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Article

Improved Methods for Production Manufacturing Processes in Environmentally Benign Manufacturing

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Abstract: How to design a production process with low carbon emissions and low environmental impact as well as high manufacturing performance is a key factor in the success of low-carbon production. It is important to address concerns about climate change for the large carbon emission source manufacturing industries because of their high energy consumption and environmental impact during the manufacturing stage of the production life cycle. In this paper, methodology for determining a production process is developed. This methodology integrates process determination from three different levels: new production processing, selected production processing and batch production processing. This approach is taken within a manufacturing enterprise based on prior research. The methodology is aimed at providing decision support for implementing Environmentally Benign Manufacturing (EBM) and low-carbon production to improve the environmental performance of the manufacturing industry. At the first level, a decision-making model for new production processes based on the Genetic Simulated Annealing Algorithm (GSAA) is presented. The decision-making model considers not only the traditional factors, such as time, quality and cost, but also energy and resource consumption and environmental impact, which are different from the traditional methods. At the second level, a methodology is developed based on an IPO (Input-Process-Output) model that integrates assessments of resource consumption and environmental impact in terms of a materials balance principle for batch production processes. At the third level, based on the above two levels, a method for determining production processes that focus on low-carbon production is developed based on case-based reasoning, expert systems and feature technology for designing the process flow of a new component. Through the above three levels, a method for determining the production process to identify, quantify, assess, and optimize the production process with the goal of reducing and ultimately minimizing the environmental impact while maximizing the resource efficiency is effectively presented. The feasibility of the method is verified by a case study of a whole production process design at the above three levels.

Keywords: Environmentally Benign Manufacturing (EBM); production process; Genetic Simulated Annealing Algorithm (GSAA); case-based; IPO model; low-carbon production

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1. Introduction

A manufacturing system is an input-output system in which manufacturing resources (materials and energy) are transformed into products or semi-products. Manufacturing is the backbone industry for economic growth; meanwhile, it consumes a large amount of limited resources and is the root of the current environmental pollution problems. It is reported that 70–80% of the global environmental pollution is caused by manufacturing. Production processing is one of the stages in the life cycle of a production that directly consumes resources, produces environmental pollution emissions and causes occupational health and safety problems [1,2]. Therefore, it is essential for the manufacturing industry to implement environmental benign manufacturing (EBM) and low-carbon manufacturing strategies that, with high technology application and economic efficiency, have less resource consumption and less environmental pollution.

A process route diagnosis and improvement method that uses EBM concepts differs from traditional enterprise diagnosis methods. EBM concepts consider the environmental impact, resource efficiency and resource consumption. The goal of this work is to offer a fundamental solution to a recurrent enterprise problem by establishing an evaluation model that incorporates EBM concepts. The ultimate aim is to balance the economic and social benefits [3–5].

The basic theory, technological process and research method of enterprise diagnosing have been described preliminarily. The problem of resource consumption and environmental pollution during manufacturing processing has become the focus of this domain, with the research on some critical technologies including in-depth analysis. The relevant research mainly concentrates on the diagnosis and improvement of manufacturing processing routes as well as decisions during the manufacturing process. Sheng *et al.* developed a process planning method for environmental consciousness based on a component character that considers environmental factors carefully based on traditional process planning [6]. A new systematic framework was presented by Kheawhom and Hirao for the synthesis of an environmentally benign process under uncertainty, which was classified depending on its source and mathematical model for structure as deterministic or stochastic [7]. Kuo presented an innovative method, namely green fuzzy design analysis (GFDA), which involves simple and efficient procedures to evaluate product design alternatives based on environmental considerations using fuzzy logic [8]. In another study, Gutowski *et al.* used a thermodynamic framework to characterize the material and energy resources used in manufacturing processes [9]. Diwekar and Shastri presented a systems analysis perspective that extended the traditional process design framework to green process design and industrial ecology leading to sustainability [10]. Xue *et al.* introduced a model for aggregating process-level material input-output models to form a combined material input-output model for a manufacturing system that permits the identification of opportunities for reducing environmental impacts at the process level [11]. A new analysis method was presented by Jiang *et al.* to aggregate process level resource consumption and environmental impact based on the of process IPO models to form a combined input-output model for manufacturing processes [12]. Rusinko found that environmentally benign manufacturing practices might be positively associated with competitive outcomes via surveys of the entire U.S. commercial carpet industry [13].

EBM has become a significant competitive dimension between companies [1]. Corporations such as Siemens in Germany, Toyota in Japan, and Ford in the U.S.A. have all set a goal to implement EBM and have taken action to improve their environmental performance, to reduce power consumption and to reduce waste in product manufacturing processes. Jayal *et al.* presented an overview of recent trends and new concepts in the development of sustainable products, processes and systems [14]. Tan *et al.* also established an analysis model for the status of product material resources consumed in manufacturing systems based on the resource classification description of the consumed resource status in manufacturing systems and the analysis of product logistics. They also developed an assessment method and a technology framework for the environmental impacts from component manufacturing processes on the basis of an IPO model [15].

Optimization and decision-making for process routes and process planning in manufacturing production, in terms of EBM, have been recently developed. However, because of the complexity of the decision and optimization of the process route itself, research that combines multiple objectives in terms of EBM in a manufacturing process is still scarce.

Practicability is restricted as a result of few effective software and database, so researchers put forward the idea of diagnosis and process improvement, which combines quality management, environment management, occupational safety and health management with enterprise management. Diagnosis and process improvement is the process after "research on key technology of process planning in terms of EBM and its application support system" and "research on several key technology of quantitative assessment on enterprise production capability". Diagnosis and process improvement can improve products' environmental performance and enterprise technologies as well as eliminate pollution resources, save power, reduce cost and enhance development capability of new products.

