International Journal of Control and Automation
Vol. 7, No. 12 (2014), pp. 291-300
http://dx.doi.org/10.14257/ijca.2014.7.12.27

Complex Mechanical Equipment Manufacturing Scheme Optimization Based on Multi-attribute Fuzzy Information Measurement Model

Gang Yang[1,a], Kangwei Chen[2,b]

[1] College of Applied Science and Technology, China University of Mining and Technology,
Xuzhou, Jiangsu Province, China PR, 221008
[2] Xuzhou Technician College, Xuzhou, Jiangsu Province, China PR, 221000
Email:[a]ygcast@163.com, [b]Ckw1980@163.com

Abstract

Design of complex mechanical equipment and scheme of manufacturing need a comprehensive consideration of constraints, and it embodies multiple layers, complexity, multiple types and uncertainty. This paper analyzes the question of scheme optimization for complex mechanical equipment and proposes a method of manufacturing scheme optimization for complex mechanical equipment based on multi-attribute fuzzy information measurement model. This method functions to build an indicator system of optimization scheme for manufacturing complex mechanical equipment. Three models are designed to evaluate all optimization indicators of the system, namely model for computation of fuzzy interval indicator's information quantity, model for computation of qualitative indicator information quantity and model for computation of fuzzy indicator's information quantity with degree of membership. Weights are given to the information quantity of optimization of indicators in different layers to get the total information quantity of the complex mechanical equipment scheme and choose the optimal strategy based on the information quantity of design and manufacture.

Keywords: *mechanical equipment, manufacturing scheme, multiple attribute optimization, fuzzy information measure*

1. Introduction

The process of designing complex mechanic equipment involves a comprehensive consideration of several aspects, including requirement of the machine, design, manufacture, maintenance, protection of the environment, overall plan, the performance, parameter and collocation of the machine and so on. With different constraints and influences on the machine and uncertainty, these factors affect the final result of the machine scheme. Thus, to determine the optimal scheme of complex mechanical equipment, we have to consider social, technical, economic, repair/maintenance and environmental-friendly factors, which makes it a complex process with multiple layers and multiple attributes, as well as quantitative and qualitative indicators [1-3]. Many scholars have researched on decision analysis of the system with uncertainty and complexity and published related findings [4-7]. However, the current methods used to analyze the decision of complex and multi-attribute system with fuzzy design indicators are usually specifying fuzzy information before the optimization, which means in essence it is not fuzzy decision analysis and hinders the reliability of the result of optimization. Meanwhile, limitations exist in the complex system optimization regarding processing quantitative and qualitative indicators in the evaluation. This paper aims to solve the problem of analyzing complex mechanical equipment scheme optimization from the perspective of factor's information quantity of mechanical equipment scheme optimization.

2. Information Axiom

Axiomatic design theory is first brought up by professor Suh N P from Massachusetts Institute of Technology, U.S.A, and it is the application of Shannon's Information Theory in the field of complex mechanical design. It is a practical method to analyze decision and system of complex mechanical equipment design, and serves as a tool to evaluate optimization of complex mechanical equipment scheme. Information axiom is one of the two most important concepts of designing in the axiomatic design, and upholds that the best system is the one with the least information quantity of design indicators in the design and analysis process. Scholars have found breakthroughs in terms of evaluation and optimization of the complex system based on information axiom [8-12]. With previous findings, this paper provides an improved complex mechanical equipment scheme optimization method based on multi-attribute fuzzy information measurement model and proposes a new solution to the problem occurred in complex equipment scheme optimization.

Information Axiom: If different optimal indicators of the optimal indicator system are independent, the manufacturing scheme or design with least information quantity will be the optimal decision. Information quantity C_{inf} is determined by the logarithmic function of probability of meeting the requirement of the given design scheme, and it is

$$C_{inf} = -\log_2 P_i = \log_2 \left(1/P_i\right) \tag{1}$$

in which P_i is the probability of meeting constrains or requirements of the given design scheme.

When variables of meeting the design requirements are continuous random variables, results of corresponding probability density function $\rho\left(P\right)$ will distribute randomly, and probability P_i is

$$P_i = \int_{\beta}^{\alpha} \rho\left(P\right) dP = \rho \tag{2}$$

in which α and β represent the upper limit and lower limit of the probability of meeting parameters demand.

