detailed maintenance action (polish/PR) for the tool is given by the machine-tool PR model.

2.2.3. Machine-tool PR model

When the machine performed a PM action at the end of each PM cycle, the current tool can be chosen to be polished or replaced. This procedure is to optimize the PR intervals of sequential tools (One tool will be in service during its PR interval; after a PR action, a new tool will be used). The machine-tool PR model focuses on the different demands for the tradeoff between EOM and COM. Accumulated non-value-added cost rate (ANVC) and accumulated non-value-added power (ANVP) are integrated to formulate a comprehensive objective. Therefore, an optimal replacement interval for a tool can be obtained by minimizing this comprehensive objective within the duration of the designed tool lifetime.

2.2.4. Integrated decision-making process

Based on the above procedures, the PM scheduling of the machine and the polish/PR optimization of sequential tools are combined to form energy-effective schemes. Finally, the integrated decision-making process illustrates the whole EJMR programming within the duration of the designed machine lifetime. This procedure provides the flowchart of the decision-making process of the EJMR policy to output the PM intervals of the machine and the PR intervals of sequential tools cycle by cycle.

2.3. Model parameters

Indices			
i:	Index of machine-tool system PM cycles	j:	Index of tool replacement cycles
Parameters about tool wear			
δ:	Tool wear rate in the steady stage	χ, w:	Coefficients of tool wear in the rapid wear stage
V:	Tool wear speed	W:	Tool wear volume
v_0:	Initial wear volume	E_W:	Energy consumption of tool wear
α, φ:	Coefficients between the wear volume and the energy consumption	c_{ij}:	Wear speed increasing factor of the ith tool in the jth PM cycle
d_{ij}:	Wear speed increasing factor of the ith tool in the jth PM cycle	f_{ij}:	Wear residual factor of the ith tool in the jth PM cycle
Parameters about maintenance decision making			
P_{ij}:	Non-value-added power of the jth PM cycle for the machine and the ith tool	P_{Pij}:	PM power of the jth PM for the machine and the ith tool
P_{Rij}:	CR power of the jth PM cycle for the machine and the ith tool	P_{Vij}:	Value-added power (working power) of the jth PM cycle for the machine and the ith tool
T_{Pij}:	Duration for the PM of the jth PM cycle for the machine and the ith tool	T_{Rij}:	Duration for the CR of the jth PM cycle for the machine and the ith tool
T_{Wij}:	Duration of PM interval of the jth PM cycle for the machine and the ith tool	$\lambda_{ij}(t)$:	Hazard rate of the jth PM cycle for the machine and the ith tool
ε_{ij}:	Environmental factor of the jth PM cycle for the machine and the ith tool	b_{ij}:	Hazard increasing factor of the jth PM cycle for the machine and the ith tool
a_{ij}:	Age reduction factor of the jth PM cycle for the machine and the ith tool	AP_{ik}:	ANVP in the previous k PM cycles for the machine and the ith tool.
AC_{ik}:	ANVP in the previous k PM cycles for the machine and the ith tool.	γ_1:	Weighting coefficients for the value functions of the power
γ_2:	Weighting coefficients for the value functions of the cost rate		
Decision variables			
T_{ij}^{M*}:	The jth PM interval for the machine and the ith tool	T_{ij}^{T*}:	PR interval of the ith tool

3. Energy consumption analysis

In the manufacturing process of a machine-tool system, its energy consumption generally involves two parts: one is for the machine O&M actions and the other is the increasing energy consumption generated by the continuous tool wear progression. As a type of key components, multiple tools are widely used to remove materials from workpieces in various processing such as turning, milling and drilling. The continuous operation of tool generates the inevitable tool wear, which results in poor product quality, increasing replacement cost and extra energy consumption. During a tool's lifetime, a typical tool wear procession can be categorized into three stages: I. initial wear, II. steady wear and III. severe wear, respectively. The wear volume of three tool wear stages is shown in Fig. 3 [34].

For the first few minutes of being started up, the tool is worn rapidly due to the unsteadily working process interacting with workpieces, which is so-called the initial wear stage. Generally, the initial wear stage appears in the period of installation and adjustment. With the machining process goes, the tool experiences a steady stage that the tool degradation speed is stable, and the wear volume increases slowly. After the steady wear stage, the tool comes to rapid degradation [45]. Because of the long-time operation, the accumulated tool wear volume will accelerate the degradation speed. As long as the accumulated wear volume reaches the disposal limit, the tool can't be used for the purpose of production and thus its useful life should be ended. Within the designed lifetime of a tool, this paper focuses on the process when the tool can be practically used, which are II. steady wear and III. severe wear stages. It is because that I. initial wear stage generally appears in the adjustment duration for a short time.

