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Luqiong Xie[1,2], Xuemei Jiang[1,2], Wenjun Xu[1,2], Qin Wei[1,2],

Ruifang Li[1,2] , Zude Zhou[1,2]

[1]School of Information Engineering, Wuhan University of Technology, Wuhan 430070, China
[2]Key Lab. of Fiber Sensing Technology and Information Processing, Ministry of Education, China
xieluqiong_whut@163.com,jxm2001@whut.edu.cn,xuwenjun@whut.edu.cn
qinwei@whut.edu.cn,liruifang@whut.edu.cn,zudezhou@whut.edu.cn

Abstract. Sustainability has been attracted extensive attention in manufacturing industry for the increasing excessive resource consumption and serious environmental pollution. The assessment of sustainable manufacturing capability is a vital factor, especially in cloud manufacturing, in which the capability assessment of the manufacturing resources is the premise of selecting the optimal manufacturing services. While the CNC machining tools are the basic manufacturing resources in production process, so the dynamic assessment of their sustainable manufacturing capabilities is investigated in this paper. A set of indicators is established considering manufacturing sustainability and a new dynamic assessment model is proposed based on a modified “vertical and horizontal” method. The model is verified through a case study and it can comprehensively evaluate the capability performance of the CNC machining systems, and also effectively follow the dynamics of their production activities.

Keywords: Sustainable manufacturing capability; CNC machining systems; dynamic assessment; “vertical and horizontal” method

1 Introduction

Currently, cloud manufacturing becomes a new manufacturing model under the promotion of manufacturing informatization. The capabilities of manufacturing resources are presented in the form of services consumers can share together globally. Selecting the optimal manufacturing resource from the global shared resource pool becomes a vital issue under cloud manufacturing. Meanwhile, sustainability has been the focus of heated discussion in recent years. There’re many definitions about sustainability. The most acceptable one is defined at 1987 World Commission on Environment and Development [1], which states, “Meeting the needs of the present without compromis-

adfa, p. 1, 2011.

ing the ability of future generations to meet their own needs." Generally, sustainable manufacturing is the reflection of sustainability in manufacturing. Meanwhile, manufacturing informatization makes digital design and manufacture become a way to improve manufacturing capability. CNC machining tools are widely used and they can solve many parts processing problems (e.g., high-precision, small batch and multi varieties production). They are the key to parts processing, which will greatly affect the processing quality, cost, time, energy, wastes, etc. So the assessment of manufacturing capability for CNC machining systems is of great significance.

2 Related Works

The concept of manufacturing capability was first proposed by Skinner in 1969[2]. He stated that manufacturing capability is a kind of ability for enterprises to achieve manufacturing strategy and is composed of costs, quality, time and the relationship between these elements. Corbett [3] pointed out that manufacturing capability is consist of quality, cost, delivery speed, flexibility and innovation. Reference [4] defined manufacturing capability as time, quality, cost, technology, service, corporate performance .etc. when selecting virtual enterprise partners. In the field of sustainable manufacturing, some scholars have applied sustainability assessment to manufacturing decision making from economic, environmental and social aspects [5, 6].

The relative assessment methods mainly have two categories: One is the subjective method which has certain subjectivity. The other is the objective method which cannot reflect the preferences of decision makers. So far, most assessment models are static. The dynamic assessments have already made some achievements [7, 8], which have two classifications. One is a twice-weighted method which confirms the weights at different times; the other is dynamically dealing with the time series data, by which the weights are updated along with the update of data. For the former, reference [9] proposed a dynamic method based on Time Entropy to assess manufacturing capability, while it only considers subjective weights ignoring the effect of objective data.

Overall, the existing relative researches mainly have two shortages. Firstly, the researches solely focus on economic benefits without considering environmental impact and resource consumption. Secondly, most assessment methods are static which cannot reflect the capability dynamically. Therefore, this paper establishes a set of indicators system of sustainable manufacturing capability for CNC machining systems. A dynamic assessment method is proposed, which combine the advantages of subjective and objective assessment methods. Finally, "time-value coefficients" are introduced to aggregate data to obtain comprehensive capability value.