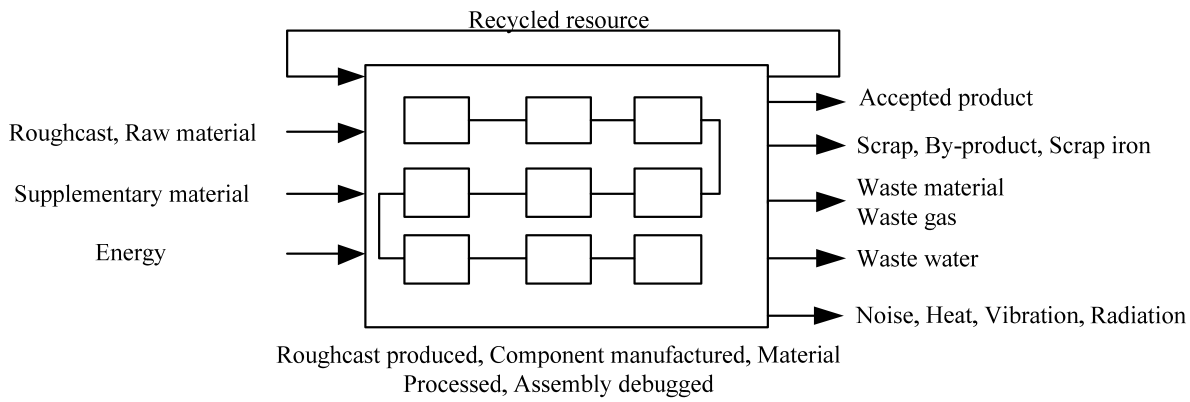
Therefore, this paper aims at developing a methodology for determining a production process by integrating three levels that focus on single new production processing, selected production processing, and batch production processing within an enterprise. This method, which is based on prior completed research, is aimed at the assessment and optimization problem of component manufacturing processes in terms of EBM. At the end of this paper, its practicality is discussed.

2. Methodology

2.1. Introduction

A product manufacturing process in the mechanical engineering industry is the main stage of the total life cycle, which directly consumes resources and produces environmental pollution. It is also the main factor that affects the performance of an enterprise in the mechanical industry in terms of EBM, which can be regarded as a resource environment input and output process according to the material balance and power balance principles, as shown in Figure 1 [4]. The input includes roughcasts, raw materials, supplementary manufacturing materials (e.g., tools and cutting fluid), and energy (electricity). After roughcasts are produced, components are manufactured, materials are processed, and assembly is debugged; acceptable products or components are thereby produced. At the same time, solid waste materials, such as scraps and by-products, and emissions, such as waste, gas, water, noise, vibration, and radiation, would threaten to affect the natural environment as well as human health, the workshop environment and production safety. The whole manufacturing process covers the arrangement and optimization of resources, operations equipment, and production operators.

Figure 1. Product manufacturing process resource-environment input and output diagram.

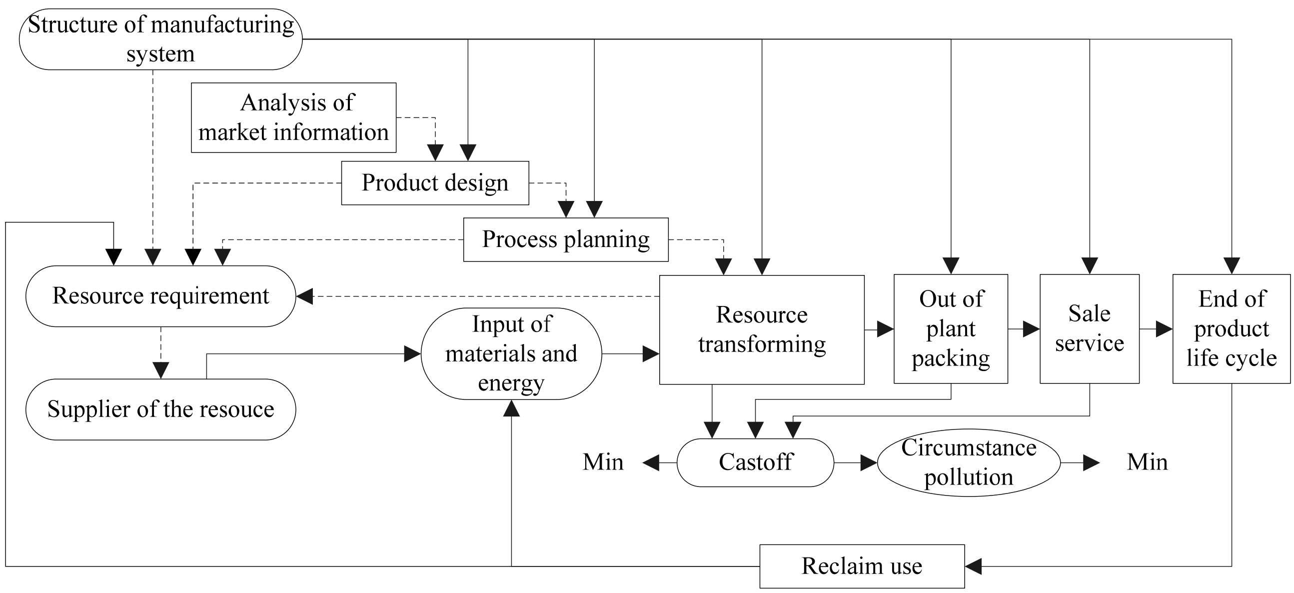


The IPO (Input-Process-Output) process of a product is regarded as an operations system. Compared with a traditional system, the measures of its performance contain not only effectiveness, efficiency, quality, productivity, profitability and quality of working life but also utilization rate and environmental impact.

Resource consumption and waste materials are the roots of environmental pollution. Thus, before the environmental characteristics of resources are analyzed deeply in process planning, in terms of EBM, the resource flow and its environmental impact in the manufacturing system have to be analyzed and described first.

The resource system of a manufacturing system could be described by the resource composition, the material flow, the power flow and the resource flow model. The resource composition concerns the configuration and classification of a manufacturing resource in a manufacturing system; the material flow concerns the whole process from the raw materials entering into the plant to the acceptable products that exit the plant; and the energy flow concerns the property of the power flow in the manufacturing process in terms of EBM. The resource flow model shows the status of the resources consumed and the impact factors in the product life cycle based on material flow, energy flow and information flow. A resource flow model in a manufacturing system in terms of EBM is shown in Figure 2, which contains the meaning of EBM and the impact factors on the status of the resources consumed in the manufacturing system.

