Evaluation of steel turning by means of probability – based multi - objective optimization with appropriate numbers of attributes

Maosheng Zheng[a], *Jie* Yu[b]

[a] Northwest University, School of Chemical Engineering,
Xi'an, People's Republic of China,
e-mail: mszhengok@aliyun.com, **corresponding author**,
ORCID iD: https://orcid.org/0000-0003-3361-4060

[b] Northwest University, School of Life Science & Technology,
Xi'an, People's Republic of China,
e-mail: yujie@nwu.edu.cn,
ORCID iD: https://orcid.org/0000-0001-6606-5462

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Abstract:

Introduction/purpose: Turning is a typical machining process. However, an appropriate solution for a concurrent optimization of minimizing surface roughness, minimizing cutting forces and vibrations, and maximizing the material removal rate in turning processes has not been found yet. This article formulates the rule of separating an independent attribute from multiple attributes by using the linear correlation coefficient in the spirit of the cluster analysis first. Moreover, the evaluation of the concurrent optimization of steel turning by means of probability - based multi - objective optimization (PMOO) is taken as an example to show the procedure including the separation of an independent attribute from multiple attributes by using PMOO.

Methods: PMOO is a promising solution for turning processes. It is necessary to have an independent attribute in the evaluation of PMOO to be analogical as an independent event in the view of the probability theory. The separation of an independent attribute from multiple attributes by using the linear correlation coefficient is conducted in the spirit of the cluster analysis. It further assumes that if the linear correlation coefficient of two attributes in the cluster analysis is higher than 0.8, i.e., in case of very strong correlation, then they could be put into one category, and only one of them could be taken as an independent attribute to join the evaluation of PMOO.

Results: The formulation reflects the essence of PMOO and its application in material machining rationally, which opens a new way for solving the *relevant problem. The example of the parameter optimization of steel turning by means of PMOO indicates the rationality of the appropriate solution.*

Conclusion: This innovative study has practical significance of making the utilization of PMOO method reasonable by providing a rational rule of separating independent attributes from multiple attributes of PMOO.

Key words: multi – objectives, cluster analysis, independent attributes, linear correlation coefficient, metal turning.

Introduction

Turning is a typical machining process. The number of turning machines is about 30% of all cutting machines in a cutting workshop (Thien Van et al, 2021; Hegde et al, 2022; Yıldız et al, 2023, Nguyen & Vo Thi, 2022).

The surface roughness of machining, cutting forces, vibrations, and the material removal rate (MRR) are usually used as the assessed attributes of quality evaluation for the overall machining process. In order to ensure the minimum value of surface roughness, Taguchi design and the Response Surface Method (RSM) were frequently used to conduct the optimization of cutting parameters such as cutting velocity, feed rate, and cutting depth in the turning process for various materials with minimizing surface roughness, or minimizing cutting forces, or maximizing the MRR, solely (Thien Van et al, 2021; Hegde et al, 2022; Yıldız et al, 2023, Nguyen & Vo Thi, 2022; Irzaev et al, 2021).

However, until now, an appropriate solution for a concurrent optimization of minimizing surface roughness, minimizing cutting forces and vibrations, and maximizing the MRR in turning processes has not been achieved yet (Thien Van et al, 2021; Hegde et al, 2022; Yıldız et al, 2023, Nguyen & Vo Thi, 2022; Irzaev et al, 2021).

Actually, the concurrent optimization of minimizing surface roughness, minimizing cutting forces and vibrations, and maximizing the MRR in turning processes is a typical optimization problem with multiple objectives (attributes); it is essentially focused on the simultaneity of the optimization of multiples objectives.

Probability – based multi – objective optimization (PMOO) is a newly developed approach to conduct the concurrent optimization problem of multiple attributes (objectives). A new idea of preferable probability and its assessment have been put forward (Zheng et al, 2024).

The core content of PMOO is taking the "simultaneous optimization of multiple attributes" from the entire or systematic viewpoint of the system theory; therefore, a probability - based method was formulated on the basis of the probability theory and the set theory, taking each attribute as an independent event in the subsequent treatment.

