Market Competitiveness Evaluation of Machining Centers by Multidimensional Vectors*

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The machining center is currently positioned as one of the core facilities in a wide range of production systems. With its increasing importance in the manufacturing environment it has become a consequential requirement for producers of machining centers to improve their market competitiveness. This implies a need for establishing a new methodology for market competitiveness analysis based specifically on the conversion of uncertain market requirements into the technological attributes rather than on statistical data. This paper proposes a methodology for systematically and rationally analyzing the market competitiveness of a machining center using multidimensional vectors: in order to quantify the competitiveness factors, user needs and performance specification of the machining center are represented by the vectors in multidimensional coordinates. The validity of the proposed method has been verified through case studies.

Key Words: Machine Tool Design, Machining Center, Market Competitiveness, Competitiveness Evaluation, Evaluation Methodology, Multidimensional Vector, User needs

1. Introduction

The machining center (MC), one of the most important products of the machine tool industry, has shown remarkable adaptability to the requirements of a changing market, accomplishing considerable advances on technical grounds such as complexity of machining function, systematization and productivity, and has attained a position as one of the core facilities in a wide range of production system. On the other hand, the user's requirements have also become more and more complicated and, recently, more individualized and diversified, while the demands for low cost have continued to intensify[1]. In such a situation, manufacturers are being forced to develop MCs whose specifications more closely match the needs of the user.

In general, the design specifications of an MC have been determined by reference to the specifications of current products or by prediction of future trends. However, in the current climate of international competitiveness and with increasing demands for customized products, such methods no longer provide efficient tools for meeting the customer requirements. This implies a need for establishing new methodologies for systematically evaluating the market competitiveness of MCs.

However, basic research on market competitiveness evaluation has largely been confined to studies of structural configuration[2] or statistical analyses and prediction of market needs[3], the latter generally approached from an economical point of view. On the other hand, the number of research works stating the importance of establishing methodologies based on the conversion of uncertain market requirements into the technical attributes is constantly increasing. Several research works by Ito relating to region and racial trait-harmonized products are examples of such topics[4],[5]. The concept of the 「Region

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and Racial Trait-Harmonized Product ⌋ relates to the manufacture of region-specified products that incorporate a consideration of the cultural differences of each nation or region. However, techniques for the quantitative evaluation of market competitiveness are not as yet established.

In this context, this paper proposes methods for evaluation of market competitiveness based on compatibility with the user needs. It uses the MC as an example and provides a number of case studies to demonstrate the validity of the proposed method. By incorporating this method in the structural configuration design process[6], the whole processes from market sales to product development can be determined systematically.

2. Analysis of Market Competitiveness Factors

In general, market competitiveness of goods depends on the following factors.

(1) The characteristics of the product, e.g., functions, performances, cost, styling, etc.

(2) Marketing activities, e.g., advertisement, aftersales service, etc.

(3) Other factors, e.g., brand name values.

However, as it is very difficult to evaluate market competitiveness based on all these factors, usually a specific point of view is emphasized in the actual evaluation. Thus, in this paper, market competitiveness of the MC is evaluated from the viewpoint of compatibility with the user needs, supposing the following preconditions.

(1) Marketing activities, such as aftersales service, delivery, etc., are not taken into account.

(2) The quantities of user needs are not considered.

(3) Evaluations are based on the compatibility or sufficiency to the user needs of the product characteristics such as performance, cost, styling, etc., and are carried out by comparison of these characteristics to other products.

Figure 1 shows the results of the analyses of the market competitiveness factors, taking into account those items which should be considered at the time of selecting or purchasing MCs. These analyses have been carried out on the MCs available in the 1990s, and are based on the key-words written on the catalogues distributed to users. As shown in this figure, the extracted key-words from various kind of MCs can be arranged in three layers. Also written in the catalogues are technical specifications which represent the functions and performance of the machine in precise numerical values. Generally, the choice of the user is determined by considering the qualitative key-words shown in Fig. 1 and also these numerical