Figure 2. Resource flow model in terms of EBM.



It has been shown by a significant amount of research and practice that different operation process plans for products in manufacturing processes have different material and resource consumption, different production efficiency and different profitability as well as different environmental impacts. The method for diagnosing and improving a process route in an enterprise production process in terms of EBM is a modern process planning method for environmental impact and resource consumption problems in manufacturing processes. We intend to determine the problems of process routes in operations processes and then to take action to improve the resource utilization efficiency and to decrease environmental pollution. As a result, the improved method can not only boost the production performance but also reduce the resource consumption, the emissions and the pollution of wastes. These actions will be at the core of competitiveness for Chinese manufacturing to meet international requirements.

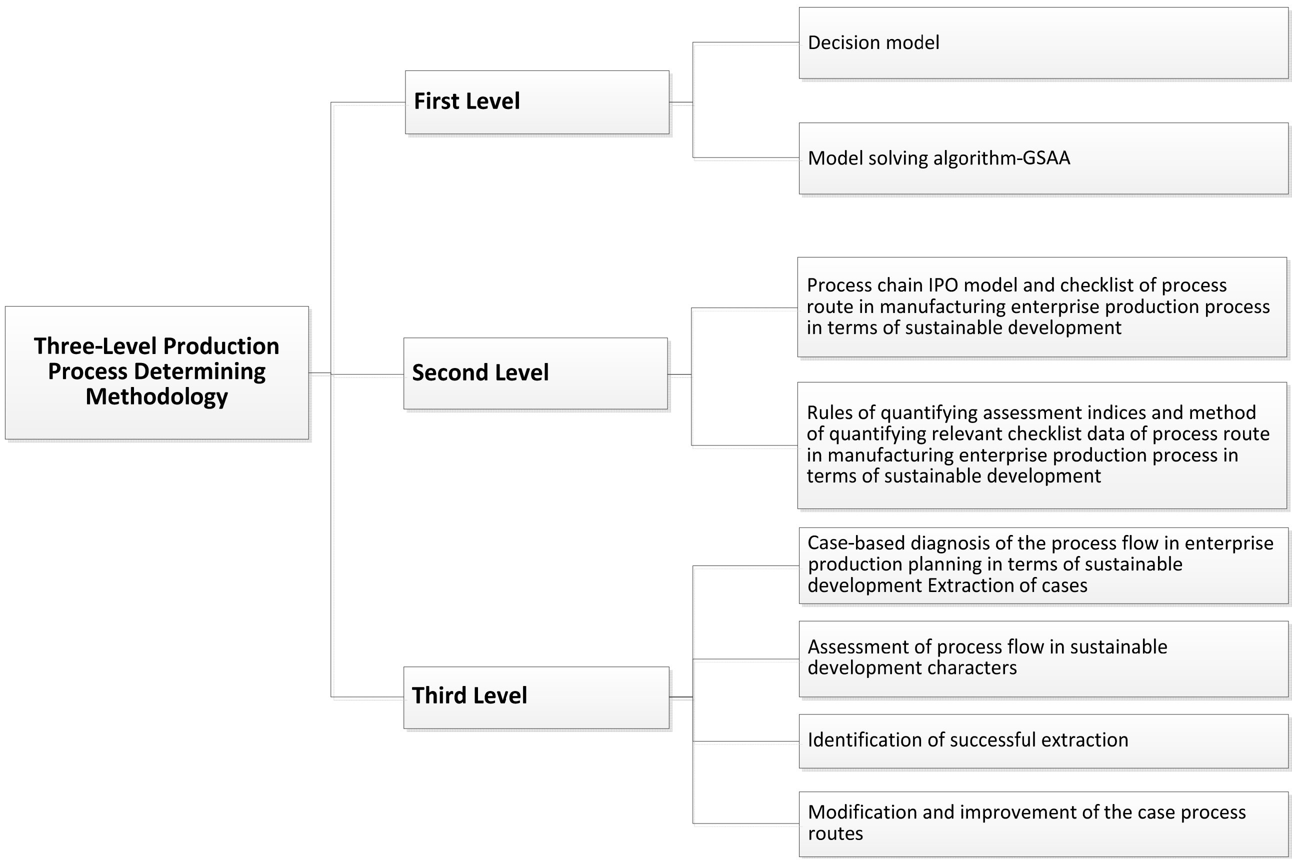
2.2. Methodology for Determining Production Processes at Three Levels

2.2.1. Architecture of the Three Levels of the Methodology for Determining Production Processes

Determination of production processes in manufacturing process planning with high environmental performance is a key factor in the success of EBM for a manufacturing enterprise. In this paper, a methodology for determining production processes is presented that integrates three levels, including single new production processes, selected production processes and batch production processes. These levels are developed to assess and optimize the performance of component manufacturing processes in terms of EBM based on prior completed research. The analysis framework was shown in Figure 3. At the first level, a decision-making model for new production processes based on the Genetic Simulated Annealing Algorithm (GSAA) method is established. At the second level of this systems methodology, a methodology based on an IPO model integrating the assessment of resource consumption and environmental impact, according to materials balance principles for a batch production process, is developed. Finally, at the third level of this systems methodology, based on the above completed first and second levels of this system, a selected production process determination method that focuses on environmentally benign manufacturing was developed. The core methodology of the third level is based on case-based reasoning, expert systems, and feature technology for designing the process flow of a new component.

Each of the above three levels affects production processes in such a way as to identify, quantify, assess, and optimize the concerned production processes. Consideration is paid to energy and material flows (inputs and outputs) and environmental parameters, with the goal of reducing and ultimately minimizing the environmental impact while also attempting to maximize the resource efficiency. The feasibility and practicability of the method are verified by a case study of a whole production process, with consideration of its flow design for the above three levels.

Figure 3. Architecture of the methodology for determining a three-level production process.