The advantages of PMOO are its probabilistic foundation in view of the system theory, rationality and certainty of its solution without any artificial factors, and a simple and convenient algorithm in mathematical treatment, which are obviously superior to other methods of multi-objective optimization such as the Analytic Hierarchy Process (AHP), the VIšekriterijumsko KOmpromisno Rangiranje (VIKOR), the Technique of Ranking Preferences by Similarity to the Ideal Solution (TOPSIS), Multi-Objective Optimization (MOO) on the basis of the Ratio Analysis (MOORA) , the Pareto solution, the Grey Relational Analysis (GRA), etc. (Zheng et al, 2024; Salomon, 2019). Besides, this approach is superior regarding simplicity in data processing to other metaheuristics.

The new approach could be employed in many fields involving multiple attributes, including energy planning, economic affairs, operation research, programming problems, material selection, mechanical design, etc. Therefore, PMOO is a promising solution for a concurrent optimization of minimizing surface roughness, minimizing cutting forces and vibrations, and maximizing the MRR of turning processes in view of the system theory (Zheng et al, 2024).

Moreover, from the perspective of the probability theory and the set theory, the intersection of independent events and the joint probability of independent events could be used to characterize the concurrent occurrence of multiple independent events as the concurrent optimization of multiple attributes. In this way, when it allocates each attribute to an independent event, the problem of the simultaneous optimization of multiple attributes becomes "rule - based". However, the allocation of each attribute to an independent event naturally relies on the separation of independent events from multiple attributes such that the PMOO method could be used rationally.

Thus, separating an independent event from multiple attributes is of considerable significance to ensure the appropriate application of the PMOO method in material selection.

While, the cluster analysis could fortunately be employed to conduct the separation of an independent attribute from multiple attributes. By classifying things rationally, problems in the material world could be clarified and understood gradually (Backhaus et al, 2021; Scitovski et al, 2021). In the process of the cluster analysis, the class is often not given in advance, but it needs to be determined according to the characteristics of the observed data, and there is no need to make any assumptions about the number and structure of classes. In the clustering results, attributes belonging to the same class tend to be similar to each other in a sense, while attributes belonging to different classes tend to be dissimilar. The purpose of the cluster analysis is to classify attributes into several classes according to certain rules. The cluster analysis can be divided into the *Q* – type cluster analysis and the *R* – type cluster analysis in accordance with different classification objectives. The *Q* - type clustering analysis is for samples and the *R* - type clustering is for performances (Backhaus et al, 2021; Scitovski et al, 2021).

Generally speaking, according to the degree of similarity, attributes (or samples) are classified one by one; closely related classes are clustered into a small taxon, and then gradually expanded, so that the alienated ones are clustered into a large taxon, until all samples (or performances) are clustered, forming a cluster diagram that represents the affinity. Samples (or performances) are classified in accordance with some requirements in turn (Backhaus et al, 2021; Scitovski et al, 2021).

The general viewpoint of classification is that the closer the similarity of attributes is, the closer their similarity coefficient is to 1 or –l, while the similarity coefficient of unrelated attributes is closer to 0.

Those with higher similarity are classified into one category, and those with higher dissimilarity are classified into different categories. The distance in the variable "space" is the characteristic between the "points". Each sample is regarded as a point in the *P*-dimensional space, and the distance between the points is measured by some kind of measurement. The points that are closer to each other belong to one category while the points that are farther away belong to different categories.

This paper mainly focuses on separating independent attributes from multiple attributes of PMOO in respect of the *R* - type cluster analysis rationally, so as to guarantee the appropriate application of the PMOO method in material selection first. The evaluation of steel turning by means of PMOO is presented as an example of the process of separating independent attributes from multiple attributes for subsequent evaluation.

Procedure of separating an independent attribute from multiple attributes in PMOO for material machining by means of the cluster analysis

The formulation of separating an independent attribute from multiple attributes in PMOO for material machining by means of the cluster analysis is as follows:

1. Representative of similarity

As a representative of similarity, the linear correlation coefficient is frequently employed as a branch to identify similarity (Backhaus et al, 2021; Scitovski et al, 2021).