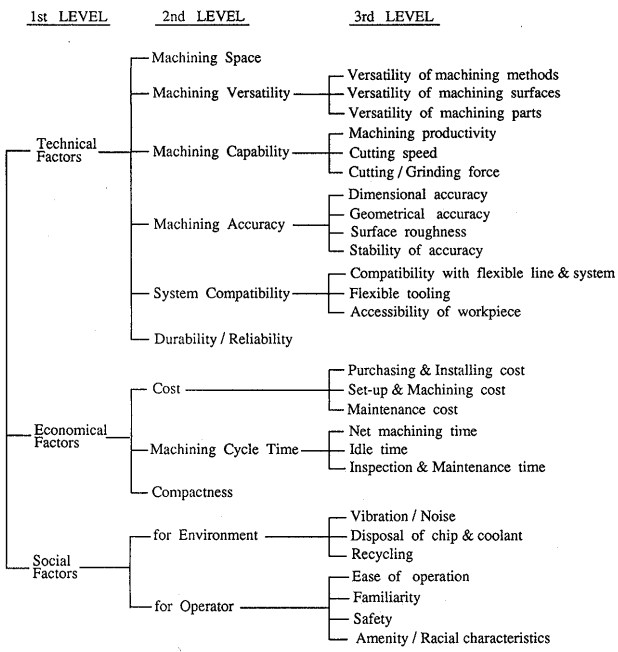

Fig. 1 Market competitiveness factors of Machining Center (MC)

values simultaneously. So if the intention is to pay attention to the user needs in the evaluation process, it is essential to understand the relationship of those qualitative factors with the quantitative technical specifications. Thus, it is desired to make a correlation table of the market competitiveness factors shown in Fig. 1 with the numerical specifications.

In this paper, it is assumed that the market competitiveness factors can be classified into a 'principal factor' and a 'related factor.' As a result of this assumption, market competitiveness factors are considered to have clear relationship with technical specifications as shown, for example, in Table 1. The reliability of the evaluation is expected to be increased if this correlation table can be made more precisely. However, at this time, the method of establishing the mutual dependancy of these factors seems to be an issue whether the factors are qualitative or quantitative. For instance, it is known that "Compactness" has a close relationship to "Purchasing & installing cost." But in this paper, to simplify the evaluation process, this viewpoint is ignored.

As mentioned above, one attractive method for evaluation of the market competitiveness of MCs is to select the important market competitiveness factors based on the intended use and then to evaluate synthetically using the correlation between the technical terms and these factors.

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Table 1 Correlation of MC specifications with market competitiveness factors

(● Principal factor, △ Related factor)

Technical terms of machining center \ Factors of market competitiveness		Technical factors													Economical factors							Social factors					
			Machining versatility			Machining capability			Machining accuracy						Cost			Machining cycle time				for Environment			for Operator			
		Machining space	Machining methods	Machining surfaces	Machining parts	Machining productivity	Cutting speed	Cutting/Grinding force	Dimensional accuracy	Geometrical accuracy	Surface roughness	Stability of accuracy	System compatibility	Durability/Reliability	Purchasing&installing cost	Set up&machining cost	Maintenance cost	Net machining time	Idle time	Inspection & maintenance time	Compactness	Vibration/Noise	Disposal of chip&coolant	Recycling	Ease of operation	Familiarity	Safety	Amenity/Racial characteristics
Constitution of axes			●	●	●								●										△		△			
Axis strokes	X,Y,Z-Axes	●			△																●				△			
	Other axes		△	●	△																△				△			
Table	Table Size	●			△																●				△			
	Min. indexing angle		●	●	△																				△			
	Indexing time					△										△			●									
Main spindle	Number of main spindles					△							●					△										
	Max. spindle speed				△	●	●									△		△										
	Motor power					●	△	●						△		△		●										
Feed	Rapid traverse					●	●									△		●	●									
	Cutting feedrates		△			●	●									△		●										
	Feed force (Z-axis)					△		●						△		△		△										
Accuracy	Positioning accuracy								●	△				△														
	Repeatability								●	△		△		△														
	Rotary positioning accuracy								●			△		△														

3. Evaluation Method Using Multidimensional Vectors

3.1 Representation of user needs using vector method

As mentioned before, MCs are used in various kinds of production systems and required performance attributes also vary depending on the functional environment. Therefore, the user needs can be defined by multiple parameters consisting of appropriate terms selected from the market competitiveness factors shown in Fig. 1 and weighted in accordance with the importance of the factors. That is, vector Xi representing the user needs can be described as the vectorial form using axes e_1 to e_n which represent market competitiveness factors, as follows.

$$Xi=\{x_{i1}(e_1), x_{i2}(e_2),\cdots, x_{in}(e_n)\} \quad (1)$$

This vector Xi will be the basis of the market competitiveness evaluation process. The magnitude of component x_{in} is assigned the weighting factor corresponding to the characteristics of the user needs. The coordinate axes of this vector represent the market competitiveness factors selected from level 1 to level 3 shown in Fig. 1, in accordance with their importance.