In the forming process of complex mechanical equipment scheme, probability P_i can also be determined by the overlapping area T of design scope D and project scope $S$of the scheme, which means that it could be calculated through the only area where the variables meet the requirements.

$$C_{inf} = -\log_2 P = \log_2 \left(1/P_i\right) = \log_2 \left(S\right) \tag{3}$$

3. Measurement Model and Algorithm of Information Quantity of Manufacturing Machine Tool Scheme

3.1 Optimal Indicator System of Complex Mechanical Equipment Scheme

Complex mechanical equipment scheme is a multi-layer, multi-attribute and complex comprehensive decision analysis process. Therefore, we should analyze from different aspects of the formation of the equipment scheme, which means it is required to consider the social, technical, economic, repair/maintenance and environmental-protection factors from the perspective of lifecycle.

After consulting the design expert in this field, I analyzed from the target layer, criterion layer and optimal indicator layer, and set social, technical, economic, repair/maintenance and environmental-friendly factors as optimal indicator system for complex mechanical equipment. Optimal indicators are listed in Table 1.

Table 1. Optimal Indicator System for Complex Mechanical Equipment

Target Layer	Criterion Layer	Indicator Layer
Optimal Indicator System for Complex Mechanical Equipment	Technical	System accuracy
		Carrying capacity
		Technology
		Assemblability
	Social	Reliability
		Security
		Compact structure
		Operability
		Environmental adaptability
	Economic	System efficiency
		Cost of design and production
		Service Life
	Environmental-friendly	Energy intensity
		Anti-contamination
		Shock and noise reduction
	Repair/ Maintenance	Maintainability
		Reconfigurability
		Testability

3.2 Computation Model for Information Quantity of Optimal Indicators with Fuzzy Interval

Suppose m complex equipment scheme meet the criteria of the design, and the corresponding measure of scheme i in terms of optimal indicator j is the fuzzy interval $v_{ij} = \left[v_{ij}(a), v_{ij}(b) \right]$, thus the standardization process of corresponding measure of fuzzy interval is

1)When optimal indicator of the complex mechanical equipment *j* is positive indicator, the standardized indicator value $u_{ij}=\left[u_{ij}(a),u_{ij}(b)\right]$ is

$$u_{ij}=\left[u_{ij}(a),u_{ij}(b)\right] \\ =\left(v_{ij}(a)/\max_{1\le j\le m}\left(v_{ij}(a),v_{ij}(b)\right),v_{ij}(b)/\max_{1\le j\le m}\left(v_{ij}(a),v_{ij}(b)\right)\right) \tag{4}$$

2)When the optimal indicator *j* is negative indicator, the standardized indicator value $u_{ij}=\left[u_{ij}(a),u_{ij}(b)\right]$ is

$$u_{ij}=\left[u_{ij}(a),u_{ij}(b)\right] \\ =\left(\min_{1\le j\le m}\left(v_{ij}(a),v_{ij}(b)\right)/v_{ij}(b),\min_{1\le j\le m}\left(v_{ij}(a),v_{ij}(b)\right)/v_{ij}(a)\right) \tag{5}$$

When optimal indicator of fuzzy interval is standardized, corresponding fuzzy distance $D\left(u_{ij}\right)$ of complex mechanical equipment scheme *i* in terms of optimal indicator *j* is

$$D\left(u_{ij}\right)=\sqrt{\frac{\left(\left|\max_{1\le i\le m}\left(u_{ij}(a)\right)-u_{ij}(a)\right|^2+|\max_{1\le i\le m}\left(u_{ij}(b)\right)-u_{ij}(b)|^2\right)}{2}} \tag{6}$$

Thus, the proximity $\psi\left(u_{ij}\right)$ of the scheme i in terms of optimal indicator *j* is

$$\psi\left(u_{ij}\right)=\left|1-D\left(u_{ij}\right)\right| \tag{7}$$

According to formula (7), the larger the $\psi\left(u_{ij}\right)$ is, the better the scheme i is in terms of optimal indicator *j*. In addition, the information quantity is the minimum, and the corresponding computation model for information quantity is

$$C_{inf}(ij)=\log_2\frac{1}{p}=\log_2 e^{1-\psi\left(u_{ij}\right)} \tag{8}$$

3.3 Computation Model for Information Quantity of Qualitative Optimal Indicator

If the optimal indicator *j* of complex mechanical equipment scheme is qualitative optimal indicator, we should transform qualitative language description into quantitative one. The fuzzy scaling method is used to achieve the transformation with the scale value from 0 to 1 (See Table 2).

