DOI: 10.3901/CJME.2010.**.***, available online at www.cjmenet.com; www.cjmenet.com.cn

Methods for Integrating Energy Consumption and Environmental Impact Considerations into the Production Operation of Machining Processes

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Received November 10, 2009; revised May 5, 2010; accepted June , 2010; published electronically June , 2010

Abstract: Energy consumption and environmental impact considerations of machining processes are viewed as the important issues for the global trends towards sustainable manufacturing. The existing research of reducing energy consumption and environmental impacts of machining processes greatly focuses on design and process planning activities, while the issue is seldom considered in production operation activities, especially for machining processes. This paper explores the systematic methodology for incorporating energy consumption and environmental impact considerations into the production operation of machining processes. Firstly, the framework of the methodology is proposed to establish the generic procedures for integrating the above considerations in production operation activities. As the two key issues of the framework, the profile index value matrix is determined by valuing the individual quantity of energy consumption and environmental impacts of machining each job on each machine, and the multi-criteria models are constructed by the operational methods. Furthermore, with the guideline of the framework, the specific formulations of the method are modeled by two sub-models for the parallel machine scheduling problem, in which makespan and energy consumption are the optimizing objectives as well as the constraints of environmental impact considerations. The specific formulations provide a practical method to integrate energy consumption and environmental impact considerations into the scheduling activity, and also can serve as a reference to other activities in the production operation. The case study for a batch of jobs including seven kinds of gear in the machining shop floor is presented to demonstrate the application of the specific formulations of the methodology. The proposed methodology provides potential opportunities for reducing energy consumption and environmental impacts in machining processes, and helps production managers in decision-making on the issues of energy consumption and environmental impacts in the production operation.

Key words: green manufacturing, energy, environmental impact, production operation, machining

1 Introduction

In recent years, there have been great concerns on energy consumption and environmental impact in manufacturing processes in response to the global trends towards sustainable manufacturing. The reasons for the concerns include regulatory requirements, product stewardship, enhanced public image, potential to expand customer base, and potential competitive advantages[1].

Machining is a material removal process that typically involves the cutting of metals using various machine tools, which is wasteful in its use of both material and energy[2]. However, given that machining is capable of creating geometries, surface finishes, and providing the precision not achievable by other operations, it is still the most widely used of machining processes [3].

In the above situations, the interests of researchers have been increasingly focused on the issues of energy consumption and environmental impact of machining processes. MUNOZ, et al[4], developed the modeling approaches specifically to the environmental issues of machining processes. Later on, they presented a methodology for considering environmental factors in machining facilities which used analytical process models embedded as the attributes of systems resources to determine energy use and mass flows based on process time and volume of material removed[5]. In parallel, this group of researchers addressed on the issues from the view of process planning[6], and systems planning[7]. GUTOWSKI, et al[2], analyzed the environmental issues of machining processes, and the energy and resource requirement of the machining process had been addressed again in Refs. [8–9]. Specifically, CHOI, et al[10], developed the assessment methodology which was used to obtain the amount of the solid waste generated, the energy consumed, the waste-water incurred and the level of noise for machining processes as well as for other manufacturing processes. Moreover, relative research on the issues had been carried on by ROMAN, et al[11] and MACZKA, et al[12]. The former proposed an approach for storing and reusing the environmentally-related process information of similar component process plans via environmental process model

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This project is supported by National Natural Science Foundation of China (Grant No. 50775228), and National Key Project of Scientific and Technical Supporting Programs of China (Grant No. 2006BAF02A03)

templates, and developed the templates for gear process planning; and the latter described the practical verification of the enhanced model for energy consumption during machining integrating the feature-based calculation of energy utilization of machining process with the activity-based energy estimation of the operations performed by machine tools.