The linear correlation coefficient is defined by

$$r_{jk} = \sum_{i=1}^{m}(y_{ij}-u_j)\cdot(y_{ik}-u_k) \Big/ [\sum_{i=1}^{m}(y_{ij}-u_j)^2 \cdot \sum_{i=1}^{m}(y_{ik}-u_k)^2]^{0.5} \quad . \qquad (1)$$

In equation (1), r_{jk} is the linear correlation coefficient which is employed to identify the degree of linear correlation between two attributes y_{ij} and y_{ik}; u_j is the average value of the *j-th* attribute and u_k is the average value of the *k-th* attribute.

Obviously, the linear correlation coefficient is just the right coefficient to reflect the linear proportional relationship between two attribute indexes y_{ij} and y_{ik}; it is more reasonable to reflect the similarity between samples or attributes; in addition, the linear correlation coefficient also has the invariance of normalization similar to the equation (Backhaus et al, 2021; Scitovski et al, 2021).

2. Rules of separating an independent attribute from multiple attributes

As mentioned previously, in the PMOO method for material selection, allocating each attribute to an independent event depends on differentiating an independent event from multiple attributes through the cluster analysis. This section gives the formulation of separation of an independent attribute from multiple attributes.

In the light of the general rule of the *R* - type clustering analysis for performance classification and the advantage of the linear correlation coefficient in the cluster analysis, the linear correlation coefficient is employed to formulate the separation of an independent attribute from multiple attributes. The appropriate rules are given in the following steps:

a) Evaluations of the similarity of attributes and classification

The linear correlation coefficient in the cluster analysis is used to characterize the similarity of attribute indexes in the performance classification first.

b) Identification of the attribute category

As for the attribute classification, it further assumes that if the linear correlation coefficient of two attributes in the cluster analysis is higher than 0.8, i.e., in case of very strong correlation, they can be put into one category, and only one of them can be used as an independent attribute to join the evaluation of PMOO while the attributes with the linear correlation coefficient lower than 0.8 in the cluster analysis are considered to be in different categories.

c) Evaluation of an independent attribute in PMOO for material machining

Take each independent attribute to join the evaluation of PMOO for material machining only. Especially, if more attributes than the independent attribute are used to join the evaluation and the analysis of the multi - objective optimization problem, it is equivalent to the increase of the weighting factors of the corresponding attributes.

Application in the optimization of the steel turning parameters

Thien Van et al. reported the results of the multi - objective optimization problem of turning EN 10503 steel by using the VIKOR method (Thien Van et al, 2021). However, the shortcomings of the “closeness” to the “virtual ideal solution” and the additional weighting factor of the VIKOR method remained.

In this article, the multi - objective optimization problem of the turning of EN 10503 steel is re-analyzed by means of PMOO with the cluster analysis rationally. In Thien Van’s research, the cutting velocity n, the feed rate f, the depth of cut t, and the insert nose radius r were chosen as the input parameters with three levels for each parameter. Taguchi's orthogonal array $L_9(3^4)$ was used to conduct the design and experiments, as shown in Table 1. The surface roughness R_a, the cutting force components F_x, F_y, and F_z (in the x, y, and z directions), the vibration component amplitudes A_x, A_y and A_z (in the x, y, and z directions), and the material removal rate (the MRR) were taken as their evaluated attributes (objectives). Their results are given in Table 2.

Table 1 – Experiment design with $L_9(3^4)$
Таблица 1 – Планирование эксперимента с $L_9(3^4)$
Табела 1 – Дизајн експеримента са $L_9(3^4)$

No.	Coded value				Actual value			
	n	f	t	r	n (rev/min)	f (mm/rev)	t (mm)	r (mm)
1	1	1	1	1	460	0.08	0.20	0.4
2	**1**	**2**	**2**	**2**	**460**	**0.194**	**0.35**	**0.6**
3	1	3	3	3	460	0.302	0.50	1.2
4	2	1	2	3	650	0.08	0.35	1.2
5	2	2	3	1	650	0.194	0.50	0.4
6	2	3	1	2	650	0.302	0.20	0.6
7	**3**	**1**	**3**	**2**	**910**	**0.08**	**0.50**	**0.6**
8	3	2	1	3	910	0.194	0.20	1.2
9	3	3	2	1	910	0.302	0.35	0.4