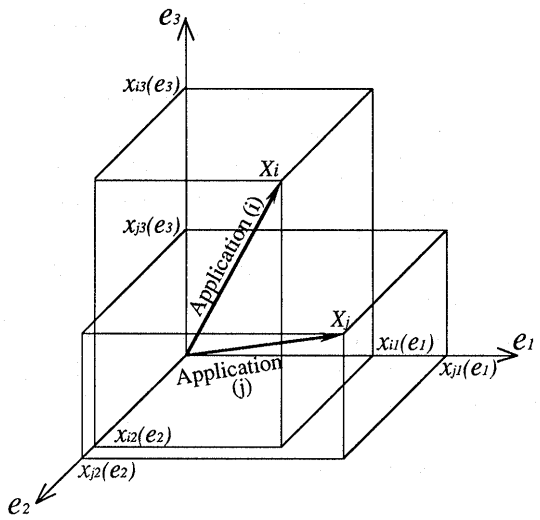

Fig. 2 Vector representation of user needs in multidimensional space ($n=3$)

3.2 Evaluation of competitiveness factors based on technical terms and fair rating of technical terms

The evaluation of the qualitative market competitiveness factors is considered to be based on the related technical terms shown in Table 1. In this case, technical characteristics (Y_{xj}) of the MCs can be evaluated for each competitiveness factor: the weighting factor (w_{jn}) is multiplied by the evaluated

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level of the principal technical terms of the MC, and the overall technical characteristics of each factor is estimated by a vectorial calculation method as follows.

$$Y_{jx}=\{(w_{j1}\cdot L_{x1})^2+(w_{j2}\cdot L_{x2})^2+\cdots\cdots\cdots+(w_{jn}\cdot L_{xn})^2\}^{1/2} \quad (2)$$

Here, L_{xn} is the evaluated level of the technical terms of model X, such as maximum chip volume, positioning accuracy, and w_{jn} is the weighting factors of the n-th technical terms assigned to the j-th competitiveness factor. The magnitudes of the weighting factors are determined as 1 or 0.5 depending on their importance, and are regulated as follows.

$$(w_{j1})^2+(w_{j2})^2+\cdots\cdots\cdots+(w_{jn})^2=1 \quad (3)$$

When evaluating an MC based on technical terms, it is essential to judge the various kinds of MCs rationally and fairly using the same evaluation scales within each group. Therefore, in this study, MCs are divided into vertical and horizontal types and technical terms are evaluated by relative functions and performance levels within each group.

In this case, there are three types of features in the technical terms, as folllows.

(1) Terms to be evaluated quantitatively; i.e., maximum spindle speed, positioning accuracy, etc..

(2) Terms to be divided into categories; i.e., constitution of axes, type of pallet, etc..

(3) Terms to be evaluated qualitatively; i.e., styling, etc..

The following methods are considered to be effective for evaluating these terms.

(1) For the quantitative terms, distribution charts for MCs currently on the market have been prepared for each technical term and the mean value of the distributions, as shown in Fig. 3, determined so as to decide the upper and lower limits of the evaluation in order to obtain the same evaluation at the mean value. In this case, the distribution of technical terms shows the following features.

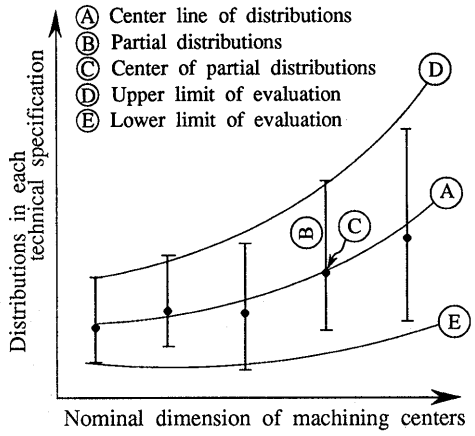

Fig. 3 Relative evaluation method of technical terms

(i) Patterns of proportionally increasing distributions with nominal dimensions of the MC.

(ii) Patterns of proportionally decreasing distributions with nominal dimensions of the MC.

(iii) Patterns of arbitrary distributions with nominal dimensions of the MC.

(iv) Compound patterns of (i)-(iii).