3 Assessment Model and Indicators

3.1 Assessment Model

For CNC machining systems, the indicator values are changing dynamically. Therefore, the issue of manufacturing capability assessment is a multidimensional decision making problem of three dimensions with indicators space, object space and time space. It can be supposed that there are n alternatives $s_1, s_2, \cdots, s_n$, m indicators $x_1, x_2, \cdots, x_m$ (suppose all the indicators are standardized), and N historical task orders drawn from N recent time periods in chronological order. The original data can be got as $x_{ij}(t_k)$, constituting a time series database shown in Tab.1. Based on the dynamic time series data, the connotation of manufacturing capability and sustainable manufacturing, this paper mainly concern economic and environmental aspects. A dynamic assessment model is proposed as Fig.1.

Table 1. Dynamic timing database

Alter-natives	t_1	t_2	$\cdots$	t_N
	$x_1, x_2, \cdots, x_m$	$x_1, x_2, \cdots, x_m$	$\cdots$	$x_1, x_2, \cdots, x_m$
s_1	$x_{11}\ t_1 \quad x_{12}\ t_1 \quad \cdots \quad x_{1m}\ t_1$	$x_{11}\ t_2 \quad x_{12}\ t_2 \quad \cdots \quad x_{1m}\ t_2$		$x_{11}\ t_N \quad x_{12}\ t_N \quad \cdots \quad x_{1m}\ t_N$
s_2	$x_{21}\ t_1 \quad x_{22}\ t_1 \quad \cdots \quad x_{2m}\ t_1$	$x_{21}\ t_2 \quad x_{22}\ t_2 \quad \cdots \quad x_{2m}\ t_2$	$\cdots$	$x_{21}\ t_N \quad x_{22}\ t_N \quad \cdots \quad x_{2m}\ t_N$
$\vdots$	$\vdots \quad \vdots \quad \vdots \quad \vdots$	$\vdots \quad \vdots \quad \vdots \quad \vdots$		$\vdots \quad \vdots \quad \vdots \quad \vdots$
s_n	$x_{n1}\ t_1 \quad x_{n2}\ t_1 \quad \cdots \quad x_{nm}\ t_1$	$x_{n1}\ t_2 \quad x_{n2}\ t_2 \quad \cdots \quad x_{nm}\ t_2$		$x_{n1}\ t_N \quad x_{n2}\ t_N \quad \cdots \quad x_{nm}\ t_N$

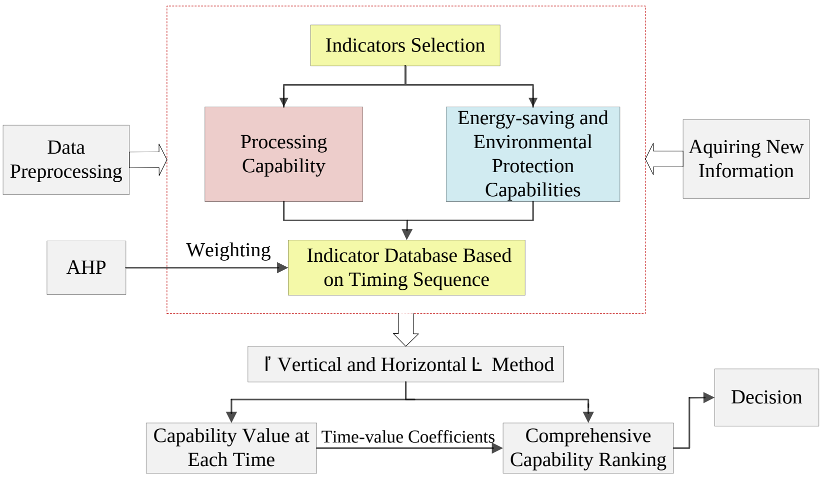

Fig. 1. Assessment Model

3.2 Assessment Indicators

According to the connotation of manufacturing capability and the demands of sustainable manufacturing, besides quality, time and cost, the basic elements of manufacturing capability, resource consumption and environmental impact are also considered in this paper. Given the actual processing of machining system, the five factors can be decomposed to establish the indicator system shown in Table2.