2.2.2. First Level of the Methodology

In the first level of this system methodology, we have studied the sequence of component machining processes in terms of EBM. We have based this part of the study on the genetic simulated annealing algorithm and combined machining time, machining cost, machining quality, resource consumption and environmental impact as one process constraint of the model that determines the process flow. We employed another three constraints, concerning sequence, clustering and adjacency, to describe the four relevant grade functions and to set up a determining model of the process flow in terms of the EBM to solve the sequence problem of the component machining processes. The purpose of this work was to obtain the machining sequence of a typical component and to obtain the final result while using EBM for the entire machining process. We also intended to identify the machining process flow of a new component of the same type in terms of EBM with a model of this typical component. These research findings will not only promote productivity but will also improve the product competence and optimize the environmental performance of the conditions of the shop floor. The process flow decision-making model is shown as a flow model (1).

The process is time variant and nonlinear. The optimization of the process route is a sort processing program with a multifactor constraint and also a nonlinear optimization problem. With code that stores one-dimensional arrays that correspond to the process units with respect to various characteristics, the serial number of the array elements represents the position of the characteristic process units in the process route. Supposing that a random characteristic process unit is $S = \{f_1, f_2, \ldots, f_n\}$; the subscript of the "$f$" stands for the serial number of the array elements and defines the process sort domain of the characteristic process unit, which satisfies the constraint set X. We look for the optimal plan model that not only satisfies the basic restrictions in the domain but also fulfills the comprehensive restrictions of green manufacturing:

$$\begin{aligned} &\max F(x) = a_{c_0}F_{c_0}(x) * a_{c_1}F_{c_1}(x) * a_{c_a}F_{c_a}(x) \Big/ a_{c_{sd}}F_{c_{sd}}(x) \qquad x \in X \\ &s.t. \quad \sum a = 1 \end{aligned} \tag{1}$$

where a_{c_0}, $F_{c_0}(x)$ are the technical constraints together with the constraints of the precedence sequences and the relevance grade function, respectively; a_{c_1}, $F_{c_1}(x)$ are the constraints of precedence clustering and the relevance grade function, respectively; a_{c_a}, $F_{c_a}(x)$ are the constraints of adjacency and relevance grade function, respectively; and $a_{c_{sd}}$, $F_{c_{sd}}(x)$ are the constraints of EBM (which considers the time (T), cost (C), quality (Q), resource consumption (R) and environmental impact (E) as technical constraints) and the relevance grade function, respectively.

Because of the deficiencies of the current assessment method for process routes, an integrated methodology, the Genetic Simulated Annealing algorithm, is developed to solve the decision-making model. In the author's prior research [15], the steps taken in solving the Genetic Simulated Annealing algorithm of the process flow in the determination process are presented in detail.

2.2.3. The Second Level of the Methodology

At the second level, an assessment methodology that aims at the assessment problem of the component manufacturing process in terms of the EBM is developed based on the material balance principle. This methodology is based on an IPO model that integrates the assessment of resource consumption and environmental impact. The material consumed, power consumed, environmental impact in the workshop, the natural environmental impact and human health impact during component manufacturing processes are quantitatively analyzed and assessed by making an IPO model of the component manufacturing process, which includes creating a checklist of the process and determining a rule for quantitative analysis. The existing problems are to be diagnosed according to the assessment results, and then relevant improvement measures will be taken.

According to the material balance and power balance principles, a process chain IPO process model is to be set up, a checklist is to be analyzed, and quantitative rules of the relevant assessment indices and a quantitative method of data in the checklist are to be presented for the process route in the manufacturing enterprise production process in terms of the EBM, based on the former work. All of the process analysis checklists can be found for the component manufacturing process, and therefore, the data can be easy to collect, quantify and analyze. The impact of the whole manufacturing process is obtained by combining the checklist analysis of every operational unit. For example, an analysis checklist of cutting is shown in Table 1. Then the whole assessment and improvement analysis of the process chain will be studied, and diagnosing and improving the method can be determined. Through a series of calculations, the assessment of a single procedure can be performed according to the standard analysis checklist and rules; the component manufacturing process usually contains several procedures. At this time, the estimate of every procedure has to be weighted and superimposed based on Table 1.

Table 1. Analysis checklist of the cutting process.

<table>
<tr><th colspan="2">Process Input: Cutting-Roughcast</th><th colspan="2">Process Output: Semi-Finished Articles</th></tr>
<tr><td rowspan="3">Raw material</td><td>Roughcast Name</td><td rowspan="2">Product</td><td>Product Name</td></tr>
<tr><td>Material Name</td><td>Weight</td></tr>
<tr><td>Weight</td><td rowspan="2">Chip</td><td>Component</td></tr>
<tr><td rowspan="2">Tool</td><td>Tool Name</td><td>Weight</td></tr>
<tr><td>Material</td><td rowspan="2">Noise</td><td>Sound Pressure</td></tr>
<tr><td rowspan="3">Process parameters</td><td>Cutting Speed</td><td>Sound Power</td></tr>
<tr><td>Cutting Rate</td><td rowspan="2">Waste water</td><td>Component</td></tr>
<tr><td>Cutting Depth</td><td>Weight</td></tr>
<tr><td rowspan="2">Electricity power</td><td>Power</td><td colspan="2" rowspan="4"></td></tr>
<tr><td>Operation time</td></tr>
<tr><td rowspan="2">Pneumatic power</td><td>Power</td></tr>
<tr><td>Operation time</td></tr>
<tr><td colspan="4">Recycle</td></tr>
<tr><td rowspan="3">Clamp</td><td>Name</td><td rowspan="3">Cooling liquid</td><td>Name</td></tr>
<tr><td>Weight</td><td>Weight</td></tr>
<tr><td>Recycle Rate</td><td>Recycle Rate</td></tr>
</table>

In this process, waste materials are classified, and the resource consumption, environmental impact, security, and harm to health are assessed. Here, variable RI is the mass of a semifinished product when it was put into process; variable RO is the mass of a finished product after processed; and variable W means the mass of the castoff during the processes. So the rules of the quantitative method to get the indices (about 4 types: resource consumption, environmental impact, security, and other influences) are shown as follows, for instance, Equations in Section 1 and Table 2) is the methods to get indices M, SM and E in Table 3.