Table 2 – Experimental results with the $L_9(3^4)$ design
Таблица 2 – Результаты эксперимента разработки $L_9(3^4)$
Табела 2 – Резултати експеримента са дизајном $L_9(3^4)$

No.	Ra (μm)	Fx (N)	Fy (N)	Fz (N)	Ax (μm)	Ay (μm)	Az (μm)	MRR (mm3/s)
1	0.840	85.2740	24.9800	107.4400	2.385	5.3594	5.5826	7.948
2	0.605	166.2340	47.5420	230.3210	3.9816	8.5019	9.0195	54.471
3	0.644	563.7300	153.285	965.2270	5.9601	12.1603	16.2276	178.071
4	1.122	219.2030	64.0220	335.7370	5.9392	8.8440	13.9882	57.823
5	0.669	152.2660	38.5830	191.5410	4.3123	7.6545	9.3600	42.398
6	0.643	175.3230	44.1470	211.6830	5.0853	9.9639	12.5087	31.447
7	0.621	191.0840	51.7270	300.1620	4.4647	7.4923	10.1177	60.009
8	0.729	212.9260	59.1170	307.8790	5.8284	8.4602	14.1956	33.694
9	0.675	124.9690	40.5450	164.2060	6.2633	10.1637	15.2682	38.130

Let us study the similarity of attributes (objectives) first.

The similarity analysis of these data shows that there is a strong linear correlation among the cutting force components of F_x, F_y and F_z, and among the vibration component amplitudes of A_x, A_y and A_z of the turning process.

The linear correlation coefficients of F_x *vs* F_y and F_x *vs* F_z are r_{FxFy} = 99.72 % and r_{FxFz} = 99.64%, respectively, see Figure 1. The linear correlation coefficients of A_x *vs* A_y and A_x *vs* A_z are r_{AxAy} = 97.77 % and r_{AxAz} = 80.39%, respectively, see Figure 2.

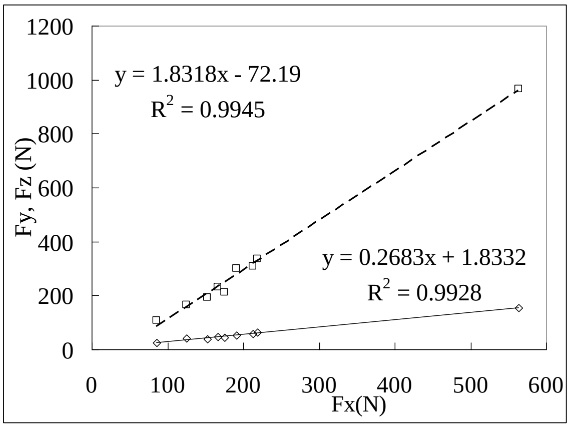

Figure 1 – Linear correlations of F_x vs F_y and F_x vs F_z
Рис. 1 – Линейные корреляции между F_x и F_y, а также между F_x и F_z
Слика 1 – Линеарне корелације између F_x и F_y, као и између F_x и F_z

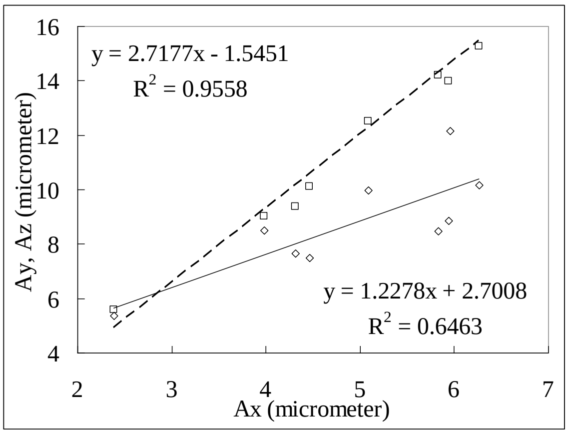

Figure 2 – Linear correlations of A_x vs A_y and A_x vs A_z
Рис. 2 – Линейные корреляции между A_x и A_y, а также между A_x и A_z
Слика 2 – Линеарне корелације између A_x и A_y, као и између A_x и A_z

As stated in the previous section, since there is a strong linear relationship among F_x, F_y and F_z, only one component of them can be employed as the independent attribute to join the evaluation of PMOO. The same applies for A_x, A_y and A_z. Therefore, F_x and A_x are taken as the independent attributes to join the evaluation of PMOO.