Table 2. Indicators for sustainable manufacturing capability assessment

Goal	Indexes	Sub-indexes
Assessment of Sustainable Manufacturing Capability for CNC Machining Systems	Processing quality	Dimension machining precision
		Surface machining precision
		Shape machining precision
	Processing cost	Workers' wages
		Equipment depreciation
		Operation expenses
		Maintenance cost
		Material cost
	Processing time	Machining time
		Auxiliary time
	Resource consumption	Main material consumption
		Auxiliary materials consumption
		Energy consumption
	Environmental impact	Air pollution
		Cutting liquid pollution
		Noise
		Wastes

4 Dynamic Assessment Based on Timing Sequence

4.1 Subjective Weight Calculation Based on AHP

Analytic hierarchy process (AHP) was first put forward by Saaty as multi criteria decision tool that quantifies the qualitative analysis [10]. It is used in this paper to determine the subjective weights. The method consists of the following steps:

1. Firstly, define the problem and find the indicators related to the decision goal.
2. Establish a hierarchical structure according to the subordinate relations between the indicators: top level is the goal of the decision; intermediate levels represent criteria or sub-criteria; and the bottom level represents the alternatives, such as Table 2.
3. Construct the comparison matrices by conducting pairwise comparison between the elements of each level with respect to each element in the immediate upper level.
4. Calculate the eigenvector of each matrix to find element's relative weight and check consistency index CI and consistency ratio CR for each eigenvector. Due to the length limitation, further details can refer to reference [10].

Based on Table 2, the subjective weight vector $w \quad (w_1, w_2, \cdots w_m)$ can be obtained by AHP. Then the weighted timing database can be got by Eq. (1)

$$x_{ij}(t_k) \quad w_j x_{ij}(t_k), i \quad 1,2,\cdots,n; j \quad 1,2,\cdots,m \tag{1}$$

4.2 Objective Weights Calculation Based on “Vertical and Horizontal”

Based on Eq. (1) and Table 1, “vertical and horizontal” method [7] is used here for dynamic assessment. For time $t_k(k=1,2,\cdots,N)$, the linear function can be defined as:

$$y_i(t_k)=\sum_{j=1}^{m} w_j x_{ij}(t_k), k=1,2,\cdots,N; i=1,2,\cdots,n \tag{2}$$

$y_i(t_k)$ is the assessment result of system s_i at time t_k; $w=(w_1,w_2,\cdots,w_m)$ is the subjective dynamic weight vector. The principle of determining w_j is to maximize the difference between systems $s_1,s_2,\cdots,s_m$, which can be described by Eq. (3).

$$\sigma^2=\sum_{k=1}^{N}\sum_{i=1}^{n}(y_i(t_k)-\bar{y})^2=w^{T}\left(\sum_{k=1}^{N}A_k^{T}A_k-\mathrm{nN}\bar{x}^{T}\bar{x}\right)w=w^{T}Hw \tag{3}$$

where $H=\sum_{k=1}^{N}H_k-\mathrm{nN}\bar{x}^{T}\bar{x}$, $H_k=A_K^{T}A_k(k=1,2,\cdots,N)$, A_k is the matrix of $x_{ij}(t_k)$; $\bar{x}=(\bar{x}_1,\bar{x}_2,\cdots,\bar{x}_m)$, $\bar{x}_j=\frac{1}{N}\sum_{k=1}^{N}\left(\frac{1}{n}\sum_{i=1}^{n}x_{ij}(t_k)\right)$, $\bar{y}=\frac{1}{N}\sum_{k=1}^{N}\left(\frac{1}{n}\sum_{i=1}^{n}y_i(t_k)\right)$.