(1) Resource Consumption [16]

Raw material use efficiency (*L*): $L = (RI - RO)/RI$

Raw material consumption (*W*), kg: $W = RI - RO$

Tool consumption (m_t), kg: $m_t = m_{tool} \int_{t=0}^{t_m} WRdt / WC$

Cutting fluid consumption (m_f), kg: $m_f = t_m (4\sigma l / g)$

Energy consumption (*E*), J: $E = P_c \cdot t_m$, where $(t_m = V / MRR)$

(2) Environmental Influence

Solid wastage (m_{chip}), kg: $m_{chip} = \rho V$

Discharge gas (m_{evap}), kg: $m_{evap} = {}^{q_c}\!/_{c_p} (T_{evap} - T_\infty) + L$

Discard solution (m'_f): $m'_f = m_f \cdot S_{EI}$

Noise, dB: Equivalent continuous sound pressure level (marked corresponding to the state standard)

(3) Security

Security The valve of degree of health hazard

(4) Other Influence (Marked according to the degree of influence, seen as the following tables).

Table 2. The ranking tables of environmental impact, healthy harm and noise.

(**a**) Ranking of environmental impact.

Method	**A**	**B**	**C**	**D**	**E**	**F**
10 points	10, 9	8, 7	6, 5	4, 3	2, 1	0
Note	A: Extremely adverse; B: Quite adverse; C: Moderately adverse; D: Fairly adverse; E: Appreciably adverse; F: No impact					

(**b**) Ranking healthy harm.

Method	**A**	**B**	**C**	**D**	**E**	**F**
10 points	10, 9	8, 7	6, 5	4, 3	2, 1	0
Note	A: Extremely harmful; B: Quite harmful; C: Moderately harmful; D: Fairly harmful; E: Inappreciably harmful; F: No impact					

(**c**) Ranking of noise.

Method	**Very Poor**	**Poor**	**General**	**Good**	**Very Good**
10 points	10, 9	8, 7	6, 5	4, 3	2, 1
Noise (db)	>95	90–95	85–89	80–84	<79

Table 3. Assessment of resource-environment characteristics in a component manufacturing process in terms of EBM.

Process	**Raw material consumption (M)**	**Supplementary material consumption (SM)**	**Energy consumption (E)**	**Emission of air pollution (G)**	**Emission of water pollution (W)**	**Waste material (S)**	**Other pollution (O)**	**Security (S)**	**Assessment (Hp)**
Pro-1	M_1	SM_1	E_1	G_1	W_1	S_1	O_1	SE_1	Hp_1
Pro-2	M_2	SM_2	E_2	G_2	W_2	S_2	O_2	SE_2	Hp_2
…	M_i	SM_i	E_i	G_i	W_i	S_i	O_i	SE_i	Hp_i
Pro-n	M_n	SM_n	E_n	G_n	W_n	S_n	O_n	SE_n	Hp_n
Weight (W)	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	

Assessment of Manufacturing process: H_m.

The assessment H_{pi} of a single procedure and the assessment H_m of a component manufacturing process can be calculated with the data in the above table, according to the rules of quantifying the assessment indices and according to the methods of quantifying the relevant checklist data for the process routes in the case study. These process routes, H_{pi} and H_m, can be expressed as follows:

$$H_{pi} = M_i w_1 + SM_i w_2 + E_i w_3 + G_i w_4 + W_i w_5 + S_i w_6 + O_i w_7 + SE_i w_8 \quad (2)$$

$$\begin{aligned} H_m &= \frac{1}{n}\left(\sum_{i=1}^{n} M_i w_1 + \sum_{i=1}^{n} SM_i w_2 + \sum_{i=1}^{n} E_i w_3 + \sum_{i=1}^{n} G_i w_4 + \sum_{i=1}^{n} W_i w_5 + \sum_{i=1}^{n} S_i w_6 + \sum_{i=1}^{n} O_i w_7 + \sum_{i=1}^{n} SE_i w_8\right) \\ &= \frac{1}{n}\sum_{i=1}^{n}(M_i w_1 + SM_i w_2 + E_i w_3 + G_i w_4 + W_i w_5 + S_i w_6 + O_i w_7 + SE_i w_8) \\ &= \frac{1}{n}\sum_{i=1}^{n}(H_{pi}) \end{aligned} \quad (3)$$

The meaning of this method is that the assessment of the whole process route can assist process workers to find the procedure with the minimum estimate in terms of EBM in the process route (such as in the design of product, the selection of material and the production technique). Improving the EBM of the procedure can improve the EBM of the component operation process route and production process planning. If the above assessment can be obtained by comparing and diagnosing the actual results of the rated resources consumption, the materials consumption and the energy consumption generated in the manufacturing process as well as the indices of the environmental impact, the objective of the improvement will be visualized and effective.

2.2.4. The Third Level of the Methodology

At the third level, after the first and the second level of the system methodology are completed, a method for determining the selected production process that focuses on environmentally benign manufacturing was developed based on case-based reasoning, expert systems, and feature technology for designing the process flow of a new component. The case-based optimization determination process for the process flow during the process planning stage, in terms of EBM, is divided into two steps.

The first step is extracting examples. The optimization of the machining method, the machining sequence and the machining process as well as the assessment method of the EBM characteristics of the production process should be identified in this step, which leads to the assessment of a similarity coefficient.

The similarity coefficient is connected not only with the component type or case type (product type, function structure, size, and diameter) and the machining method and feature (major and subordinate features), but also with the component information, such as the material type, the heat treatment method, the blank type, and the shape features (e.g., accuracy, roughness, and tolerance). These factors directly affect the optimization of the process parameters and must be considered in the similarity coefficient.