This evaluation method is considered to be a simple but rational way to measure the relative position of the objective MC within the overall distributions of MCs regardless of its nominal sizes.

(2) For the categorical terms, the evaluation levels are assigned to each category and the objective MC allocated to the appropriate category.

(3) For the qualitative terms, the quality of the objective MC is classified as 'good', 'ordinary' or 'poor' and a value of 1, 0.5 or 0 respectively is allocated to each category. In this way, the qualitative data is quantified and made suitable for subsequent statistical manipulation.

3.3 Proposal of evaluation method of market competitiveness based on user needs

In the proposed methodology, the qualitative market competitiveness factors are evaluated based on the related technical terms, as described in Section 3.2, and then the results are expressed as the multidimensional vectors, as shown in Fig. 4.

$$Y_x=\{Y_{x1}(e_1),\ Y_{x2}(e_2),\cdots\cdots\cdots,\ Y_{xn}(e_n)\} \quad (4)$$

The subsequent evaluation process of market competitiveness based on the user needs is to multiply this vector Y_x by the unit vector (Si) of vector Xi, defined in Section 3.1 as the representative vector of user needs, and to compare the magnitude of the scalar product H_{xi}.

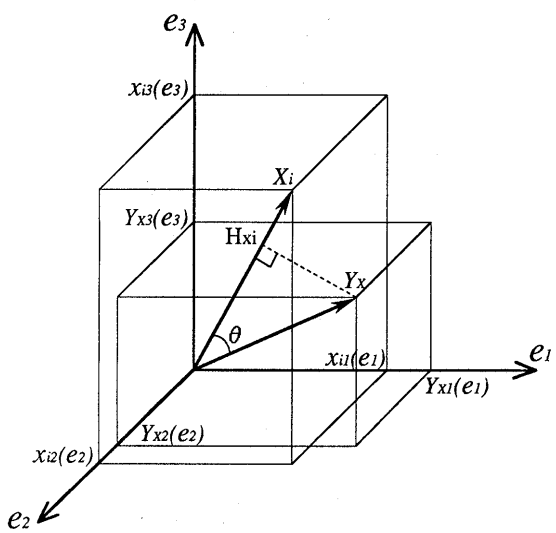

Fig. 4 Vector representation of user needs (Xi) and MC specification level (Y_x) in multidimensional space $(n=3)$

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Table 2 Examples of weighting factors based on various applications

Application	Factors of Market Competitiveness					
	Machining productivity	Cutting speed	Machining accuracy	System compatibility	Compactness	Purchasing cost
MC for FTL (Emphasis on system compatibility)	0.8	0.3	0.3	1.0	0.4	0.8
MC for general purpose (Emphasis on cost performance)	1.0	0.3	0.5	0.3	0.3	1.0
MC for grooving molds (Emphasis on high-speed machining)	0.5	1.0	0.8	0.0	0.0	0.3
MC for machining jig & fixtures (Emphasis on machining accuracy)	0.3	0.3	1.0	0.0	0.0	0.5

Table 3 Examples of weighting factors (w_{jn}) and technical specifications to market competitiveness factors

Factors	Technical terms	Specified weighting factors		Factors	Technical terms	Specified weighting factors	
		Ratio of weighting factors	Weighting factors (W_{jk})			Ratio of weighting factors	Weighting factors (W_{jk})
Machining productivity	Max. chip volumes	1.0	0.6325	System compatibility	Constitution of axes	1.0	0.6325
	Rapid traverse	1.0	0.6325		Number of main spindles	0.5	0.3162
	Max. cutting feed rates	0.5	0.3162		Tool storage capacity	0.5	0.3162
	ATC time (tool to tool)	0.5	0.3162		Type of APC	1.0	0.6325
Cutting speed	Max. spindle speed	1.0	0.5547	Compactness	Compactness index of floor space * Note	1.0	1.0000
	Rapid traverse	1.0	0.5547				
	Max. cutting feed rates	1.0	0.5547				
	ATC time (tool to tool)	0.5	0.2774				
Machining accuracy	Positioning accuracy	1.0	0.6667	Cost	Purchasing cost	1.0	1.0000
	Repeatability	0.5	0.3333				
	Stability of accuracy	1.0	0.6667				

$$\text{* Note: Compactness index of floor space}^{(7)} = \frac{(\text{Width of machine} \times \text{Depth of machine})}{(\text{Table X-dimension} + \text{X-travel}) \times (\text{Table Y-dimension} + \text{Y-travel})}$$

$$H_{xi} = |Si| \cdot |Y_x| \cos\theta = (x_{i1} \cdot Y_{x1} + x_{i2} \cdot Y_{x2} + \cdots\cdots + x_{in} \cdot Y_{xn}) / (x_{i1}^2 + x_{i2}^2 + \cdots\cdots + x_{in}^2)^{1/2} \quad (5)$$