Finally, the surface roughness R_a, the cutting force components F_x, the vibration component amplitudes A_x, and the material removal rate *MRR* were taken as the actual evaluated independent multiple attributes.

Furthermore, in accordance with PMOO, the *MRR* belongs to the beneficial performance index to join the evaluation of partial preferable probability while R_a, F_x, and A_x, belong to the unbeneficial performance index to join the evaluation of their partial preferable probabilities.

The assessed consequences are shown in Table 3 which indicates that experiment No. 2 has the highest total preferable probability P_t at the first glance, followed by experiment No. 7.

However, the optimal configuation of Thien Van et al. is just experiment No. 7 which obviously exibits poorer responses than experiment No. 2 integrally (see the following detail for comparison).

As for experiment No. 2, the responses of the surface roughness, the cutting force and the vibration component amplitudes (in the X, Y, and Z directions), and the material removal rate (MRR) of experiment No. 2 are 0.605 μm, 166.2340 N, 47.5420 N, 230.3210 N, 3.9816 μm, 8.5019 μm, 9.0195 μm, and 54.471 mm^3/s, respectively, while in experiment No. 7, the responses of the surface roughness, the cutting force and the vibration component amplitudes (in the X, Y, and Z directions), and the material removal rate (MRR) are 0.621 μm, 191.084 N, 51.727 N, 300.162 N, 4.465 μm, 7.492 μm, 10.118 μm, and 60.009 mm^3/s, respectively.

Furthermore, the range analysis can be conducted for the total preferable probability P_t to perform successive optimization, as shown in Table 4. It indicates that the order of impact of the input variables is $r > t > f > n$, and the subsequent optimal configuration will be $r_2t_3f_2n_3$.

Table 3 – Assessed results of preferable probability and ranking
Таблица 3 – Полученные результаты предпочтительной вероятности и ранжирования
Табела 3 – Добијени резултати пожељне вероватноће и рангирање

No.	P_{Ra}	P_{Fx}	P_{Ax}	P_{MRR}	P_t×10^4	Rank
1	0.0986	0.1427	0.1863	0.0158	0.4135	9
2	**0.1247**	**0.1222**	**0.1388**	**0.1081**	**2.2875**	**1**
3	0.1204	0.0216	0.0800	0.3533	0.7344	6
4	0.0673	0.1088	0.0806	0.1147	0.6767	8
5	0.1176	0.1258	0.1290	0.0841	1.6051	3
6	0.1205	0.1199	0.1060	0.0624	0.9558	4
7	**0.1230**	**0.1159**	**0.1245**	**0.1191**	**2.1123**	**2**
8	0.1110	0.1104	0.08309	0.0669	0.6870	7
9	0.1170	0.1327	0.0710	0.0757	0.8329	5

Table 4 – Results of the range analysis
Таблица 4 – Результаты анализа ранжирования
Табела 4 – Резултати анализе рангирања

Level	n	f	t	r
1	1.1451	1.0675	0.6854	0.9505
2	1.0792	1.5265	1.2657	1.7852
3	1.2107	0.8410	1.4839	0.6994
Range	0.1315	0.6855	0.7985	1.0858
Order	4	3	2	1
Optimum	n_3	f_2	t_3	r_2

Conclusion

By using the linear correlation coefficient as similarity of the cluster analysis to conduct the classification of attributes, the separation of an independent attribute from multiple attributes could be performed rationally for the assessment of PMOO for material machining. In the evaluation, only each independent attribute could join the evaluation of PMOO. If more attributes than an independent attribute are used to join the analysis and the evaluation of multi - objective optimization problem, it is equivalent to the increase of the weighting factors of the corresponding attributes. The example of parameter optimization of steel turning by means of PMOO indicates the rationality of the appropriate solution.