First, we model the energy consumption process for a tool in its steady wear and server wear stages. In II. steady wear stage, the wear rate is relatively stable. After entering III. server wear stage, the tool is close to its designed lifetime and suffers a rapid wear procession. The wear volume in the server stage increases exponentially. Based on the wear rule mentioned above in the steady wear stage and the server wear stage, we introduced different wear rate parameters to construct the wear speed as follow:

$$V(t) = \delta + \chi w e^{wt} \tag{1}$$

where δ is the wear rate in II. steady stage, χ and w are introduced to represent the tool enters into III. severe wear stage. Then, combining the initial wear volume v_0 generated in I. initial wear stage, we evaluate the integral of tool wear speed constructed in Eq. (1) and generate the wear volume during the lifetime of a tool as follow:

$$W(t) = v_0 + \int_0^t V(t) = v_0 + \delta t + \chi e^{wt} \tag{2}$$

Meanwhile, the wear procession also results in extra energy consumption. Referring the study of relationship between wear volume and energy consumption [46], we convert the tool wear volume calculated

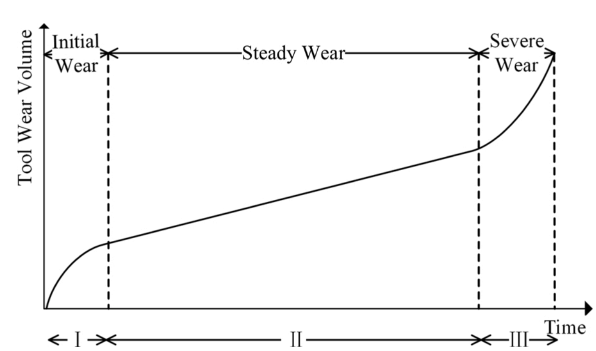

Fig. 3. Three stages of tool wear.

by Eq. (2) into energy consumption. The tool wear energy consumption can be obtained by:

$$E_{\mathrm{W}} = \alpha W(t)^{\varphi} = \alpha(v_0 + \delta t + \chi e^{wt})^{\varphi} \tag{3}$$

where α and φ are the coefficients between the wear volume and the energy consumption.

Analysis of energy consumption structure is a prerequisite for energy consumption optimization. From the O&M management perspective, operation energy consumption and maintenance energy consumption are two important branches. Apart from maintenance energy consumption, the total energy for a machine consists of operation energy from the electrical machinery and extra energy consumed by tool wear. Thus, the total energy consumption for a machine-tool system during the operation period can be given by:

$$E_{\mathrm{total}} = P_{\mathrm{V}}t + E_{\mathrm{W}} = P_{\mathrm{V}}t + \alpha(v_0 + \delta t + \chi e^{wt})^{\varphi} \tag{4}$$

where P_{V} presents the operation power of the machine that the motor drives the spindle running in the manufacturing process. It can be understood that P_{V} belongs to the value-added power due to its direct participation in the effective operation and energy transformation process of workpieces.

4. EJMR decision-making policy

4.1. Energy-oriented PM scheduling

The energy-oriented PM scheduling aims to minimize the TNVE during each PM cycle sequentially to obtain the optimal PM intervals. Meanwhile, each PM action of machine also provides opportunities for the tool to perform polish or PR actions. That is, a tool is polished by utilizing the period of machine PM action, while the PR action of this tool is finally arranged to end its service in the machine-tool PR model. Therefore, the energy-oriented PM scheduling is the first step to consider the energy optimization and provide tool polish/PR opportunities for a machine-tool system.

The manufacturing process can be viewed to include the energy input, the energy conversion and finally outputting finished products ordered by customers. To figure out the effective energy consumption, the energy generated by the machine and tool jointly during the O&M process is divided into value-added-energy consumption (VE) and NVE. On the one hand, the products are manufactured with the operation energy consumption, which is regarded as VE. On the other hand, the tool wear procession and maintenance actions have no direct contribution to the products but result in considerable energy spending. The companies normally try to eliminate these activities that occupy the operation time and consume the non-effective energy. Therefore, the energy consumption caused by the tool wear, maintenance actions (PM, polish/PR, CR) and corresponding energy loss due to the breakdown of the system constitute TNVE. By integrating the total cycle duration and TNVE, the non-value-added power of the j th PM cycle for the machine and the i th tool can be developed as:

$$P_{ij} = \frac{E_{\mathrm{W}} + P_{\mathrm{P}ij}T_{\mathrm{P}ij} + P_{\mathrm{R}ij}T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt + P_{\mathrm{V}ij}(T_{\mathrm{P}ij} + T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt)}{T_{\mathrm{W}ij} + T_{\mathrm{P}ij} + T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt}$$

$$= \frac{\alpha_{ij}W(t)^{\varphi_{ij}} + (P_{\mathrm{P}ij} + P_{\mathrm{V}ij})T_{\mathrm{P}ij} + (P_{\mathrm{R}ij} + P_{\mathrm{V}ij})T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt}{T_{\mathrm{W}ij} + T_{\mathrm{P}ij} + T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt} \tag{5}$$

where the numerator and denominator represent the TNVE and the total duration of the jth PM cycle for the machine. $P_{\mathrm{P}ij}$ is the power for the PM of machine and the polish of the ith tool, while $P_{\mathrm{R}ij}$, $P_{\mathrm{V}ij}$ are CR power and the value-added power (operation power), respectively. Moreover, $T_{\mathrm{P}ij}$ is the duration for the PM of the machine and polish/PR of the ith tool, while $T_{\mathrm{W}ij}$ and $T_{\mathrm{R}ij}$ are the duration of PM interval (operation duration) and CR action. $\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt$ represents the expect CR duration of the jth PM cycle. Thus, the total durations of sequential PM cycles will be $T_{ij}^{M^*} = T_{\mathrm{W}ij} + T_{\mathrm{P}ij} + T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt$. They can be obtained by minimizing Eq. (5) through $dP_{ij}(T_{\mathrm{W}ij})/dt = 0$ to have the optimal PM intervals $T_{\mathrm{W}ij}$.