The component type and the machining method are the most important characteristics for matching a new component with previous components. If these characteristics do not match, then the similarity coefficients are meaningless. For example, if a gear is a cylindrical gear and the machining method is hobbing, the similarity coefficient, K_s, of the gear hobbing is the following:

$$K_s = a_{ml}k_{ml} + a_{mf}k_{mf} + a_{af}k_{af} \tag{4}$$

where:

$$a_{ml} + a_{mf} + a_{af} = 1$$

and:

a_{ml} is the weighting coefficient for the material matching;

a_{af} is the weighting coefficient for the feature matching;

a_{mf} is the weighting coefficient for the component information matching;

k_{ml} is the material matching ratio, which measures the degree to which the new component material matches the material type of the previous material;

k_{mf} is the machining feature matching ratio, which measures the degree to which the machining features match; and

k_{af} is the component information matching ratio, which measures the degree to which the component information matches.

k_{ml} is defined as:

$$k_{ml} = \begin{cases} 1, \text{when the material types match} \\ 0, \text{when the material types do not match} \end{cases} \tag{5}$$

k_{mf} is defined as:

$$k_{mf} = \frac{2N_{nf}}{N_{nf} + N_{if}} \tag{6}$$

where:

N_{nf} is the number of features in the new components that match features in the previous case;

and:

N_{if} is the number of features.

k_{af} is defined as

$$k_{af} = \frac{2N_{ni}}{N_{ni} + N_{ii}} \tag{7}$$

where:

N_{ni} is the number of the new component's processing information items that match items of the previous case; and

N_{ii} is the total number of the component processing information items.

Because the numerator is always less than or equal to the denominator, K_s is always less than or equal to one. The similarity coefficients obtained from the comparisons are used to find the best match for the new component.

The second step is to modify the process route and to perform the related environmental assessment. At the lower level, decisions should be made to choose the machining process equipment (machines, tools and cutting fluid), the process parameters (cutting parameters, amount of feed, depth of cutting) and the estimate of energy saving and noise reduction (materials, energy, environmental impact). Different levels should be coupled in lateral and longitudinal directions. The relationship of different levels and operations flows are shown in Figure 4.

3. Case Study

The case-based diagnosis and improvement of the process flow in enterprise process planning in terms of EBM is used for a new component in the application determining system. The basic information of the new component is as follows, seen as Figure 5: material-45; module number-3; teeth number-46; external diameter-144; cutting width-70; helix angle-0; and production batch-jobbing work.

3.1. Single New Part Database

Through the first and the second level of this system methodology, many single new production processes, in terms of EBM, can be determined. Furthermore, we keep a large part of the chosen process in a parts database characterized by EBM, and each new part is associated with a specific production process in the EBM.

Figure 4. Cased-based optimization flow chart for the process flow of process planning in terms of EBM.

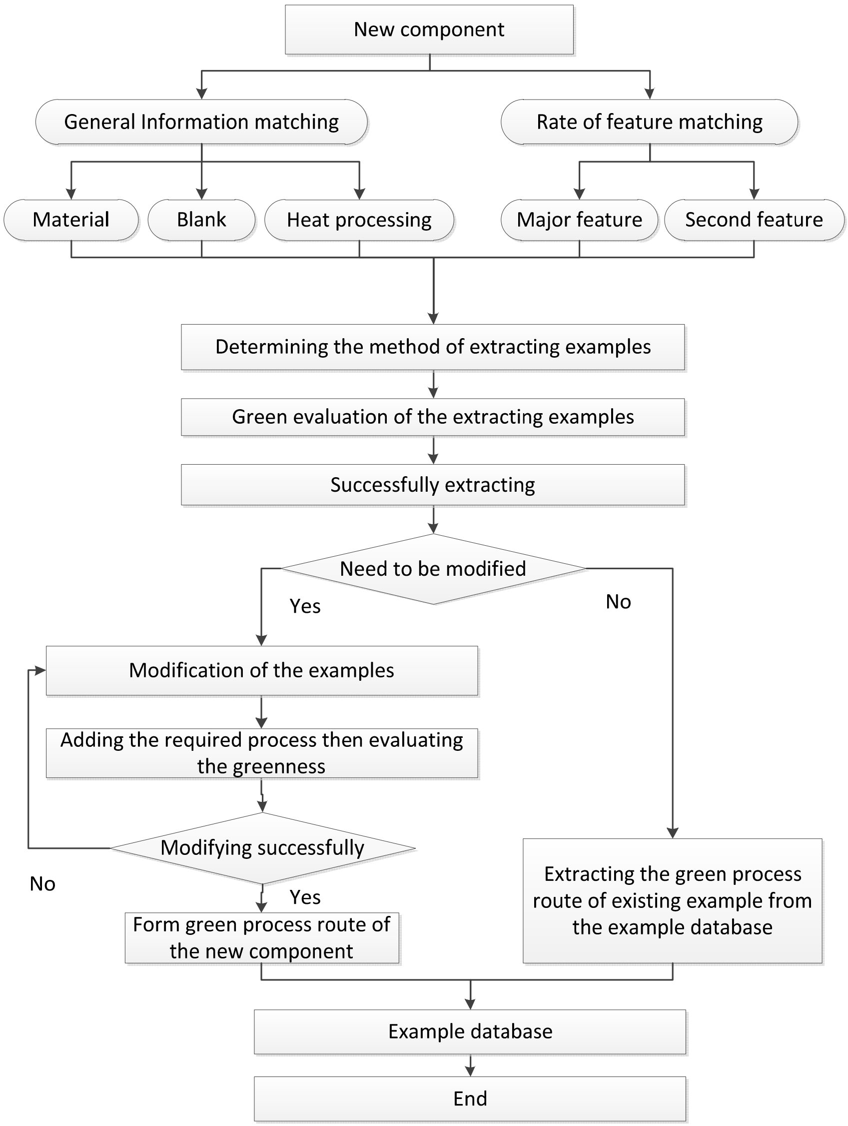
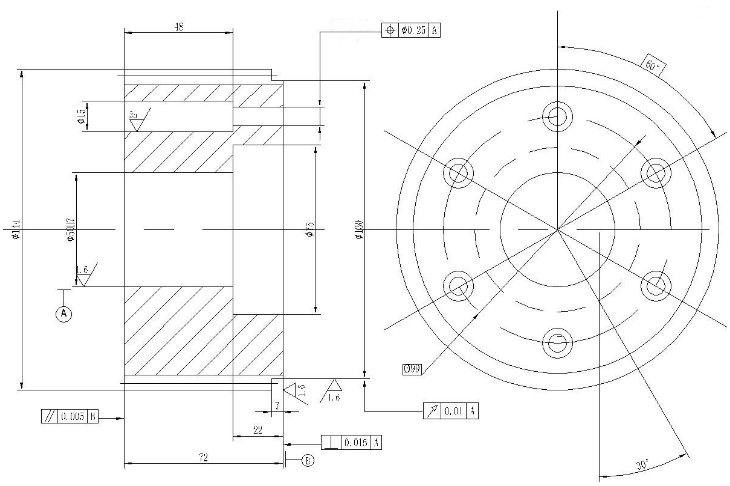


Figure 5. The picture of the component.



