

Evaluating the performance of free-formed surface parts using an analytic network process

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Abstract. To successfully design parts with a free-formed surface, the critical issue of how to evaluate and select a favourable evaluation strategy before design is raised. The evaluation of free-formed surface parts is a multiple criteria decision-making (MCDM) problem that requires the consideration of a large number of interdependent factors. The analytic network process (ANP) is a relatively new MCDM method that can systematically deal with all kinds of dependences. In this paper, the factors, which come from the life-cycle and influence the design of free-formed surface parts, are proposed. After analysing the interdependence among these factors, a Hybrid ANP (HANP) structure for evaluating the part's curved surface is constructed. Then, a HANP evaluation of an impeller is presented to illustrate the application of the proposed method.

1. Introduction

As the global business competition environment becomes more intense, enterprises depend on new product development (NPD) for competitive advantage[1]. Most NPD budgets are committed during the design phase, before the actual work tasks take place. Adequate planning is one of the key factors required to satisfy project quality, to reduce financial and scheduled risks, and to help in the success of a project. The management of the planning phase of an NPD project is both significant and complicated. The evaluation of alternatives is the first basic step of product planning. The selection of alternatives can be used to direct the project planning process (e.g., project organization, budget, and schedule), which can determine the success of a project [2][3]. In the up-front design process, the systematic evaluation and verification of the design solution are critical since they could shift the product development paradigm from the traditional trial-and-error and heuristic know-how methods to more scientific calculation, analysis and simulation. Solution needs to be developed to ensure the efficient and accurate assessment and evaluation of design.

On the other hand, with the development of Group Technology and Mass Customization, the budget for common parts is reduced, while the budget rate for special parts rises sharply. These parts have a free-formed surface, which raises the difficulty of designing, manufacturing and testing, especially in the aviation industry, the mold industry, and the motor industry[4][5][6]. In this paper, multi-objects for free-formed surface part (FSP) evaluation are proposed, they are the designing performance, the manufacturing performance and the testing performance. Based on the multi-objects, a hybrid ANP model is established for FSP evaluation. The rest of the paper proceeds as follows. Section 2 provides a quick review of related literature. The ANP method is introduced in section 3. Then, the factors in FSP evaluation are analyzed in section 4. Established hybrid ANP evaluation



structure is discussed in section 5. Section 6 evaluated impellers as a case study. Finally, section 7 concludes the paper.

2. Literature review

Many studies have evaluated product performance. P. Duverlie used an analogical method to evaluate design based on cost [7]. The analogical method allows for a cost-evaluation of a product compared with the cost of existing products. Hsu-Fang Hung evaluated design alternatives in collaborative development based on cost, time and quality. Product strategy is identified as the most important factor in this evaluation [8]. R. Sharma developed a system according to the criteria of time and cost, which allows the designer to estimate manufacturability and also explore different scenarios of parametric variation in the design[9]. Shehab and Abdalla proposed a manufacturing cost estimation tool for conceptual design using a CAD system in conjunction with a process planning system to estimate cost and generate initial plans[10]. The evaluation criteria mainly focused on individual development stages, such as: design, manufacture, quality, and testing. Today, evaluation of a individual development stage is deeply researched (e.g., manufacturing design, client-oriented design, and quality-oriented design).

The evaluation of a individual development stage mainly focuses on one object (for function, manufacturability or cost). In the design stage, the designers pour their energy into product function. Engineers think about how to realize the scenario in the manufacturing stage. In testing, personnel hope that the performance is easy to test and that the criteria are independent of each other. The criteria for these stages are interdependent, however. Subsequently, product design problems are decomposed into sub-problems, which evaluate the many aspects of a large problem. This step involves specialized knowledge from many fields that cannot be mastered by a single designer. Different aspects of a problem should be modeled and solved by different people who have appropriate core competencies [11][12]. Separate evaluation of the performances in a single development stage causes difficulty in evaluating general performance, especially when the product contains free-surface parts like the impeller, bodyworks, and mold pocket, since there are different objects to be matched in different stages.

Several methods have been proposed in the literature for multi-objective decision making problems. When considering intangible factors, some authors suggest using an analytic hierarchy process (AHP). The analytic hierarchy process (AHP) was developed by Thomas Saaty in the early 1970s[13]. The strength of the AHP approach lies in its ability to hierarchically structure a complex, multiattribute, multiperson and multiperiod problem. In addition, it can also handle both qualitative (through representing qualitative attributes in terms of quantitative values) and quantitative attributes. Pairwise comparisons of the elements (usually, alternatives and attributes) can be established using a scale that indicates the strength with which one element dominates another with respect to a higher level element. This scaling process can be translated into priority weights (scores) for a comparison of alternatives. However, AHP is based on an independence assumption, ignoring the interdependence fact in solving those problems.