Obviously, σ^2 have no upper limit if w isn’t limited. Limit $w^{T}w=1$. When w is the corresponding eigenvector of the largest eigenvalue $\lambda_{\max}(H)$, σ^2 reaches the maximum. If $w>0$, normalize w to make it satisfy $\sum_{j=1}^{m}w_j=1$. If $\forall j\in(1,2,\cdots\mathrm{m}), w_j\geq 0$, w can be obtained by the following nonlinear programming problem:

$$\begin{aligned}&\max w^{T}Hw\\&s.t.\ w^{T}w=1, w\geq 0\end{aligned} \tag{4}$$

4.3 Obtaining Time-value Coefficient

The system capability of different time $y_i(t_k)$ has been obtained from Eq. (2). The linear comprehensive assessment function can be defined as

$$y_i=\sum_{k=1}^{N}v_k y_i(t_k), i=1,2,\cdots,n \tag{5}$$

v is the time weighting vector. Furthermore, time-degree factor $\lambda=\sum_{k=1}^{N}\frac{N-k}{N-1}v_k$ is introduced to characterize the preference degree to time series. The closer λ to 0, it indicates the more attention to the recent data. The closer λ to 1, it indicates the more attention to the distant data. The principle of determining v is to find a set of stable time weights which have small fluctuation. It can be described by the variance of v, which can be calculated by the following mathematical programming problem. The solution of this problem can be easily got in reference [11].

$$
\begin{aligned}
&\min(D^2(v) = \frac{1}{N}\sum_{k=1}^{N} v_k^2 - \frac{1}{N^2}) \\
&s.t. \quad \sum_{k=1}^{N} \frac{N-k}{N-1} v_k, \quad \sum_{k=1}^{N} w_k = 1, w_k \in [0,1], k = 1,2,\cdots,N
\end{aligned}
\tag{6}
$$

5 A Case Study and Implementation

5.1 A Case Study

The case about selecting the machining system which has the optional sustainable manufacturing capability for machining a batch of shafting parts is presented. s_1, s_2, s_3 are the matched alternatives. Based on Table 1, pruning some indicators with small difference comparatively, 11 indicators are selected: quality(x_1 dimension machining precision; x_2 surface machining precision; x_3 shape machining precision), time(x_4 processing time; x_5 auxiliary time), cost(x_6 operation expenses; equipment depreciation), resource consumption(x_8 electricity), environmental impact(x_9 noise; x_{10} cuttings; x_{11} liquid wastes). The original data are shown in Table 3.

Table 3. The value of indicators

		x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}
t_1	s_1	0.05	0.05	0.05	20	10	50.8	1.0	5.02	80.2	1.23	6
	s_2	0.09	0.09	0.09	30	13	32.5	1.5	5.25	75.3	2.28	5.5
	s_3	0.06	0.06	0.05	18	10	30	0.8	5.50	82.6	1.35	6.1
t_2	s_1	0.05	0.06	0.05	21	10	51.8	1.2	5.08	82.2	1.25	5.8
	s_2	0.08	0.09	0.09	32	14	34.5	1.6	5.25	76.5	2.01	5.4
	s_3	0.05	0.06	0.06	20	11	32	1.4	5.48	85.0	1.59	6.5
t_3	s_1	0.07	0.06	0.05	21	10	52.8	1.0	5.02	82	1.85	6.2
	s_2	0.10	0.09	0.08	33	13	32.5	1.5	6.25	78	2.30	5.9
	s_3	0.06	0.07	0.07	19	12	30	1.2	5.88	83	1.50	6.5
t_4	s_1	0.08	0.07	0.05	20	10	41.8	1.2	5.02	82	1.72	5.6
	s_2	0.09	0.10	0.09	29	14	42.5	1.3	5.25	76	2.30	4.7
	s_3	0.08	0.06	0.08	19	10	32	1.1	5.88	84	1.35	5.8
t_5	s_1	0.08	0.07	0.09	25	12	58	0.8	4.84	77.9	1.19	5.8
	s_2	0.09	0.07	0.09	24	12	59	0.7	5.04	80	1.98	5.7
	s_3	0.09	0.08	0.07	25	12	60	0.8	5.84	79	1.28	5.5