Table 2. Evaluation Standards for Fuzzy Optimal Indicators 0-1

Optimal Indicators	Degree of importance
0	Irrelevant

0.2	Not important
0.4	Moderately important
0.6	Important
0.8	Very important
1.0	Extremely important
0.1,0.3,0.5,0.7,0.9	Intermediate value between each indicator

Suppose *m* complex mechanical equipment scheme meets the requirements, qualitative indicators are transforms according to the criteria in Table 2. If the corresponding value of complex mechanical equipment scheme *i* in terms of qualitative optimal indicator *j* is $v_{ij}=\left[v_{ij}(a),v_{ij}(b)\right]$, the information quantity computation model of corresponding qualitative optimal indicator *j* is

1)When complex mechanical equipment scheme optimal indicator *j* is optimal indicator, the larger the value of v_{ij}, the better the scheme *i* in terms of optimal indicator *j*. The information quantity is the minimum, and the corresponding computation model for information quantity is

$$C_{inf}(ij)=\log_2\frac{1}{p}=\log_2 e^{1-\frac{v_{ij}(a)+v_{ij}(b)}{2}} \tag{9}$$

2)When optimal indicator *j* is negative indicator, the smaller the value of v_{ij}, the better the mechanical equipment scheme *i* in terms of optimal indicator *j*. The information quantity is the minimum, and the corresponding computation model for information quantity is

$$C_{inf}(ij)=\log_2\frac{1}{p}=\log_2 e^{\frac{v_{ij}(a)+v_{ij}(b)}{2}} \tag{10}$$

3.4 Computation Model for Information Quantity of Fuzzy Optimal Indicator Based on Membership Degree

Some optimal indicator can get fuzzy membership degree function $\phi(v_{ij})$ with the application of related design theory or consultants from the experts in this field, which will be the continuous value in the scope of [0, 1], and information quantity of corresponding optimal indicator can be calculated with the membership degree function $\phi(v_{ij})$.

If optimal indicator is positive indicator, the larger the value of corresponding membership degree function $\phi(v_{ij})$, the better the complex mechanical equipment scheme i in terms of optimal indicator j, the smaller the information quantity. The computation model for information quantity is

$$C_{inf}(ij)=\log_2\frac{1}{p}=\log_2 e^{1-\phi(v_{ij})} \tag{11}$$

If this optimal indicator is negative indicator, the smaller the values of corresponding membership degree function $\phi\left(v_{ij}\right)$, the better the scheme i in terms of optimal indicator j the smaller the information quantity. The computation model for information quantity is

$$C_{inf}\left(ij\right)=\log_2\frac{1}{p}=\log_2 e^{\phi\left(v_{ij}\right)} \qquad (12)$$

To conclude, the standardized optimal indicator value of different type are all within the scope of [0, 1]. Thus, all optimal indicators have one standard, and the difference in evaluation between optimal indicators is eliminated, which functions to increase reliability and accuracy level of complex mechanical equipment scheme optimization.

3.5 Measurement Model of Multi-attribute Fuzzy Information and Algorithm Implementation of Complex Mechanical Equipment Scheme

Based on the axiomatic design theory, in the process of information quantity measurement analysis of complex mechanical equipment scheme, a hierarchical optimal indicator system which meets criteria of independent axiom should be built on the first hand. And with the information axiom, information quantity measurement computation model of optimal indicator, which is a hierarchical optimal measurement framework, is built to analyze mechanical equipment scheme of different types. Total information quantity measure of different types in each layer is got. Similarly, based on the total information quantity measure of optimal indicator from each layer, we can compute the information quantity measure of the scheme in the optimization system, which helps us to determine the best scheme among many designs based on the information quantity.

Thus, considering the weight w_j of optimal indicator in different criterion layer, the sum of information quantity of optimal indicator in different criterion layer is

$$C_{inf}^{\Sigma}\left(ij\right)=\sum_{j=1}^{n}\left(w_j * C_{inf}\left(ij\right)\right) \qquad (13)$$

Since different criterion layers have different weights, the system information quantity of optimal indicator in complex mechanical equipment scheme i in terms of all criterion layers is

$$C_{inf}^{\Sigma}\left(i\right)=w_T * C_{inf}^{\Sigma-T}\left(ij\right)+w_S * C_{inf}^{\Sigma-S}\left(ij\right)+w_E * C_{inf}^{\Sigma-E}\left(ij\right)+w_M * C_{inf}^{\Sigma-M}\left(ij\right)+w_P * C_{inf}^{\Sigma-P}\left(ij\right) \qquad (14)$$

in which $C_{inf}^{\Sigma-T}\left(ij\right), C_{inf}^{\Sigma-S}\left(ij\right), C_{inf}^{\Sigma-E}\left(ij\right), C_{inf}^{\Sigma-M}\left(ij\right)$ and $C_{inf}^{\Sigma-P}\left(ij\right)$ represent information quantity of technical, social, economic, repair/maintenance and environmental-protection criteria respectively, and w_T, w_S, w_E, w_M and w_P represent the weights of corresponding criterion.