3.2. Case-Based Diagnosis of the Process Flow in Enterprise Production Planning in Terms of EBM Extraction of Cases

After we input the process information and the basic parameters (e.g., the process information with regard to the component type, component materials, heat treatment method, blank type, and the basic parameters, including teeth number, module number, external diameter, cutting depth, and helix angle) of the new component, the system will calculate the similarity coefficient, which measures the degree of matching in the process information between the new component and the existing cases according to the constraints. The system chooses cases with a high similarity coefficient (if $0.7 < K < 1$, the case is considered to be feasible) and plans a series of machining processes on them.

In the formula for K_s from Section 2.2.4, the numerator of the formula is always less than or equal to the denominator. Thus, K_s is less than or equal to one. The similarity coefficient can be obtained from the calculation of the formula. Based on the similarity coefficient, the system can select a series of cases of machining processes that optimally or preferably match the new component. The system chooses cases with a higher similarity coefficient (if $0.7 < K < 1$, the case is considered to be feasible) and plans a series of machining processes for them. The basic machining process information of the selected cases (YB3120-90301, YKA3120A-031301 and YKA4232A-051308) is listed.

3.2.1. Assessment of the Process Flow in Terms of EBM Characteristics

The process flows of selected cases should be assessed from two perspectives: the resource consumption and the environmental impact. A checklist analysis is made for each procedure of the process flow in terms of the resource-environmental characteristics, and an overall assessment value is calculated based on the weights of the indices. The overall value of the process flow can be obtained from that of its procedures, and its overall resource-environmental characteristic values can be calculated as well.

3.2.2. Identification of Successful Extraction

A case with a more similar process flow and a green characteristic can be obtained by calculating $S = a_1 k + a_2 S_{Gm}$, as shown in Tables 4–6.

Table 4. Integrated EBM values of the case (YKA3120A-031301).

Process	**Raw material consumption (M)**	**Supplementary material consumption (SM)**	**Energy consumption (E)**	**Emission of air pollution (G)**	**Emission of water pollution (W)**	**Waste material (S)**	**Other pollution (O)**	**Security (S)**	**Assessment (Hp)**
Gross turning	7.002	5.002	6.002	6.002	4.002	10.002	8.001	8.01	6.663
Hardening & tempering	4.002	4.002	5.002	6.002	6.001	14.502	8.001	7.02	7.043
Fine turning	0.002	7.002	9.002	9.002	8.001	10.002	8.67	0.0	7.309
Fine grinding out	3.02	3.01	4.02	4.02	3.01	8.02	4.01	5.00	4.294
Hobbing	6.002	6.57	6.002	7.502	6.17	10.02	6.51	5.02	6.840

Table 4. *Cont.*

Gross grinding teeth	4.002	3.01	4.02	4.03	6.03	10.01	4.02	5.02	5.081
Quenching	6.002	5.668	6.002	7.502	6.168	10.502	6.502	6.02	6.924
Broaching	4.02	13.02	8.01	4.02	2.01	10.01	6.02	5.02	6.036
Weight	0.06	0.08	0.12	0.2	0.16	0.12	0.16	0.1	
Overall assessment value: 6.274									

Table 5. Integrated EBM values of the case (B3120-90301).

Process	**Raw material consumption (M)**	**Supplementary material consumption (SM)**	**Energy consumption (E)**	**Emission of air pollution (G)**	**Emission of water pollution (W)**	**Waste material (S)**	**Other pollution (O)**	**Security (S)**	**Assessment (Hp)**
Gross turning	7.002	5.335	6.002	5.335	4.668	10.502	8.001	9.02	6.823
Hardening & tempering	0.002	7.002	8.001	1.001	8.001	10.502	8.335	7.84	6.379
Fine turning	4.002	3.668	5.002	4.002	3.001	10.002	5.002	6.02	5.017
Hobbing	6.002	5.5668	6.002	7.502	6.168	10.502	6.502	6.02	6.916
Boring	6.002	5.002	6.002	6.666	4.335	10.502	8.001	0	6.048
Gross grinding teeth	4.002	4.002	5.002	5.835	6.502	10.252	5.002	5.02	5.900
Fine grinding out	3.002	3.668	5.002	5.002	5.668	13.002	6.002	5.02	6.004
Broaching	4.002	3.001	8.001	4.002	2.668	11.002	7.002	6.02	5.710
Fine grinding	4.002	3.001	4.502	4.002	5.502	10.502	5.002	5.02	5.264
Fine grinding teeth	8.001	2.001	8.001	2.001	2.668	13.502	6.002	5.02	5.510
Weight	0.06	0.08	0.12	0.2	0.16	0.12	0.16	0.1	
Overall assessment value: 5.957									

Table 6. Integrated EBM values of the case (YKA4232A-061308).

Process	**Raw material consumption (M)**	**Supplementary material consumption (SM)**	**Energy consumption (E)**	**Emission of air pollution (G)**	**Emission of water pollution (W)**	**Waste material (S)**	**Other pollution (O)**	**Security (S)**	**Assessment (Hp)**
Gross turning	7.002	5.335	6.002	5.335	4.668	10.502	8.001	9.02	6.822
Hardening & tempering	0.002	7.002	8.001	1.001	8.001	10.502	8.335	0	5.595
Fine turning	4.002	3.668	5.002	4.002	3.001	10.002	5.002	6.02	5.015