Firstly, standardize the data and use AHP to calculate the weights (normalized)

$$w = (0.089, 0.183, 0.049, 0.156, 0.104, 0.140, 0.07, 0.09, 0.055, 0.029\ 0.036)$$

Then we can get the weighted time series database $x_{ij}(t_k)$ by using Eq. (1). The objective weight vector is calculated by Matlab based on Eq. (4)

$$w \quad (0.113, 0.251, 0.081, 0.242, 0.177, 0.004, 0.055, 0.029, 0.004, 0.040, 0.004)$$

So we get $y_i(t_k)$ by using Eq. (5). Let $\quad 0.3$ by attaching more importance to the recent data. The time weighting vector $v \quad (0.04, 0.12, 0.2, 0.28, 0.36)$ is obtained based on Eq. (6). The assessment results are shown in Table 4 by the expansion without affecting the ranking. From the results, we see s_1 is the optimal.

Table 4. Alternative value table

	t_1	t_2	t_3	t_4	t_5	Comprehensive value	Capability Ranking
s_1	11.72	10.44	10.07	9.18	6.85	8.77	1
s_2	2.63	1.84	1.58	1.60	6.83	3.55	3
s_3	11.12	9.98	8.58	9.94	5.72	8.20	2

5.2 Results Analysis

1. The dynamic assessment method proposed considers both the references of decision makes and the impact of objective data. The weights at different time are consistent, so we can compare the capabilities of alternatives at the same time from the horizontal and get the capability trends with time from the vertical. The capabilities of three alternatives are shown in Fig.2. We can know that s_1 is on the decline but it is optimal overall. s_2 improves much at t_5. Finding out the possible causes of the improvement can provide guidance for improving capability.
2. The proposed dynamic assessment method is based on the time series data. If the data are updated, the weights change correspondingly. So it effectively follows the dynamics of manufacturing process. The weight vector of each time can be calculated by Matlab within seconds for one time, so it has less computation.
3. From w, we can know x_2 and x_4 are the key factors of capability. More attention should be attached to them to improve the sustainable manufacturing capability.
4. The time-value factor can affect the comprehensive assessment value. Take as 0, 0.2, 0.4, 0.6, 0.8, and 1 respectively, the corresponding capabilities are shown in Fig.3. How to adjust the time-value coefficients to forecast the capability of machining system at next time is the next research content.

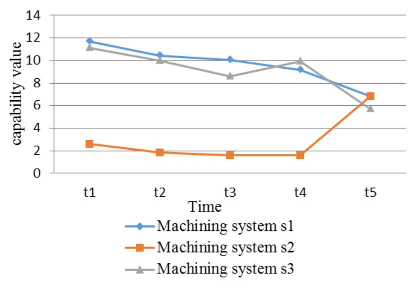

Fig. 2. Trend of capability for alternatives

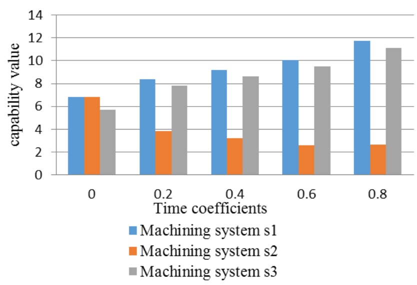

Fig. 3. The capabilities of different

6 Conclusion

This paper focuses on the dynamic assessment of sustainable manufacturing capability for CNC machining systems. A set of indicators system is established from quality, time, cost, resource consumption and environmental impacts. Then a dynamic assessment method based on “vertical and horizontal” method and AHP considering “time-value coefficients” is proposed to assess the capability dynamically and effectively. Its application in a case study verified its advantages and effectiveness. The dynamic assessment model is also applicable to other dynamic decision making problems, such as economic decision-making, performance assessment of systems, etc.

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