Although a number of researchers have conducted research on discovering the methodologies for reducing the energy consumption and environmental impact of machining processes, relatively little research has been done on the issues of energy consumption and environmental impact from the point of production operations, and mainly focused on the process production industry, such as assembly lines, dairy industry, and treatment surface lines. For example, WORHACH, et al[13], presented a methodology for the operational control of assembly systems of printed circuit board(PCB) with respect to environmental objectives on managing per-unit and per-setup waste flows. MELGYK, et al[14], proposed a single tool, named green manufacturing resources planning (MRP), which integrated environmental concerns into the material planning, scheduling, and execution, and was used into a truck taillight assembly line. BERLIN, et al[15], addressed on the issue for dairy industry as well as in other food industries, and described an inter-disciplinary approach making use of both production scheduling and environmental systems analysis to counteract the adverse environmental consequences of the ongoing development of dairy industry. SUBAI, et al[16], explored the possibility of taking into account environmental constraints in scheduling solutions for “cleaner” treatment surface, and proposed a systemic approach which involved the productivity criteria and also both cost and environmental criteria in the decision process. In the most recent, some research also began to focus on the issue of manufacturing processes. For example, MOUZON, et al[17], developed a method for machine scheduling to reduce the energy consumption of manufacturing equipment by turning off the non-bottleneck manufacturing equipment during the interval of the next job arrival. Additonally, we have also addressed on the scheduling problem for green manufacturing in their past research[18–20].

Following the earlier research efforts on the issues of the energy consumption and environmental impacts of machining processes, we explore the energy consumption and environmental impact considerations in the production operation of machining processes. Since the characteristics of energy consumption and environmental impacts generated in machining are very complicated, using one single model for all the considerations and any production operation problem is too complex to be practical. And also, in the actual production situation, production managers usually pay attention to some of the above considerations depending on the different specific problems. Therefore, this paper proposes a systematic methodology which is a guideline for modeling the specific problems. The establishment of the specific model provides a practical method to integrate the interested considerations by production managers into production operation activities. The objective of this research is to assist production managers in minimizing energy consumption and environmental wastes during the production operation.

2 Framework for the Methodology

2.1 Description of the methodology

In the production operation, given that the existing process planning and machine tools are not altered, the different machining process can be described with two types of situations. One is to machine the same job with the different machine tools, and the other is to machine different jobs with the same machine tool. It is observed that in both of the above two situations, the energy consumption and environmental impacts are different in terms of different machining processes. For the latter, this is a common sense; and the former was also investigated by some researches. For example, DAHMUS, et al[2], presented that 14.2 kJ/cm^3 energy is needed by the production machining center in order to machine a material Al, but only 4.9 kJ/cm^3 energy would be needed if the same material is processed on manual milling machines. Also, we confirmed this in Refs. [18–19]. Therefore, a proper machining process for both jobs and machines would play a significant roles on saving energy and reducing environmental impacts. With aims to finding an optimized machining process at the production operational level, we therefore propose a framwork establishing schematic procedures that can incorporate energy consumption and environmental impact considerations of machining processes into the production operation. The framework is shown in Fig. 1.