The scalar product H_{xi} is projected on to the component of vector Y_x in the Xi direction and this gives the magnitude of the evaluated level of the technical characteristics of the objective MC in the direction representing the user needs. That is, the magnitude of H_{xi} represents the market competitiveness of the objective MC compatible with the user needs (i). Thus, comparing the magnitudes of H_{xi}, the relative market competitiveness of the MCs can be ranked.

4. Application of Proposed Methodology

To verify the validity of the proposed methodology, some case studies have been carried out for the actual MCs currently on the market. In these case studies, initially four categories of uses are assumed and the market competitiveness factors and their initial weighting factors are determined corresponding to these uses, as shown in Table 2. Next, related technical terms and their weighting factors (w_{jn}) are actually determined as shown in Table 3.

Based on these data, market competitiveness evaluations are carried out for a group of small sized vertical MCs. The results are shown in Table 4 and plotted in two dimensional space in Fig. 5. From Table 4 and Fig. 5, we can deduce the following facts. These findings imply that the proposed methodology is very effective for measuring quantitatively the difference in market competitiveness of MCs.

(1) "Emphasis on cost performance" shows close correlation with "Emphasis on high-speed machining", so the MC of "Emphasis on cost performance" type should be of good high-speed machining performance. This inference corresponds well with empirical observation.

(2) In Fig. 5, "Emphasis on system compatibility" shows no relation with "Emphasis on machining accuracy", and MCs of "Emphasis on system compatibility" type have $/XYZC$ like constitution of axes, as shown in Table 4. This type of constitution is the distinctive structural feature of system compatible type MCs, showing good accessibility of workpiece.

Moreover, as shown in Fig. 6, plotting together

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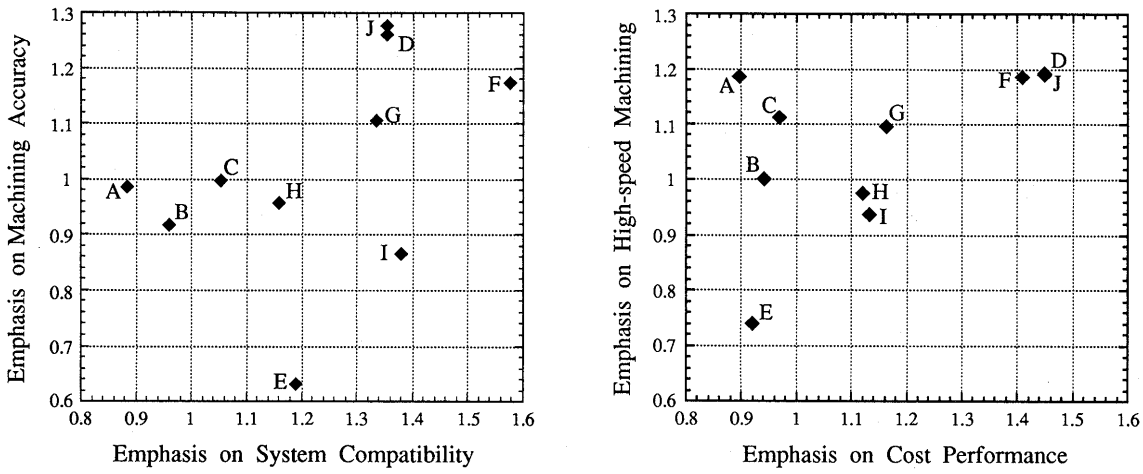
Table 4 Evaluated market competitiveness of MC