Note that, the energy-oriented PM scheduling considers the machine PM and tool polish actions, both of them cannot make the equipment to be as good as new. Therefore, the hazard rate of the machine and the tool wear condition should be updated during sequential cycles. On the one hand, the hazard rate of machine is influenced by the internal/external factors. In terms of the internal factors, the effects of maintenance actions represent the restore ability decided by the maintenance technology and resource. Generally, a PM action cannot return a machine to be new, while frequent PM actions accelerate the speed of degradation. Thus, in a new PM cycle, the hazard rate retains a certain residual value and increases more quickly than the previous cycle. In terms of external factors, the environmental conditions such as the temperature and humidity also directly affect the deterioration speed. Taking these factors into the consideration, the hazard rate evolution of the machine between two successive PM cycles is given by:

$$\lambda_{i(j+1)}(t) = \varepsilon_{ij}b_{ij}\lambda_{ij}(t + a_{ij}T_{ij}^{M^*}) \tag{6}$$

where λ_{ij} is the hazard rate in the j th PM cycle. Here, ε_{ij}, b_{ij} and a_{ij} ($\varepsilon_{ij} > 1$, $b_{ij} > 1$, $0 < a_{ij} < 1$) are the environmental factor, the hazard increasing factor and the age reduction factor, respectively.

On the other hand, a tool normally utilizes the opportunity of machine PM to be polished or even be preventively replaced to avoid unnecessary breakdowns. A PR action is applied for using a new tool, thus the wear stage turns back to the initial wear stage. During a tool's service, with the increasing frequency of the polish actions, the wear speed increases quickly. Taking the wear features aforementioned into the consideration, the wear speed between two successive cycles of the ith tool can be given by extending Eq. (3):

$$V_{i(j+1)}(t) = c_{ij}\delta_{ij} + \chi_{ij}d_{ij}w_{ij}e^{d_{ij}w_{ij}t} \tag{7}$$

where $c_{ij}(c_{ij} > 1)$ and $d_{ij}(d_{ij} > 1)$ represent the wear speed increasing factor of the ith tool in the steady wear stage and the server stage respectively.

Tool polish actions can eliminate part of the wear volume, but not help to be as good as new. Thus, the wear residual factor $f_{ij}(0 < f_{ij} < 1)$ is introduced to describe the residual wear volume after a polish. Combined with Eq. (7), the wear volume for the $j+1$th PM cycle of the ith tool is defined as:

$$W_{i(j+1)}(t) = v_0 + f_{ij}\int_0^{T_{\mathrm{W}ij}}V_{ij}(t)dt + \int_0^{t}V_{i(j+1)}(t)dt \tag{8}$$

In sum, both the updated hazard rate of the machine in Eq. (3) and the extended wear volume of a tool in Eq. (8) are utilized in Eq. (5) to dynamically schedule the optimal PM intervals $T_{\mathrm{W}ij}$ (operation duration) cycle by cycle.

4.2. Machine-tool PR model

Based on the dynamically scheduled PM intervals, we continue to figure out the PR interval for the current tool (At the end of which PM cycle to change the tool) by utilizing these PM opportunities within its lifetime. The aim is to avoid the rapid increase of wear energy consumption and the shutdown of tool. It can be understood that over long PR interval can result in considerable TNVE generated by the server tool wear stage, while over short PR interval means that the tool is not efficiently used and more replacement cost will be needed. Therefore, a comprehensive machine-tool PR model is developed in this work to seek the tradeoff between the economy and the energy consumption.

The EOM and COM are integrated to determine the tool PR interval. On the one hand, an ANVP formulation is developed to ensure the energy-efficient O&M process in the EOM. From the first PM cycle to the current kth PM cycle of the machine-tool system, all non-value-added activities including the tool wear, PM, polish, CR actions, and corresponding energy loss are integrated to construct the ANVP function. The objective in the EOM is to minimize the ANVP in the previous k PM cycles for the machine with the i th tool. The ANVP AP_{ik} is defined by:

$$AP_{ik}=\frac{\sum_{j=1}^{j=k}\alpha_{ij}W(T_{\mathrm{W}ij})^{\varphi_{ij}}+\sum_{j=1}^{j=k}(P_{\mathrm{P}ij}+P_{\mathrm{V}ij})\cdot T_{\mathrm{P}ij}+\sum_{j=1}^{j=k}(P_{\mathrm{R}ij}+P_{\mathrm{V}ij})\cdot T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt}{\sum_{j=1}^{j=k}T_{ij}^{\mathrm{M}*}} \tag{9}$$

where the numerator is the sum of NVE in the previous PM cycle ($j=1, 2, \ldots, k$), while the denominator equals to the total duration of the previous PM cycles ($j=1, 2, \ldots, k$). The lifetime of the ith tool is defined as T', and the denominator satisfies that $\sum_{j=1}^{j=k}T_{ij}^{\mathrm{M}*}\le T'_i$.