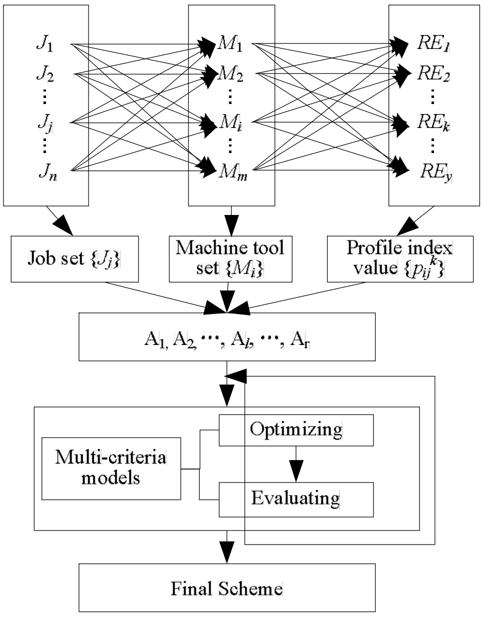

Fig. 1. Description of the methodology

In order to present the framework clearly, we first define J as the set of jobs, and define M as the set of avaible machine tools for the corresponding jobs. Also, we define j as the index of jobs, and let j\in (a symbol of belonging to) J, and define i as the index of machines, and let i\in M. With these definitions, all jobs and machine tools can then be denoted as follows: $\{J_j| j=1, 2,\cdots, n\}$ and $\{M_i|i=1, 2,\cdots, m\}$. Additionally, we define the profile indices of energy consumption and various environmental impacts as $\{RE_1, RE_2,\cdots, RE_k,\cdots, RE_y\}$ regarding to the machine tools in $\{M_i|i=1, 2,\cdots, m\}$ machining those jobs in $\{J_j| j=1, 2,\cdots, n\}$. Each of the profile indices is valued by the quantity of the individual energy and material flows which go though M_i with the input of job J_j, and the value of each profile index denoted with $\{p_{ij}^k\}$ is then determined by the assessment methods. Usually, besides energy consumption and environmental impacts, the conventional objectives, such as completion time or due date, might be concerned by production managers when they make decision analysis. Therefore, we define another set of multiple criteria of production managers' decision-making, $\{A_l|l=1, 2,\cdots, r\}$. Obviously, $\{A_l\}$ is a comprehesive, complex multi-criterion set, and there exist interrelation and conflict among these criteria, for instance, in some cases, the optimization goal of energy consumption seriously conflicts with the one of enviromnental impacts. One single mutli-criteria model for optimizing all of criteria in $\{A_l\}$ is too complicated to be practical. Therefore, depending on the managers' decision-making preference, the construction of the multi-criteria models consists of the optimization of the criteria which are required to obtain the optimal solution, and the evalution of the criteria which are used to analyze the performance of the optimal solution. When production managers do not satisfy the evaluation results, the multi-criteria models can be reconstructed by adjusting the optimizing criteria and evaluating criteria.

In the above procedures of the methodology, there are two key issues for integrating the profile indices into the production operation: (1) determining the profile index value $\{p_{ij}^k\}$; (2) establishing the multi-criteria model.

2.2 Profile index value of energy consumption and environmental impact considerations

In machining processes, material and energy flows go though machine tool, and are transformed into products (or semi-products) as well as environmental hazards. The materials as the input to the machine tool are divided into two categories: the primary material making up of the primary material out (product) and the secondary catalyst facilitating the machining process. When the materials go though machine tools, the primary material out (product) is the desired output while there are some primary unwanted outputs in the form of the material script, the catalyst waste and noise, and so on. These outputs are hazardous to the environment, namely, environmental impacts. Energy flow is another kind of important item which goes though the machine tool. The input energy of the machine tool is the total quantity of the producing process of the primary material (or job). The partial of the total input energy is employed to the material removal while the remainder is wasted, such as maintaining the unload running of machine tools.

From the level of production operation, the primary material can be regarded as the job that needs to be machined. Because the jobs are already arranged according to the production plan, the primary material and the energy consumption for the material removal are also unchangeable. Therefore, for production operation activities, the profile indices of energy consumption and environmental impact considerations mainly consist of the wasteful energy and the unwanted environmental impacts, which are denoted with $\{RE\}$.

Different machine tools may generate the different quantities of each profile index even when they are machining the same job. Also, the same machine tool also produces the different quantities of each profile index when it processes different jobs. Hence, the machine set and job set respectively designate the rows and columns of each profile index value matrix. Furthermore, assuming the set $\{RE_1, RE_2,\cdots, RE_k,\cdots, RE_y\}$ contain y profile indices, there are y profile index value matrices for the machine set and job set, which are denoted with the set $\{p_{ij}^k|k=1, 2,\cdots, y\}$, as shown in Fig. 2.