Hence, Satty modified the AHP into an ANP approach to counterweigh the demerit[14]. The ANP captures the interdependence of decision criteria and improves the limitation of AHP. There are many authors who have recently applied this technique in MCDM problems. For example, Meade et al. presents an overall systemic methodology, which includes ANP and utility theory, for making a business case for strategic alliance formation and justifying the conclusion that strategic relationships are a critical step in the case firm[15]. Sarkis integrated the environmentally conscious business practice elements and attributes into a strategic assessment and applied the systems using ANP[16]. This integration highlighted the importance of the natural environment in everyday and long term organizational practices and processes at a level that is unparalleled since the start of the industrial solution. Meade and Sarkis showed what lies in the linkage of disparate strategic logistics and system issues in a single systematic study framework[17]. Here, ANP not only provides solutions to strategic logistics alternative selection, but it also provides a structure for an organization to develop and

enhance logistics strategy. Wu and Lee used ANP to ensure the successful implementation of knowledge management[18]. They also raised the critical issue of how companies can better evaluate and select a favorable knowledge management strategy before that implementation. Thus, the ANP research method is most suitable and valid for this MCDM problem and interdependency relationships.

In this paper, we deal with FSP evaluation as a multi-objective decision making problem. First, the paper proposes three phases to build network systems for comprehensive evaluation. The authors' analyzed the evaluating factors of free-formed surface parts (FSP). Second, all the factors are classified into three layers. Third, the second layer is treated as the network layer, and a hybrid ANP model is established for FSP evaluation.

3. Principles of the ANP Method

3.1. The typical structure of an analytic network process

The typical network architecture is made up of two parts (shown as Figure 1). These parts include: (1) a control layer and (2) a network layer. In the control layer there are some decision-making criteria, like $P_1 \dots, P_i \dots P_m$. These elements are only controlled by the goal element, and can be divided into sub-criterion according to need. This means that the control layer can have many goal elements or only one. The other part is the network-layer. It contains some element clusters, such as $\{C_1 \dots, C_i \dots C_n\}$, here, C_i denotes element cluster $\{e_{i1}, e_{i2}, \dots, e_{im}\}$. The weights of the elements in the control-layer can be obtained by the AHP. In the network layer, they must be obtained via super-matrix.

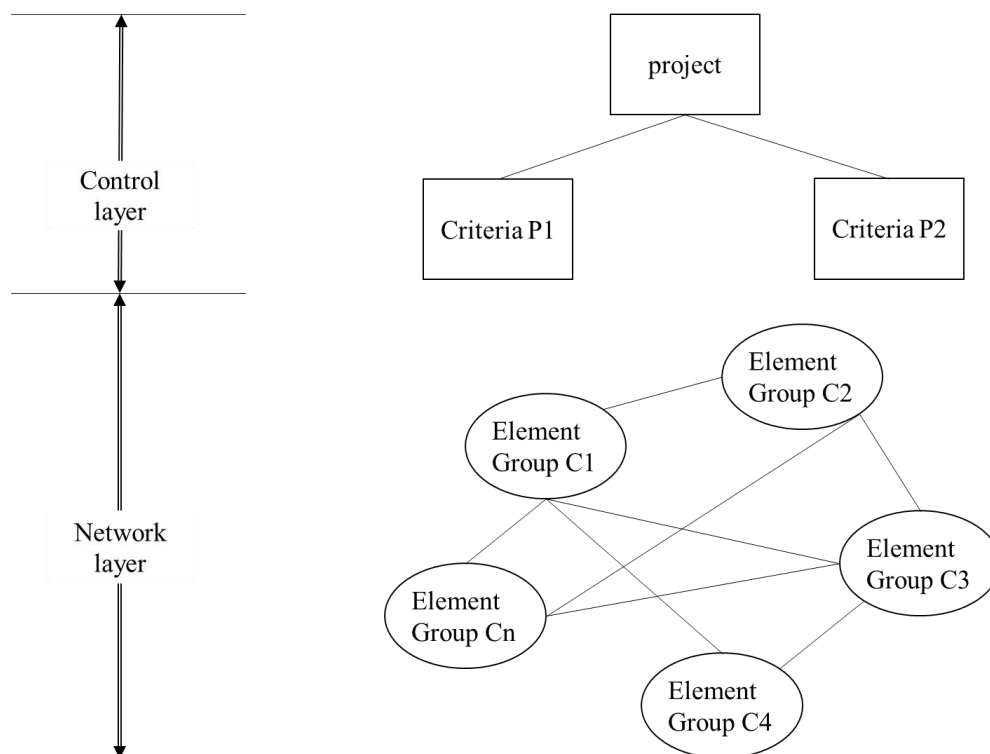


Figure 1. ANP structure.