On the other hand, in order to obtain an economically-effective tool PR interval, the objective in COM is to minimize the ANVC AC_{ik} for the previous k PM cycles for the machine with the ith tool. Thus, AC_{ik} is defined as:

$$AC_{ik}=\frac{C_{\mathrm{C}ij}+\sum_{j=1}^{j=k}(C_{\mathrm{P}ij}+C_{\mathrm{V}ij})+\sum_{j=1}^{j=k}(C_{\mathrm{R}ij}+C_{\mathrm{V}ij})\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt}{\sum_{j=1}^{j=k}T_{ij}^{\mathrm{M}*}} \tag{10}$$

where the numerator is the sum of non-value-added cost used in the previous PM cycle ($j=1, 2, \ldots, k$). $C_{\mathrm{P}ij}$ is the cost of PM for the machine and tool polish for the ith tool. $C_{\mathrm{C}ij}$, $C_{\mathrm{R}ij}$, $C_{\mathrm{V}ij}$ are the tool replacement cost, the CR action cost and the cost of value-added production loss, respectively.

Both of the ANVP and the ANVC are combined by applying the decision weights to obtain specific replacement intervals, which consider the economy optimization and the energy optimization simultaneously. Taking the multi-attribute value theory into the consideration, the function AC_{ik}/AC_{ik}^* and the function AP_{ik}/AP_{ik}^* are defined as the value functions of the cost rate and the power to eliminate differences in unit and quantity. For each single objective, its value function is preferred to be 1, which means its best objective is achieved. Since the lower ANVP and ANVC are required, the optimization model including global objective function and corresponding constraints in the previous k PM cycles for the machine with the ith tool is given by:

$\min O_{ik}=\gamma_1\frac{AP_{ik}}{AP_{ik}^*}+\gamma_2\frac{AC_{ik}}{AC_{ik}^*}$

subject to

$$\gamma_1+\gamma_2=1$$

$$\gamma_2,\gamma_2>0$$

$$AP_{ik}=\frac{\sum_{j=1}^{j=k}\alpha_{ij}W(T_{\mathrm{W}ij})^{\varphi_{ij}}+\sum_{j=1}^{j=k}(P_{\mathrm{P}ij}+P_{\mathrm{V}ij})\cdot T_{\mathrm{P}ij}+\sum_{j=1}^{j=k}(P_{\mathrm{R}ij}+P_{\mathrm{V}ij})\cdot T_{\mathrm{R}ij}\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt}{\sum_{j=1}^{j=k}T_{ij}^{\mathrm{M}*}} \tag{11}$$

$$AC_{ik}=\frac{C_{\mathrm{C}ij}+\sum_{j=1}^{j=k}(C_{\mathrm{P}ij}+C_{\mathrm{V}ij})+\sum_{j=1}^{j=k}(C_{\mathrm{R}ij}+C_{\mathrm{V}ij})\int_0^{T_{\mathrm{W}ij}}\lambda_{ij}(t)dt}{\sum_{j=1}^{j=k}T_{ij}^{\mathrm{M}*}}$$

where AP_{ik}^* is the energy-attribute minimal ANVP from Eq. (9),AC_{ik}^* is the economy-attribute minimal ANVC from Eq. (10). γ_1 and γ_2 ($\gamma_1+\gamma_2=1$) are the weighting coefficients for the value functions of the power and cost rate. Weighting coefficients are selected depending on the decision-maker's preference. The higher the weighting coefficient, the more preference is given to the attached objective. The ith tool is replaced at the k_j^* th PM period, and the PR interval of the ith tool is thus obtained as $T_{ij}^{\mathrm{T}*}=\sum_{j=1}^{j=k_j^*}T_{ij}^{\mathrm{M}*}$. After a PR action, the $(i+1)$th tool starts to be used, then the PM cycle of the machine-tool system restarts counting from the cycle $j=1$. To sum up, the optimization model c

4.3. Integrated decision-making process

As presented above, we propose an energy-oriented joint optimization of machine maintenance and tool replacement (EJMR) policy by integrating energy consumption mechanisms and joint maintenance opportunities in a machine-tool system. As two entities, the machine and its sequential tools are modelled jointly to schedule maintenance intervals for planning the energy-effective and the cost-effective schemes. In the proposed decision-making processes, the energy consumption analysis provides the related mechanism to evaluate the energy consumption by the tool wear procession. Then, the energy consumption caused by non-value-added activities is integrated to plan the PM intervals for the machine-tool system. Within the lifetime of the machine, a comprehensive machine-tool PR model is developed to arrange sequential tool replacements by balancing energy and economy. Fig. 4 shows the flowchart of the proposed EJMR policy for the machine-tool system.

Step (1) Parameters input. Combining with the intelligent monitoring and prediction technologies, machine degradation and tool wear information can be acquired, stored and processed in an efficient way. Starting from the first PM cycle of machine and the first brand-new tool, all parameters about tool wear, energy consumption, and machine hazard function are collected and put into the decision-making process.