$$\begin{array}{c|ccccc}
RE_k & J_1 & \cdots & J_j & \cdots & J_n \\
\hline
M_1 & \left(\begin{array}{c} p_{11}^k \\ \cdots \\ p_{i1}^k \\ \cdots \\ p_{m1}^k \end{array}\right. & \begin{array}{c} \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{array} & \begin{array}{c} p_{1j}^k \\ \cdots \\ p_{ij}^k \\ \cdots \\ p_{mj}^k \end{array} & \begin{array}{c} \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \end{array} & \left.\begin{array}{c} p_{1n}^k \\ \cdots \\ p_{in}^k \\ \cdots \\ p_{mn}^k \end{array}\right)
\end{array}$$

$$\begin{array}{c|c}
RE_k & \begin{array}{ccccc} J_1 & \cdots & J_j & \cdots & J_n \end{array} \\
\hline
\begin{array}{c} M_1 \\ \cdots \\ M_i \\ \cdots \\ M_m \end{array} & \begin{pmatrix} p_{11}^k & \cdots & p_{1j}^k & \cdots & p_{1n}^k \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{i1}^k & \cdots & p_{ij}^k & \cdots & p_{in}^k \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{m1}^k & \cdots & p_{mj}^k & \cdots & p_{mn}^k \end{pmatrix}
\end{array}$$

Fig. 2. Profile index value matrices

The element p_{ij}^k is the value which characterizes the profile index RE_k generated by the machine tool M_i when machining the job J_j. When the quantity of the profile index is easy to be measured by some devices or sensors, the value is a number, such as energy consumption which can be collected by power meter; otherwise, for environmental impact indices, the values of these profile indices are generally determined with qualitative evaluation by experts or persons with rich experience, and such as the fuzzy set method is also employed to calculate the values[21].

2.3 Multi-criteria models

In the production operation activities, obviously, minimizing the energy consumption and environmental impacts of machine tools is an unavoidable performance criterion. However, in the real situation, it is not the only kind of criterion pursued by production managers. For example, in the scheduling activities, such as makespan, earliness and tardiness are the usual performance criteria considered by production managers [22]. Consequently, the multi-performance criterion set $\{A_l\}$ may consist of the energy and environmental impact performance criteria as well as the usual performance criteria, which have been concerned by managers when they are making decision analysis.

The set of performance criteria $\{A_l\}$ is established to include all desired considerations by managers. Depending on the preference of managers' decision-making, all of the performance criteria in the set $\{A_l\}$ can be considered in the managers' decision-making via three categories: the first one is regarded as the very important performance criterion, and required to be the objectives obtaining the optimal results; the second one is desired to be as the constraints seeking the optimization; and the last one is employed to evaluate the performance of the operation activities which is also taken care of by managers. Therefore, given the production operation activity δ, the general form of the multi-criteria model is composed of the following three kinds of formulations.

The optimization formulation is as follows:

$$D=M(A_1(\delta),p^1(\delta))\cap M(A_2(\delta),p^2(\delta))\cap\cdots\cap M(A_{c_1}(\delta),p^{c_1}(\delta)). \tag{1}$$

The evaluation formulation is as follows:

$$E=\{A_1(D),\ A_2(D),\cdots,\ A_{c_2}(D)\}. \tag{2}$$

The constraints are as follows:

$$f(A_i(\delta),p^i(\delta))\le F_i,\ \ i=1,2,\cdots,c_3, \tag{3}$$

$$O(\delta)=O(A_{c_3+1})\cap O(A_{c_3+2})\cap\cdots\cap O(A_{c_4}), \tag{4}$$

$$c_1,c_2,c_4\le r. \tag{5}$$

Eq. (1) describes the multi-objective optimization function used to obtain the optimal results for the subset criteria $\{A_1,A_2,\cdots,A_{c_1}\}$, and Eq. (2) denotes the multiple functions used to evaluation the performance of the subset criteria $\{A_1,A_2,\cdots,A_{c_2}\}$. Eqs. (3) and (4) indicate the constraints with definite limits of the subset criteria $\{A_1,A_2,\cdots,A_{c_3}\}$ and the forbidding constraints for the subset criteria $\{A_{c_3+1},A_{c_3+2},\cdots,A_{c_4}\}$, respectively. Eq. (5) represents that all criteria in the subset belong to the set $\{A_l|l=1,\ 2,\cdots,\ r\}$. Usually, the establishment of the subset criteria for different formulations is dependent on the preference of manager's decision-making.