According to the complex mechanical equipment scheme system, size of information quantity can determine the best scheme. Thus, if it satisfies

$$C_{inf}^{\Sigma}=min\left(C_{inf}^{\Sigma}\left(1\right), C_{inf}^{\Sigma}\left(2\right), \cdots, C_{inf}^{\Sigma}\left(m\right)\right)=C_{inf}^{\Sigma}\left(k\right) \qquad (15)$$

It means complex mechanical equipment scheme k with the smallest value of information quantity is the best.

4. An Example

In this section, a scheme of driving system equipment is analyzed as an example to explain the algorithm. Based on the design experience in this field, experience in design, theories and related techniques in designing and manufacturing, I get mechanical drive equipment scheme A_1 , fluid drive equipment scheme A_2 and electric drive equipment scheme A_3. Weights of optimal indicator and parameters based on the optimal indicator system are calculated (See

Table 3).

Table 3. Optimal Indicator System and Parameters

Criterion Layer	Weight	Indicator Layer	Weight	Parameter		
				A_1	A_2	A_3
Technical	0.28	System accuracy	0.30	0.90	0.93	0.95
		Carrying capacity	0.20	18	26	22
		Technology	0.30	0.93	0.90	0.90
		Assemblability	0.20	0.95	0.93	0.93
Social	0.18	Reliability	0.25	0.88-0.94	0.91-0.95	0.91-0.95
		Security	0.20	0.91-0.95	0.85-0.95	0.90-0.94
		Compact structure	0.20	0.91-0.95	0.85-0.95	0.93-0.97
		Operability	0.15	0.83-0.87	0.90-0.94	0.83-0.87
		Environmental adaptability	0.20	0.93-0.97	0.91-0.95	0.93-0.97
Economic	0.20	System efficiency	0.30	83-87	89-91	94-96
		Cost of design and production	0.30	8.00	11.00	12.50
		Service Life	0.40	7.50	10.80	14.60
Environmental-friendly	0.16	Energy intensity	0.35	0.83-0.87	0.91-0.95	0.93-0.97
		Anti-contamination	0.35	0.85-0.95	0.83-0.87	0.93-0.97
		Shock and noise reduction	0.30	0.83-0.87	0.85-0.95	0.91-0.95
Repair/ maintenance	0.18	Maintainability	0.40	0.85-0.95	0.85-0.95	0.91-0.95

		Reconfigurability	0.30	0.91-0.95	0.85-0.95	0.93-0.97
		Testability	0.30	0.83-0.87	0.83-0.87	0.91-0.95

According to the computation model for information quantity of optimal indicator and algorithm in this paper, we can get specific values (See Table 4).

Table 4. Specific Values Results

Criterion Layer	Indicator Layer	A_1		A_2		A_3	
		Indicator value	Criterion value	Indicator value	Criterion value	Indicator value	Criterion value
Technical	System accuracy	0.144	0.177	0.101	0.094	0.072	0.128
	Carrying capacity	0.444		0		0.216	
	Technology	0.101		0.144		0.144	
	Assemblability	0.072		0.101		0.101	
Social	Reliability	0.115	0.116	0.101	0.120	0.101	0.109
	Security	0.101		0.144		0.115	
	Compact structure	0.101		0.144		0.072	
	Operability	0.216		0.115		0.216	
	Environmental adaptability	0.072		0.101		0.072	
Economic	System efficiency	0.216	0.345	0.144	0.311	0.072	0.177
	Cost of design and production	0		0.394		0.519	
	Service Life	0.701		0.375		0	
Environmental-friendly	Energy intensity	0.216	0.191	0.101	0.154	0.072	0.081
	Anti-	0.144		0.216		0.072	

	contamination						
	Shock and noise reduction	0.216		0.144		0.101	
Repair/ maintenance	Maintainability	0.144	0.153	0.144	0.166	0.101	0.092
	Reconfigurability	0.101		0.144		0.072	
	Testability	0.216		0.216		0.101	

Considering weights of different criterion layer, we can get the overall information quantity of the system on three cases (See Table 5)

Table 5. Information for Equipment Plans

Equipment plan	A_1	A_2	A_3
Information	0.198	0.169	0.120
Ranking	3	2	1

We can see from Table 5 that the information quantity of scheme A_3 of electric drive equipment is the least, and it is the best scheme. The result is in accordance with the actual practice result of the scheme, which proves that the algorithm and model proposed in this paper are effective and feasible.