Step (2) Energy-oriented PM scheduling. After integrating the TNVE and corresponding durations, the intervals of machine PM and tool polish is acquired by minimizing Eq. (5).

Step (3) Tool lifetime limit check. Identify whether the accumulated PM intervals is greater than the tool designed lifetime $\sum_{j=1}^{j=k}T_{ij}^{\mathrm{M}*}>T'_i$ or not. If no, turn to Step (4) to update the machine hazard rate and the tool wear speed to sequentially output PM intervals. If yes, go to Steps (5) and (6) to use the machine-tool PR model to decide when to replace the i th tool.

Step (4) Machine hazard rate and tool wear speed update. Introduce the machine hazard rate in Eq. (6) and the wear speed evolution in Eq. (8) to describe conditions of machine health and tool wear for the

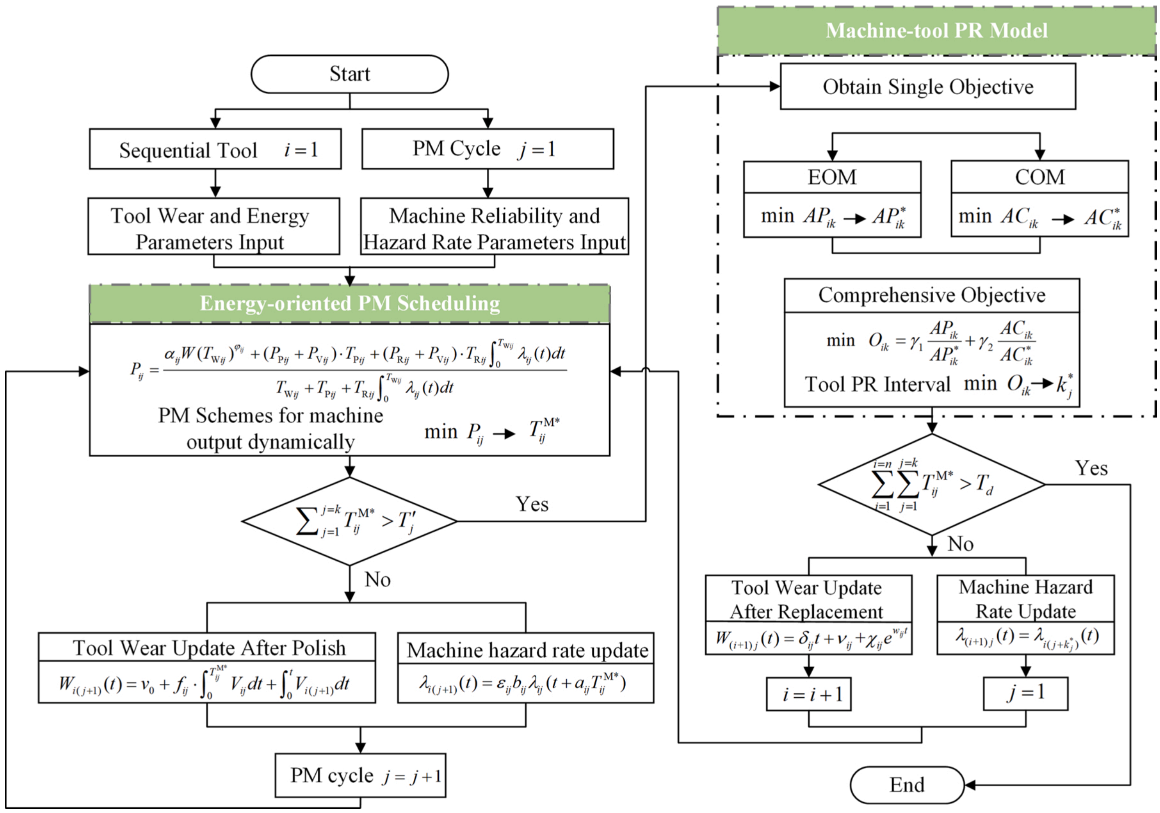

Fig. 4. Flowchart of the decision-making process for the EJMR policy.

next PM cycle. Assign $j=j+1$ and go back to Step (2).

Step (5) Single-objective AP/AC scheduling. Within the tool designed lifetime T', the minimal AP_{ij}^* and AC_{ij}^* can be found by minimizing the functions of ANVP and ANVC at the end of certain PM cycle, respectively.

Step (6) Machine-tool PR decision-making. By integrating AP_{ij}^* and AC_{ij}^* obtained in Step (5), the value functions of the cost rate AC_{ik}/AC_{ik}^* and the power AP_{ik}/AP_{ik}^* can be developed. Then, with the weighting coefficients for the EOM and COM, the optimal tool PR interval can be obtained as $T_{ij}^{T*}=\sum_{j=1}^{j=k_j^*}T_{ij}^{M*}$ to replace the current i th tool.

Step (7) Decision duration limit check. After (n-1) tool PR actions and during the service of the nth tool, if the accumulated k PM cycles exceeds the system decision-making duration $\sum_{i=1}^{i=n}\sum_{j=1}^{j=k}T_{ij}^{M*}>T_d$, the EJMR programming will be ended. Otherwise, turn to Step (8) to accomplish the update for the wear volume of the new tool.