3 Specific Formulations of the Method

The above framework is a generic guideline for the issue that is to consider energy consumption and environmental impacts in production operation activities. Given a specific production operation problem in actural situations, we model the specific problem with the specific formulations guided by the framework. Based on the guideline, the different formulations can be established depending on the different specific problems and managers' preference on the considerations in the actural production situation. Actually, the establishment of the specific formulations provides a practical method to integrate the interested considerations by production managers into production operation activities.

Scheduling is one of the common activities in the production operation activities. In the remainder of the paper, we deal with the parallel machine scheduling problem, and the mathematic formulations are developed to provide an operational method for integrating the energy consumption and environmental impact considerations, which also serves as a reference to other activities in the production operation.

Given the parallel machine scheduling problem δ, we denote the job set with $\{J_j|\ j=1,\ 2,\cdots,\ n\}$ and the machine set with $\{M_i|i=1,\ 2,\cdots,\ m\}$. Suppose that the jobs are scheduled on the set of machines that are available from time zero and that can handle only one job at a time, and each job requires only one operation and the preemption is not allowed.

As mentioned before, when integrating the energy consumption and environmental impact considerations, the scheduling problem may have multiple performance criteria. For the given scheduling δ, the makespan of the scheduling is the preferred performance criterion by the production managers. Meanwhile, the energy consumption is also the focused objective. For environmental impacts, they want to avoid to assigning the jobs to the unfriendly machine tools, especially the jobs that may cause a large amount of wastes. Therefore, the specific formulations of the method are modeled by two sub-models for integrating energy consumption and environmental impacts into the scheduling δ is developed in two steps, and the 0–1 integer linear programming of the scheduling δ is as follows.

(1) The first sub-model: In the constraints of environmental impacts (forbidding assigning the jobs with massive wastes to the unfriendly machine tools), computing the minimization of the makespan for the scheduling δ.

(2) The second sub-model: Then in the constraints of the minimal makespan, minimizing the total energy consumption of the scheduling δ.

The first sub-model can be expressed as follows:

$$\begin{cases}\min\ \ T,\\ T=\max\limits_i\left[\sum\limits_j x_{ij}\bullet t_{ij}\bullet(\prod\limits_q p_{ij}^q)\right],\end{cases} \tag{6}$$

$$\text{s.t.}\quad p_{ij}^{q}=0,1,\ p_{ij}^{q}\in\{p_{ij}^{k}\,|\,k=1,2,\cdots,y\},\tag{7}$$

$$\sum_{i}\left[x_{ij}\bullet(\prod_{q}p_{ij}^{q})\right]=1,\ \forall j,\tag{8}$$

$$\sum_{i}\left(\prod_{q}p_{ij}^{q}\right)\neq 0,\ \forall j,\tag{9}$$

$$x_{ij}=0,1,\ \forall i,\ \forall j.\tag{10}$$

Eq. (6) means the minimization of the maximum makespan with the considerations of environmental impacts. Eq. (7) depicts the constraints of environmental impacts that are to forbid the jobs with massive wastes to being assigned to the unfriendly machine tools. The set $\{EI_q|q=1, 2,\cdots, z\}\in\{RE_k\}$ represents the profile indices of the environmental impacts. Eq. (8) expresses that each job has to be machined by one machine tool at least. Eq. (9) represents that there is at least one machine tool that can execute each job. Eq. (10) depicts that if the job i is assigned to the machine tool j, x_{ij} is “1”; otherwise, x_{ij} is “0”. And Eqs. (7)–(10) are also the constaints of the second sub-model.