5. Conclusion

This paper proposes improved complex mechanical equipment optimal method based on multi-attribute fuzzy information measurement model. The method analyzes relevant restriction factors of complex mechanical equipment design plans and select specific evaluation system consisting of several criteria, including social, technical, economic, repair/maintenance and environmental-friendly factors. Meanwhile, on the basis of information axiom, the author proposes different criterion calculation models, quantitative criterion value calculation models and fuzzy indicator calculation models with membership for each type of optimal criterion. Different optimal criteria and weights are examined to obtain information of several equipment plans and select the best equipment plan. The method proposed in this paper is proven both feasible and effective through experiments.

References

[1]. H. Wang, G. Liu and Z. Yang, “Multi-criteria Comprehensive Evaluation Method of Mechanical Product Design Scheme”, Journal of Harbin institute of technology university, vol. 3, no. 46, **(2014).**
[2]. G. Wang, Y. Jia and Z. Guangwen, “Evaluation Method and Application of CNC Machine Tool's Green Degree Based on Fuzzy-EAHP”, Journal of Mechanical Engineering, vol. 3, no. 46, **(2010).**
[3]. P. Wang, D. Zhang and B. Chen, “Evaluation of Multi-process Plans Based on Fuzzy Comprehensive Evaluation and Grey Relational Analysis” Journal of Aerospace Power, vol. 9, no. 27, **(2012).**
[4]. F. Liu and G. Wei, “Fuzzy Optimization of Hydraulic Project Scheme Based on Improved Grey Relation Analysis”, Journal of Hydroelectric Engineering, vol. 1, no. 31, **(2012).**

[5]. F. Yang, M. Yang and L. Weidong, "Evaluation of Automobile Form Design Based on Fuzzy TOPSIS", Computer Integrated Manufacturing Systems, vol. 2, no. 20, **(2014).**
[6]. J. Wang, K. Fan and W. Wang, "Integration of Fuzzy AHP and FPP with TOPSIS Methodology for Aero Engine Health Assessment", Expert Systems with Applications, vol. 12, no, 37, **(2010).**
[7]. Y. Chen, U. Liu, and T. Liu, "Comprehensive Fuzzy Evaluation for Generalized Product Quality Based on Entropy Weight", Journal of Northeastern University, vol. 2, no. 31, **(2010).**
[8]. M, Ogot, "Conceptual Design Using Axiomatic Design in a TRIZ Framework", Procedia Engineering, vol. 9, **(2011).**
[9]. O. Kulak, M. B. Durmuşoğlu and C. Kahraman, "Fuzzy Multi-attribute Equipment Selection Based on Information Axiom", Journal of Materials Processing Technology, vol. 3, no. 169, **(2005).**
[10]. T. Wang, B. Chen and L. Bu, "Multi-attribute Optimal Selection Model of Large-Scale Hydraulic Turbine Scheme Design Based on Information Axiom", Journal of Nanjing University of Aeronautics & Astronautics, vol. 6, no. 43, **(2011).**
[11]. R. Zhang, Q. Jia and L. Meng, "Evaluation Method for Design Scheme Based on Fuzzy Information Axiom", Journal of Beijing University of Posts and Telecommunications, vol. 6, no. 35, **(2012).**
[12]. R. Xiao, X. Cheng and X. Liao, "Evaluation Method and Its Application for Design Scheme Based on Fuzzy Information Axiom", Computer Integrated Manufacturing Systems, vol. 12, no. 13, **(2007).**

Authors

Gang Yang, Aged 35, Doctor's degree working in College of Applied Science and Technology, China University of Mining and Technology. The major field is advanced design and manufacturing method. The address is College of Applied Science and Technology, CUMT, Xuzhou, Jiangsu Province, China PR.

Kangwei Chen, Aged 34, Master's degree working in Xuzhou Technician College. The major fields are design and manufacturing of mechanical equipment. The address is Xuzhou Technician College, Xuzhou, Jiangsu Province, China PR.