Step (8) Update new tool wear. After a tool replacement, the wear volume of the new tool restores as $W_{(i+1)j}(t)=\delta_{ij}t+\nu_{ij}+\chi_{ij}e^{w_{ij}t}$. Then assign $i=i+1$ for the tool number, and assign $j=1$ for the beginning PM cycle. Turn to step (2) to perform the energy-oriented PM scheduling for the new tool.

5. Numerical example and discussion

5.1. Numerical example

In order to illustrate the proposed EJMR policy, data about the O&M process of a Boehringer NG200 Crankshaft Turning CNC has been collected by the professional engineers with cooperative enterprise, who is one the leading automotive company in China. Then these data can be applied as a numerical example to schedule the energy-saving maintenance schemes. The total system decision-making duration is given as $T_d=6000$h. The hazard rate of the machine is formulated by using Weibull distribution, which has been widely used to describe the failure rate in mechanical and electronic engineering [47]. The hazard rate for the first cycle ($i=1, j=1$) is shown as:

$$\lambda_{ij}(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{12}$$

where β and η are the shape and scale parameters respectively that can be acquired by the numerical analysis of the reliability tests [48]. In addition, the related energy parameters ($P_{\mathrm{P}ij}$, $P_{\mathrm{V}ij}$ and $P_{\mathrm{R}ij}$) and maintenance parameters ($C_{\mathrm{P}ij}$, $C_{\mathrm{R}ij}$, $C_{\mathrm{V}ij}$ and $C_{\mathrm{C}ij}$) should be estimated by reliability engineers in real manufacturing processes. Among them, the working power values $P_{\mathrm{V}ij}$ are usually remarked on equipment nameplates, while the other actual parameters are collected from reliability engineers, since it will be their duty to evaluate the energy consumption of each maintenance action within the plant. Moreover, in order to obtain the hazard rate evolution and tool's data practically, the

Table 2
Decision-making parameters.

Tool wear and energy consumption		Machine hazard rate		Maintenance parameters	
Variable	Value	Variable	Value	Variable	Value
v_0	500	β	2	$P_{\mathrm{P}ij}$	40
δ	1.200	η	2000	$P_{\mathrm{V}ij}$	70
w	0.050	a_{ij}	0.050	$P_{\mathrm{R}ij}$	89
δ	0.010	b_{ij}	1.050	$C_{\mathrm{P}ij}$	200
c_{ij}	1.200	ε_{ij}	1.035	$C_{\mathrm{R}ij}$	800
d_{ij}	1.100			$C_{\mathrm{V}ij}$	600
f_{ij}	0.280			$C_{\mathrm{C}ij}$	2000
α	0.220			$T_{\mathrm{P}ij}$	18
φ	1.300			$T_{\mathrm{R}ij}$	40
T'	5000				

Table 3
Results of energy-oriented PM scheduling for machine and the 1st tool.

j	1	2	3	4	5	6	7
P_{1j}(kW)	9.260	11.299	12.757	14.404	16.321	18.567	21.202
T_{1j}^{M*}(h)	867	814	743	677	617	562	511
t_{1j}^{M*}(h)	867	1681	2424	3101	3718	4280	4791

environmental factor ε_{ij}, the hazard increasing factor b_{ij}, the age reduction factor a_{ij} and the related tool wear data should be estimated through historical information or state prediction. Under the help of cooperative enterprise, all the parameters mentioned above can be derived by professional reliability engineers with corresponding experimental tests. Thus, the parameters about machine reliability, tool wear procession and maintenance actions are estimated by reliability engineers and shown in Table 2.

According to the decision-making process of the EJMR policy, the machine PM intervals can be obtained by minimizing the TNVE. Following the process of energy-oriented PM scheduling, Table 3 shows the non-value-added power, PM cycle durations and the accumulated durations in detail. Within the lifetime of the first tool, 7 PM actions are arranged for the machine. For example, in the 3rd PM cycle for the machine with the 1 st tool, the non-value-added power is 12.757KW, PM cycle duration is 743 h, and the total duration from the beginning to the 3rd PM action performed is 2424 h. From the results shown in Table 3, we can draw the following conclusions: (1) With the increasing of PM cycles, the PM interval between two PM actions decreases since the deterioration of the machine is faster with aging and more PM actions are required to maintain the healthy condition of the machine-tool system. (2) The non-value-added power of every PM cycle increases due to the worse of the tool wear. The results match the O&M process in reality that more frequent maintenance actions are required along with the deterioration of the machine and the tool.

Referring to the machine-tool PR model proposed in Section 4.2, the tool PR interval is obtained by the combinations of different weights to balance the EOM and COM. In this work, three different types of cases are given to illustrate the validation of machine-tool PR model. As for CASE 1, the weighting coefficients for ANVP and ANVC are 0 and 1 respectively ($\gamma_1 = 0, \gamma_2 = 1$). It represents that the economy optimization is preferred without considering the energy consumption. In terms of CASE 2, the weights for the cost rate value function and power value function are 0.5 and 0.5 ($\gamma_1 = 0.5, \gamma_2 = 0.5$), which means the economy optimization and energy optimization are of equal importance. As for CASE 3 ($\gamma_1 = 1, \gamma_2 = 0$), the objective for the machine-tool PR model only involves the optimization of EOM. The final result of the 1 st tool preventive replacement cycle is shown in Table 4.