The second sub-model can be expressed as follows:

$$\min\ \left[x_{ij}\bullet e_{ij}\bullet\left(\prod_{q}p_{ij}^{q}\right)\right],\tag{11}$$

$$\text{s.t.}\quad \max_{i}\left[\sum_{j}x_{ij}\bullet t_{ij}\bullet\left(\prod_{q}p_{ij}^{q}\right)\right]\leq T^{*}.\tag{12}$$

Eq. (11) means the minimization of energy consumption with the considerations of environmental impacts, $\{e_{ij}\}_{m\times n}\in\{RE_k\}$ denotes the energy consumption of maching job J_j on machine M_i; Eq. (12) depicts the constraints of the optimal makespan obtained via the first sub-model.

In the above model, the criteria of environmental impacts are considered as the forbidding constraints, so the profile index value of environmental impacts p_{ij}^{q} can be evaluated with 0 or 1. If the criteria of environmental impacts are desired to be the evaluation objectives, the method, such as the fuzzy set theory, can be employed to determine the profile index value p_{ij}^{q}, and then evaluate the criteria A_q by Eq. (2).

4 Case Study

The machining shop floor case in the gear-producing facility is used to demonstrate the application of the methodologies proposed in the paper to incorporate energy consumption and environmental impact considerations in production operation processes. In the case, the production operation activity is to assign a batch of jobs which includes seven kinds of gears, and each of gear can be regarded as a job for modeling the issue. The t_j is the symbol of the processing time of gear j, and the subscript i is omitted when the processing time of j gear does not depend on the machine tools. The details of gears are shown in Table 1.

Table 1. Details of the gears for assignment

Gear No.	J09032	J09033	J09035	J09037	J09038	J09039	J09041
Job j	1	2	3	4	5	6	7
Processing time t_j/min	22.4	8.4	28.3	10.8	4.3	17.1	10.0

According to the machining process specifications and production plan of the gears, there are five types of available hobbing machines including Y3180H, YB3120, YKB3120A, YKX3132 and YKS3120 for the jobs. Theoretically, without energy consumption and environmental impact considerations, production managers can allocate the jobs to any of the above available hobbing machines. In the actual production situation, the scheduling rule that balancing the processing time of each hobbing machine is usually to used to deal with this assignment problem. In terms of this rule, and without energy and environmental impact considerations, the assignment adopted in the production situation is shown in Table 2.

Table 2. Assignment adopted in the production situation

Hobbing machine	Job j
Y3180H	1
YB3120	2, 7
YKB3120A	3
YKS3120	4, 5
YKX3132	6

In the machining processes of gears, energy consumption and environmental impacts are generated by the machine tools. In this case study, the production managers mainly consider four profile indices under investigation including energy consumption, solid wastes, liquid wastes, gaseous wastes and other wastes. According to the methodology and the formulation proposed in the paper, the profile index value is required to be determined for each profile index. These four profile index value set are denoted with $\{e_{ij}, p_{ij}^{1}, p_{ij}^{2}, p_{ij}^{3}, p_{ij}^{4}\}$, in which e_{ij} represents the energy consumption value and the environmental impact index set $\{p_{ij}^{q}\,|\,q=1,2,3,4\}$ denotes the solid wastes, liquid waste, gaseous waste, and other wastes, respectively.

e_{ij} can be calculated by multiplying the power consumption of the machine tool M_i with the processing time of the job J_j. For the same job J_j, e_{ij} mainly represents the wasteful energy of the machine tool M_i, namely, the idle energy consumption which depends on the main spindle speed required by the process planning parameters of the job J_j[20]. Therefore, instead of the total power consumption of the machine tool M_i, the idle power consumption is used to calculate e_{ij}. The idle power consumption is measured by power meters. In this case, given the process planning parameters of the jobs (Table 3), the corresponding idle power consumption of machine tools is shown in Table 4.