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Оценка точения стали, основанная на вероятности многоцелевой оптимизации с соответствующим количеством атрибутов

Маошенг Чжэн[а], *Джи* Йю[б]

Северо-западный политехнический университет,
г. Сиань, Народная Республика Китай

[а] факультет химической инженерии, **корресподент**

[б] факультет естественных наук и технологий

РУБРИКА ГРНТИ: 27.47.00 Математическая кибернетика,
81.09.00 Материаловедение
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Точение − это типичный процесс механической обработки металла. Однако подходящее решение по одновременной оптимизации минимизации шероховатости поверхности, минимизации силы резания и вибраций, максимального увеличения скорости удаления стружки в течение точения пока не найдено. В данной статье на основании кластерного анализа сформулировано правило выделения независимого атрибута из множества атрибутов с использованием коэффициента линейной корреляции. Помимо того, на примере оценки одновременной оптимизации токарной обработки стали с помощью многокритериальной вероятностной оптимизации (PMOO) продемонстрирована процедура выделения независимого атрибута из множества атрибутов с помощью PMOO.

Методы: РМОО является перспективным решением в токарной обработке. В оценке РМОО необходимо присутствие независимого атрибута, аналогичного независимому событию в теории вероятностей. Выделение независимого атрибута из множества атрибутов с помощью коэффициента линейной корреляции осуществляется на основании кластерного анализа. Далее предполагается, что если коэффициент линейной корреляции двух признаков при кластерном анализе превышает 0,8, т.е. в случае очень высокой корреляции, то их можно отнести к одной категории и только один из них может рассматриваться как независимый атрибут в оценке РМОО.

Результаты: Формулировка отражает суть РМОО и ее применения в механической обработке материалов, что открывает новые возможности для решения важной задачи. Пример оптимизации параметров точения стали с помощью РМОО свидетельствует о рациональности соответствующего решения.

Выводы: Это инновационное исследование имеет практическое значение, поскольку оно подчеркивает удобство использования методов РМОО, предоставляя рациональное правило для выделения независимых атрибутов из множества атрибутов РМОО.

Ключевые слова: многоцелевой подход, кластерный анализ, независимые атрибуты, коэффициент линейной корреляции, токарная обработка металла.

Евалуација окретања челика помоћу вишекритеријумске оптимизације на бази вероватноће са одговарајућим бројем атрибута

Маошенг Ценг[а], *Ђаи* Ју[б]

Универзитет Северозапад, Сијан, Народна Република Кина

[а] Факултет хемијског инжењерства, **аутор за преписку**

[б] Факултет природних наука и технологија

ОБЛАСТ: математика, материјали
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Окретање је типичан процес машинске обраде. Међутим, још није пронађено адекватно решење за истовремену оптимизацију свођења храпавости, сила резања и вибрација на најмању могућу меру уз највећу брзину уклањања материјала при процесу окретања. У овом раду формулише се правило за одвајање независног атрибута од вишеструких атрибута коришћењем *коефицијента линеарне корелације, најпре на основу кластер анализе. Штавише, на примеру евалуације истовремене оптимизације окретања челика помоћу вишекритеријумске оптимизације на бази вероватноће (РМОО) приказан је поступак одвајања независног атрибута од вишеструких атрибута њеним коришћењем.*

Методи: У прецесима окретања РМОО би могла бити добро решење. Неопходно је да постоји независни атрибут у евалуацији РМОО, слично независном догађају у теорији вероватноће. Одвајање независног атрибута од вишеструких атрибута помоћу коефицијента линеарне корелације врши се у складу са кластер анализом. Претпоставља се да ако је коефицијент линеарне корелације два атрибута у кластер анализи већи од 0,8, односно ако је корелација веома висока, тада они могу бити стављени у једну категорију, а само један од њих може, као независни атрибут, да се придружи евалуацији РМОО.

Резултати: Формулација одсликава суштину РМОО и њену примену у машинској обради материјала на рационалан начин, што отвара нове могућности за решавање битног проблема. Пример оптимизације параметара окретања челика помоћу РМОО указује на рационалност одговарајућег решења.

Закључак: Ова иновативна студија има практичан значај, јер истиче погодност коришћења метода РМОО, представљајући рационално правило за одвајање независних атрибута од вишеструких атрибута РМОО.

Кључне речи: вишекритеријумски, кластер анализа, независни атрибути, коефицијент линеарне корелације, окретање метала.

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