It should be noticed that the tool PR actions for these three cases utilize the 6th, 3rd, and 1 st machine PM respectively, along with the PR intervals are 4280 h, 2424 h, and 867 h respectively. The conclusions can be obtained as follows: (1) From CASE 1 to CASE3, the tool PR intervals are decreasing since the preference for the energy optimization is increasing; (2) It is obviously that the ANVP of the first tool is decreasing while the ANVC is increasing due to the confliction between the economy optimization and energy optimization.

Combining with three different combinations of weighting coefficients, the global energy-saving schemes of machine maintenance and tool replacement are generated referring to the EJMR policy. The detail results of sequential tool PR arrangements under these three cases are illustrated in Fig. 5. It can be indicated that the tool PR frequency and the total non-value-added cost (TNVC) is increasing, while the TNVE decreases from CASE1 to CASE3. The machine is performed PM actions 8 times in CASE 1, and its tool experiences the first PR by utilizing the opportunity of the 6th PM action, while the tool is polished 7 times at other PM periods. Taking CASE 1 as an example, the TNVC within the decision duration is 11,802$ and the TNVC is 85,451 KWh. Under CASE 2, the machine experiences PM actions for 7 times and its tools are replaced at the 3rd and 6th PM periods. The TNVC and TVNE are 12,498$ and 68,356 KWh respectively. As for CASE3, the machine experiences 7 PM cycles in total and its tools are replaced at every PM action. In the CASE 3, 23,810$ are spent while the electricity of 65295KWh is consumed.

Table 4
Results of the 1st tool PR decision under different weights.

Combinations of weighting coefficients	k_1^*	$CP_{1k_1^*}^*$ (kW)	$CC_{1k_1^*}^*$ ($)	$O_{1k_1^*}$	$T_{1k_1}^{T*}$ (h)
CASE1	6	14.094	1.973	1.000	4280
CASE2	3	11.593	2.181	1.150	2424
CASE3	1	9.710	3.576	1.000	867

5.2. Comparison experiments

In order to prove the effectiveness of this EJMR policy for machine-tool systems, we also compare the proposed policy with two conventional maintenance polices by applying the same parameters. One is the PPM policy, while the other is the EPM policy. The comparison of these polices on the values of TNVC and TNVE is shown in Fig. 6.

The PPM policy is broadly studied in academic research and applied in industrial field [49]. It aims to find a cyclic maintenance schedule in a given duration and minimize the corresponding costs in the O&M process. However, the dynamic health degradation, tool wear procession and energy consumption focused in this study are ignored [50]. The tool is still replaced by utilizing the PM period, which is the nearest PM cycle to the designed lifetime of the tool. Under the PPM policy, the machine PM interval and tool PR interval are fixed, which equal to 990 h and 4950 h respectively. Thus, the corresponding values of TNVC and TNVE are 11,957$ and 196730KWh.

In terms of the EPM policy, it constructs the maintenance energy rate by integrating the total maintenance energy consumption including the energy of a PM action and possible energy of CR actions [23]. The optimal PM interval can be obtained by minimizing the maintenance energy rate. Different from the PPM policy, this policy takes the dynamic health degradation of machine into consideration. It is noted that the hazard rate evolution is updated after PM actions cycle by cycle in the EPM policy. However, the energy loss due to the tool wear procession is neglected. The detailed results of the EPM policy are given in Table 5. The tool is replaced at the 8th PM cycle (at the time of 4934 h). The TNVE and TNVC are 99112KWh and 13,021$ respectively. It is also illustrated that the interval of PM cycles is decreasing due to the faster deterioration of tool and machine.

Fig. 6 represents the values of TNVC and TNVE under three maintenance policies, and the results of the EJMR policy are demonstrated under three kinds of weighting coefficients. It is obvious that the energy efficiency of the EJMR policy is improved in terms of the PPM policy and EPM policy. The three cases of the EJMR policy consume 85451KWh, 68356KWh and 65295KWh, which are even fewer than the EPM policy. Let alone compared with the PPM policy, the energy-saving of the EJMR policy for the three cases can achieve 111279KWh, 12837KWh and 131435KWh respectively. In the decision-making process, CASE 1 ($\gamma_1 = 0, \gamma_2 = 1$) and CASE 2 ($\gamma_1 = 0.5, \gamma_2 = 0.5$) both consider the economy efficiency. Therefore, their TNVC values are close to conventional