Table 6. *Cont.*

Hobbing	6.002	5.5668	6.002	7.502	6.168	10.502	6.502	6.02	6.802
Quenching	6.002	5.668	6.002	7.502	6.168	10.502	6.502	6.02	6.922
Boring	6.002	5.002	6.002	6.666	4.335	10.502	8.001	0	6.048
Gross grinding teeth	4.002	4.002	5.002	5.835	6.502	10.252	5.002	5.02	5.899
Fine grinding out	3.002	3.668	5.002	5.002	5.668	13.002	6.002	5.02	6.002
Broaching	4.002	3.001	8.001	4.002	2.668	11.002	7.002	6.02	5.708
Fine grinding	4.002	3.001	4.502	4.002	5.502	10.502	5.002	5.02	5.262
Semi-fine grinding teeth	3.002	3.335	5.002	5.002	6.002	13.002	5.002	6.02	5.969
Fine grinding teeth	8.001	2.001	8.001	2.001	2.668	13.502	6.002	5.02	5.508
Weight	0.06	0.08	0.12	0.2	0.16	0.12	0.16	0.1	
Overall assessment value: 5.971									

3.3. Modification and Improvement of the Case Process Routes

The process flow of the selected case should be diagnosed as to whether it requires supplementing, adapting, modifying or improving to meet the demands of the new component. If necessary, the case will be modified and the process equipment, such as machines, tools and cutting fluid, and the process parameters of the added procedures should be modified as well. It is necessary to re-assess the added procedure in terms of multiple objectives and to combine the new assessment with the original assessment value to obtain a new assessment on the process flow. Otherwise, the original assessment value will become the assessment value of the new one. The process flow (machining process, process parameters, process equipments) of the new component and its virtual assessment in terms of EBM are selected to be reserved in the database and to be printed, as shown in Tables 7–10 and Figure 6.

Table 7. Result of estimated process route EBM overall merit.

Project Name	General Score	Similarity Value	EBM Overall Merit
YKA4232A-51308	2.573	0.88	6.522

Table 8. Optimization result of process equipment and parameters for the hobbing procedure.

Scheme	Materials	Module	Tech Number	External Diameter	Gear Cutting Breadth	Helix Angle
Yka4332A-051308	45# Steel	2	65	142.34	70	20

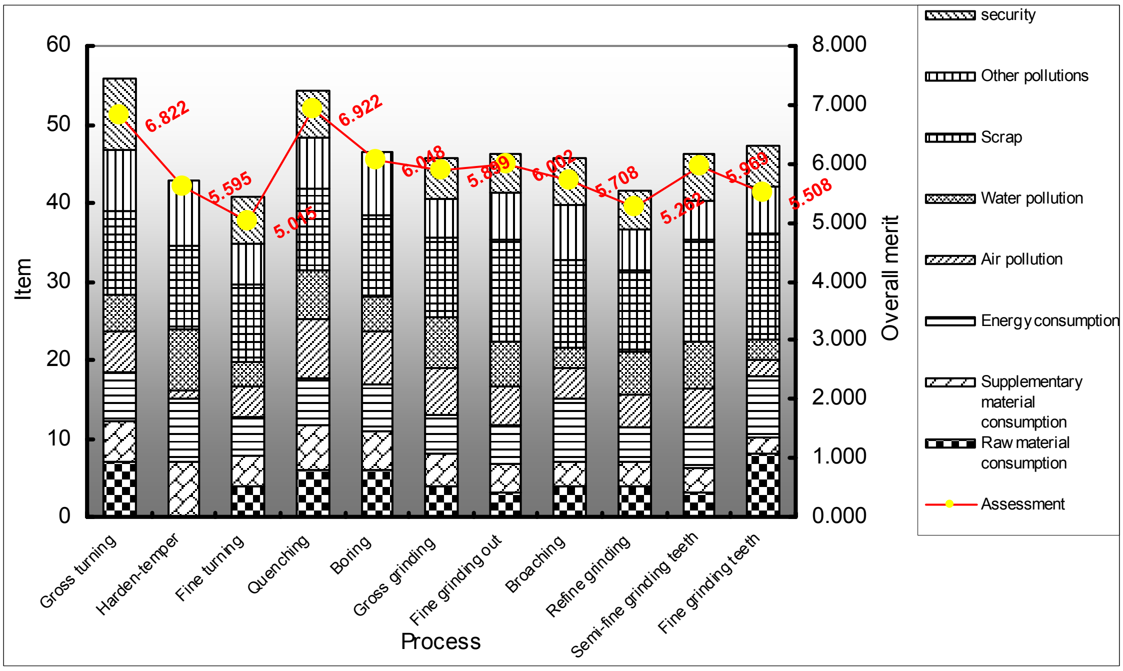
Table 9. Machine tool and cutting fluid for the gear processing.

Gear Cutting Machine	Gear Tools					
YkA4332A	Materials	Module	Head number	Rotation direction	Ordinance	Accuracy grade
Fine grinding	Coat HSS	2	1	Dextrorotation	¢32*¢70*110	AA

Table 10. Optimization result of cutting parameter.

Cutting mode	Cutting speed m/min	Hobbing-rotational speed r/min	Amount feed for axial mm/r	Pickup depth mm	Division change gear	Differential change gear
Up milling	45	200	1	4.35	70*65/60*65	62*70/65*72

Figure 6. Cross-longitudinal comparison of each recourse and environment in the gear manufacturing process.



4. Concluding Remarks

Currently, climate change and environmental pollution as well as energy shortages are the three main problems faced by human civilization. These concerns are very serious in China because of its accelerated industrialization and urbanization. Manufacturing industries are dominant with respect to these problems because of their toxic chemicals and other waste emissions, their huge energy consumption, and their carbon emissions. How to design and implement a production process with the characteristics of low carbon emissions and low environmental impact as well as high manufacturing performance is a key factor in the success of implementing low-carbon production to address climate change for the large carbon emission source manufacturing industry. This challenge occurs because of the high energy consumption and the environmental impact of the manufacturing stages throughout the life cycle of a production process.

In this paper, a methodology for determining a production process is developed that integrates the determination of the process at three different levels. These levels are the determination of a single new production process, the optimization of a selected production process and the selection of a batch production process. These levels take place within a manufacturing enterprise and are based on prior research. The aim of the methodology presented here is to provide decision support for implementing EBM and low-carbon production to subsequently improve the environmental performance of the manufacturing industry. The most notable difference between the methodology presented in this paper and traditional methodology is that this method considers not only the traditional characteristics, such as cost, quality and time, but also considers resource consumption and environmental impact.

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