Table 3. Spindle speed parameters of jobs

Job j	1	2	3	4	5	6	7
Spindle speed $n/(\mathrm{r} \bullet \mathrm{min}^{-1})$	200	150	250	300	400	350	500

Table 4. Idle power consumption e_{ij} of machine tools machining the jobs kW

Type	Job1	Job 2	Job 3	Job 4	Job 5	Job 6	Job 7
Y3180H	3.84	3.36	4.20	4.84	6.02	4.84	7.24
YB3120	3.26	3.04	3.68	4.48	5.44	4.48	6.58
YKB3120A	2.88	2.72	3.20	3.84	4.48	3.84	5.34
YKX3132	3.25	2.80	3.90	4.40	5.90	5.20	7.60
YKS3120	5.60	5.60	6.00	6.00	6.10	6.00	6.10

The environmental impact index set can be valued via the fuzzy set theory. Since environmental impact criteria is dependant on both jobs and machines, the fuzzy linguistic sets of the jobs and machines are established to evaluate the degree of generating environmental impacts, respectively. There are 7 scales in the fuzzy linguistic set {VL, L, ML, M, MH, H, VH}, in which VL represents the lowest degree and VH denotes the highest degree. In this case, the fuzzy linguistic of jobs and machines are shown in Table 5.

Table 5. Fuzzy linguistic sets of jobs and machines

Environmental impact index	Job set $J_j, j=1, 2, \cdots, 7$	Machine tool set $M_i, i=1, 2, \cdots, 5$
Solid wastes	{H, VL, H, M, L, M, VH}	{VH, H, H, M, ML}
Liquid wastes	{L, VL, ML, M, M, MH, VH}	{VH, H, MH, M, L}
Gaseous waste	{L, VL, L, ML, MH, M, H}	{VH, VH, H, M, ML}
Other wastes	{VL, VL, VL, ML, M, ML, H}	{H, H, M, L, VL}

The evaluation of the environmental impacts criteria is done through the use of fuzzy numbers. Since the triangular fuzzy numbers are most widely used due to its simplified interpretation, it is used in this case. The membership function for the fuzzy set of the environmental impact index set is the multiplication of the triangular fuzzy numbers of the J_j job and the M_i machine tool, and defuzzification is accomplished by using the mean value. The final environmental impact constraints $\{p_{ij}^q \mid q=1, 2, 3, 4\}$ are determined by the production managers referring to the rank of mean value of the environmental impact index, which is shown in Table 6.

The parameters of the case are used to solve the two sub-models in section 3. Meanwhile, for the comparison analysis, the assignment solution of the maximal energy consumption is also calculated by changing the minimization objective of the second model to the maximization objective, and also the comparison analysis is done for the assignment solutio without energy and environmental impact considerations (Table 2). The comparison analysis of the three kinds of solutions are shown in Table 7.

Table 6. Environmental impact constraints

Environmental impact index	Constraints $\{p_{ij}^q\}$
Solid wastes	$\begin{pmatrix} 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$
Liquid wastes	$\begin{pmatrix} 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$
Gaseous waste	$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$
Other wastes	$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$

Table 7. Comparison analysis of the three kinds of solutions

Objective	Solutions		Makespan T/min	Energy consumption $E/(\mathrm{kW} \bullet \mathrm{h})$
Minimizing energy consumption	Job1	YKX3132	28.3	6.65
	Job 2	Y3180H		
	Job 3	YB3120		
	Job 4	YKB3120A		
	Job 5	YKX3132		
	Job 6	YKB3120A		
	Job 7	YKS3120		
Maximizing energy consumption	Job 1	YB3120	28.3	8.53
	Job 2	Y3180H		
	Job 3	YKS3120		
	Job 4	Y3180H		
	Job 5	YB3120		
	Job 6	YKX3132		
	Job 7	YKX3132		
Without energy and environmental impact considerations	Job 1	Y3180H	28.3	7.47
	Job 2	YB3120		
	Job 3	YKB3120A		
	Job 4	YKS3120		
	Job 5	YKS3120		
	Job 6	YKX3132		
	Job 7	YB3120		

Table 6 shows the different results of these three assignment schemes. In this case study, although the makespan of these solutions is the same, the minimal energy consumption is 1.88 kW • h less than the maximal one. For the solution based on the usual scheduling rule in the production situation, without energy considerations, the energy consumption is still 0.92 kW • h more than the minimal one. Fig. 3 shows the detailed data of energy consumption of each machine tool in comparison with these two solutions. According to the solution of the minimal energy consumption, the machine tool YKB3120A is assigned to jobs, and there is more balance of the energy consumption among the machine tools in comparing to the solution of the maximal energy consumption, in which the machine tool YKB3120A machines no job.