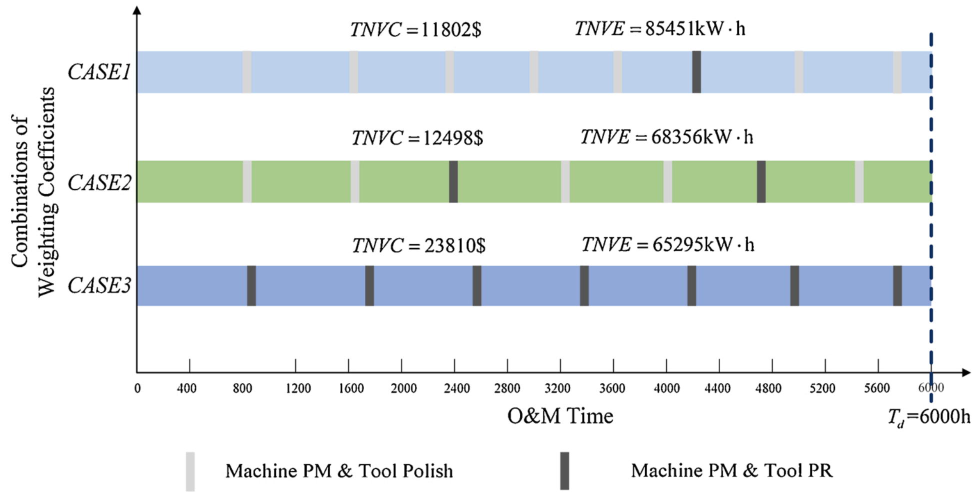

Fig. 5. Maintenance schemes for the machine-tool system of three cases.

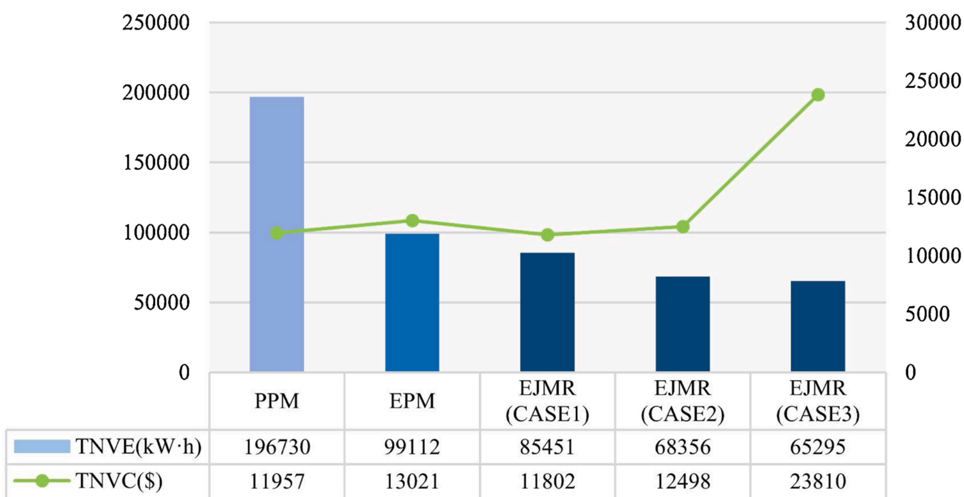

Fig. 6. Comparison of TNVC and TNVE under different maintenance policies.

Table 5
Results of EPM policy.

T^*_{11}(h)	T^*_{21}(h)	T^*_{31}(h)	T^*_{41}(h)	T^*_{51}(h)	T^*_{61}(h)	T^*_{71}(h)	T^*_{12}(h)	T^*_{22}(h)	TNVE(kW·h)	TNVC($)
848	794	744	698	655	616	579	544	512	99,112	13,021

maintenance policies, while large amount of energy consumption can be saved by EJMR programming. As for CASE 3, the energy efficiency is the exclusive objective while the economy efficiency is ignored, which leads to frequent tool replacements. Thus, it is illustrated that the TNVE is reduced obviously while the TNVC is much higher. This is why we develop the multi-attribute machine-tool PR model to comprehensively integrate the cost-efficiency and energy-efficiency. In conclusion, the proposed EJMR policy for machine-tool systems is effective to promote the sustainable manufacturing by considering the energy consumption mechanism and deterioration rules. Without additional cost increase, the TNVE of the machine and tools can be significantly reduced.

6. Conclusion

Most studies on the maintenance policies focus on cost-efficiency and the health degradation of a single machine. For a machine-tool system, by integrating the machine degradation and the tool wear, we propose the EJMR policy to obtain the energy-saving schemes involving machine PM and tool polish/PR. Firstly, the wear volume is modeled and then transformed into the corresponding energy consumption by analyzing the tool wear progression. Secondly, the energy-oriented PM scheduling is dynamically performed based on the TNVE caused by tool wear, PM actions, CR actions and the operation energy loss. Thirdly, the EOM and the COM are combined to establish a comprehensive objective to sequentially schedule the tool PR. The final maintenance schemes for a machine-tool system is obtained by EJMR programming. Results have indicated that the TNVE consumed by the EJMR policy is much lower than conventional maintenance polices, with no additional cost needed.

The future extension of the proposed EJMR policy can focus on the maintenance scheduling for multi-machine systems with multiple types of tools. Different system structures including series systems, parallel systems, and series-parallel systems can be analyzed to extend the research scope according to the practice of manufacturing process. Moreover, the trade-off between the economy, the energy and other objectives (e.g. the exhaust emission) can be involved to promote the future sustainable manufacturing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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