Model name	Major specifications								Evaluated values (Hxi) & Rankings							
	X-Travel (mm)	Constitution of axes	Max. chip volumes (steel,cc/min)	Max. spindle speed (rpm)	Rapid traverse (m/min)	Positioning accuracy (±mm)	Compactness index of floor space	Purchasing cost (thousand yen)	Emphasis on system compatibility		Emphasis on cost performance		Emphasis on high-speed machining		Emphasis on machining accuracy	
									Evaluated values	Rank -ings	Evaluated values	Rank -ings	Evaluated values	Rank -ings	Evaluated values	Rank -ings
A	560	X/YZC	42.6	20,000	36	0.003	8.41	28,000	0.8830	(10)	0.8943	(10)	1.1879	(3)	0.9873	(6)
B	560	X/YZC	42.6	6,000	36	0.003	3.17	17,500	0.9582	(9)	0.9388	(8)	1.0026	(7)	0.9194	(7)
C	700	X/YZC	190.0	20,000	24	0.002	2.20	29,000	1.0500	(8)	0.9686	(7)	1.1145	(5)	0.9989	(5)
D	560	XY/ZC	165.0	8,000	30	0.003	3.93	8,800	1.3506	(4)	1.4462	(1)	1.1923	(2)	1.2624	(2)
E	400	/XYZC	18.5	8,000	24	0.020	7.06	12,000	1.1881	(6)	0.9186	(9)	0.7418	(10)	0.6328	(10)
F	650	/XYZC	195.0	8,000	36	0.003	3.67	13,500	1.5741	(1)	1.4076	(3)	1.1871	(4)	1.1769	(3)
G	200	/XYZC	15.0	15,000	24	0.0025	11.22	8,150	1.3334	(5)	1.1607	(4)	1.0965	(6)	1.1076	(4)
H	510	XY/ZC	150.0	4,000	24	0.005	4.28	12,000	1.1564	(7)	1.1195	(6)	0.9767	(8)	0.9598	(8)
I	200	/XYZC	7.0	17,000	24	0.008	4.89	7,000	1.3773	(2)	1.1306	(5)	0.9385	(9)	0.8679	(9)
J	800	XY/ZC	180.0	8,000	30	0.003	2.97	10,500	1.3511	(3)	1.4457	(2)	1.1941	(1)	1.2801	(1)



(A) (B)

Fig. 5 Two dimensional representation of market competitiveness of MC

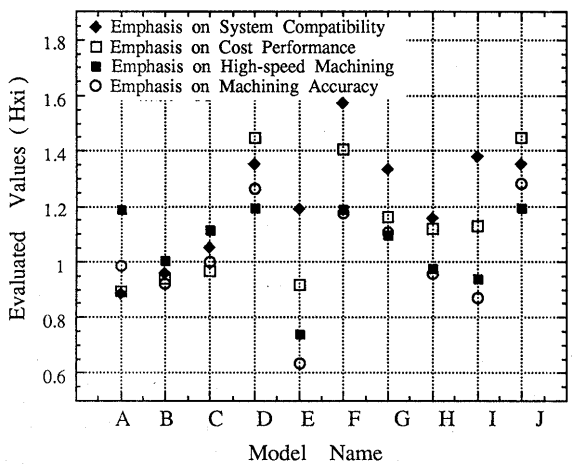


Fig. 6 Evaluated market competitiveness values (H_{xi}) of various MC models

the results of market competitiveness evaluation for various categories of uses, total market competitiveness and also the distinctive features of objective MCs may be clearly distinguished. For instance, it is clear that model A is an MC for high speed machining and also has good cost performance, model B is an MC for general purpose use having well balanced performance and model F is an MC of line type having good cost performance.

5. Concluding Remarks

This paper has proposed a methodology for synthetically evaluating market competitiveness of MCs, considering both the user needs, up to now usally expressed in qualitative terms, and technical features of the MC, for example functions and performances.

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The proposed methodology has been adopted to evaluate market competitiveness of the MCs. In this methodology, weighting factors are determined corresponding to the characteristics of the user needs, and then the user needs and the technical features of the MC are represented by multi-dimensional vectors, so that various factors can be evaluated simultaneously and synthetically.

Results of this study can be summarized as follows.

(1) This paper propose a new methodology to evaluate the compatibility of an MC with the user needs, that is, its market competitiveness. It uses the scalar product of the unit vector, representing the features of the user needs, and the vector representing the evaluated technical features of the objective MC.

(2) Using the proposed methodology, a market competitiveness evaluation is carried out for a group of MCs and the validity of the proposed methodology has been verified thereby. In other words, the methodology proved capable of ranking a group of objective MCs in order of compatibility with the user needs.

Moreover, the proposed methodology is able to classify the characteristics of an MC and may be used to investigate the specifications of a new model to be developed.

The proposed methodology is expected to be applicable to other products.

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