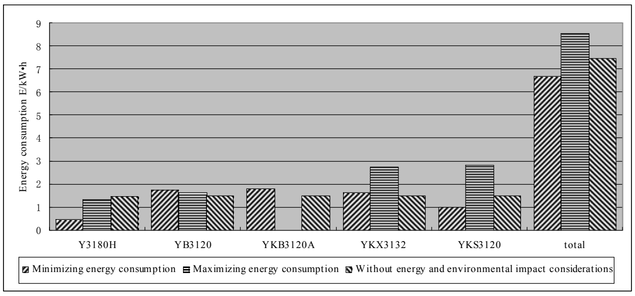

Fig. 3. Detailed data of energy consumption of each machine tool in comparison with the three solutions

In this case study, the optimal assignment scheme can save 1.88 kW • h energy consumption just for machining seven jobs. If there are a large numbers of jobs, the amount of the saving energy consumption will be significant.

Since the environmental impact criteria are not taken into account in the optimization objectives, the evaluation of environmental impact corresponding to the optimal assignment solution obtained by minimizing energy consumption is done by the fuzzy members of environmental impact indeices. The comparison of each environmental impact criterion among the machine tools with regards to the optimal assignment solution is shown in Fig. 4.

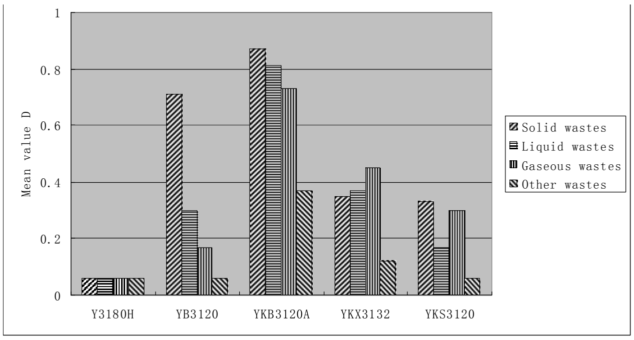

Fig. 4. Comparable evaluation of each environmental impact criteria for the optimal assignment solution

Fig. 4 shows that the aggregated environmental impacts of the assignment solution are imbalanced among machine tools. The most serious environmental impacts are generated by machine tool YKB3120A, and the machine tool YKX3132 also causes the massive solid wastes and gaseous wastes. Besides, although the environmental impacts on machine tool YB3120 are better than those of the above two machine tools, the mass generation of the solid wastes can not be ignored. When the imbalance of the environmental impacts is not satisfied by the production managers, the assignment scheme can be re-optimized by adjusting the optimization objectives corresponding to the environmental impact indices.

5 Conclusions

(1) This paper addresses on the energy consumption and environemntal impacts of machining processes from the production operation level. Using the operational methods, we propose the methodology to consider energy consumption and environmental impacts in production operation activities.

(2) The framework of the methodology is established to describe the gereric procedures, in which the profile index value of energy consumption and environmental impact considerations is determined depending on both machine tools and jobs, and the multi-criteria model is established with the formulation of the three categories of criteria including optimization criteria, evaluation criteria and constraint criteria.

(3) Based on the framework, the specific formualtions of the methodology, which is used for scheduling activity, is presented by optimizing the conventional scheduling objective as well as the energy consumption, meanwhile considering the environmental impacts as the constraints.

(4) The application of the methodology is introduced by the machining shop floor case within the gear-producing facility. It is shown that energy consumption and environmental impacts are considered as well as the conventional issues in the production operation level, which benefit production managers' making-decsion in the trade-off among the conventional issues, energy and environmental issues.

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