The Analytic Network Process (ANP) provides a general framework for dealing with decisions without making assumptions about the independence of higher-level elements from lower level elements or the independence of the elements within a level (as in a hierarchy). In fact, the ANP uses a network without a need for special levels.

4. Analyse the Factors in FSP Evaluation

4.1. Evaluation criteria

These evaluation criteria are management focused and mainly evaluate the cost, delivery and quality, while it is difficult to control the result without controlling the process. In order to better evaluate the FSP, the criteria from the three development stages are proposed here.

Evaluation criteria come from three phases: (1) design process, (2) manufacturing process, and (3) test process.

The evaluation factors for the design performance of FSP include: S_1 hydromechanics, S_2 aesthetics, S_3 kinetics, S_4 toughness, S_5 other performance, S_6 fairing S_7 , free-formed surface shape, S_8 smoothing, S_9 the fairing of key section curve, S_{10} Gauss Curvature, S_{11} principal Curvature, S_{12} inflexion and Variable torsion Point, S_{13} mean curvature, S_{14} parameter continuity, S_{15} Geometric continuity, S_{16} curvature, S_{17} inflexion, S_{18} Variable torsion Point, S_{19} second derivative point, S_{20} control point, S_{21} weight factor, S_{22} node vector, S_{23} data points, S_{24} the number of data point, S_{25} the distribution of data point.

The reachable matrix among the criteria is established using a normative method after the matrix is hierarchically ordered, a sub-triangular matrix is elicited as shown in Figure 2.

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}
S_1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_7	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_8	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_9	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{10}	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{11}	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{12}	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{13}	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
S_{14}	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
S_{15}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
S_{16}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_{17}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
S_{18}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S_{19}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
S_{20}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
S_{21}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
S_{22}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
S_{23}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
S_{24}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
S_{25}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Figure 2. Criteria in the design process.

According to the above matrix (Figure 2), S_1, S_2, S_3, S_4, S_5 and S_6 belong to the first layer. $S_7, S_8, S_9, S_{10}, S_{13}, S_{14}$ and S_{14} belong to the second layer. S_{16}, S_{17}, S_{18} and S_{19} belong to the third layer, along with S_{20}, S_{21}, S_{22} and S_{23} . S_{24} and S_{25} belong to the sixth layer.

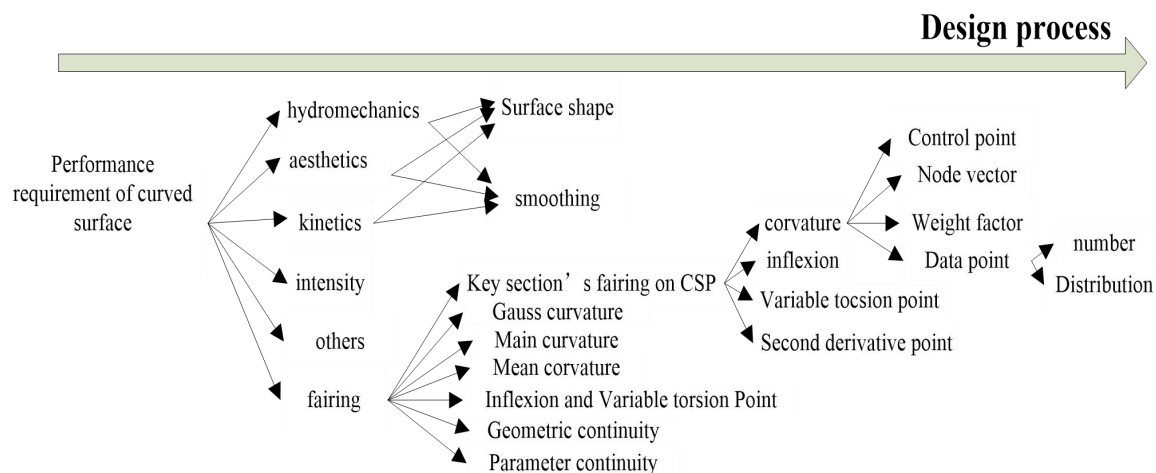


Figure 3. Criteria in the design process.

First, the above numerals elements were arrayed according to the mentioned hierarchy. The directed graph (DG) according to element “1” in the interchange place was then drawn. The hierarchical DG was then obtained, which presents the direct relationship of elements in different layers, similar to the above chart (Figure 3). The chart is a gradually specific design process from left to right. The criteria model in manufacturing and testing are set up at the same way, which is displayed in the following picture Figure 4.

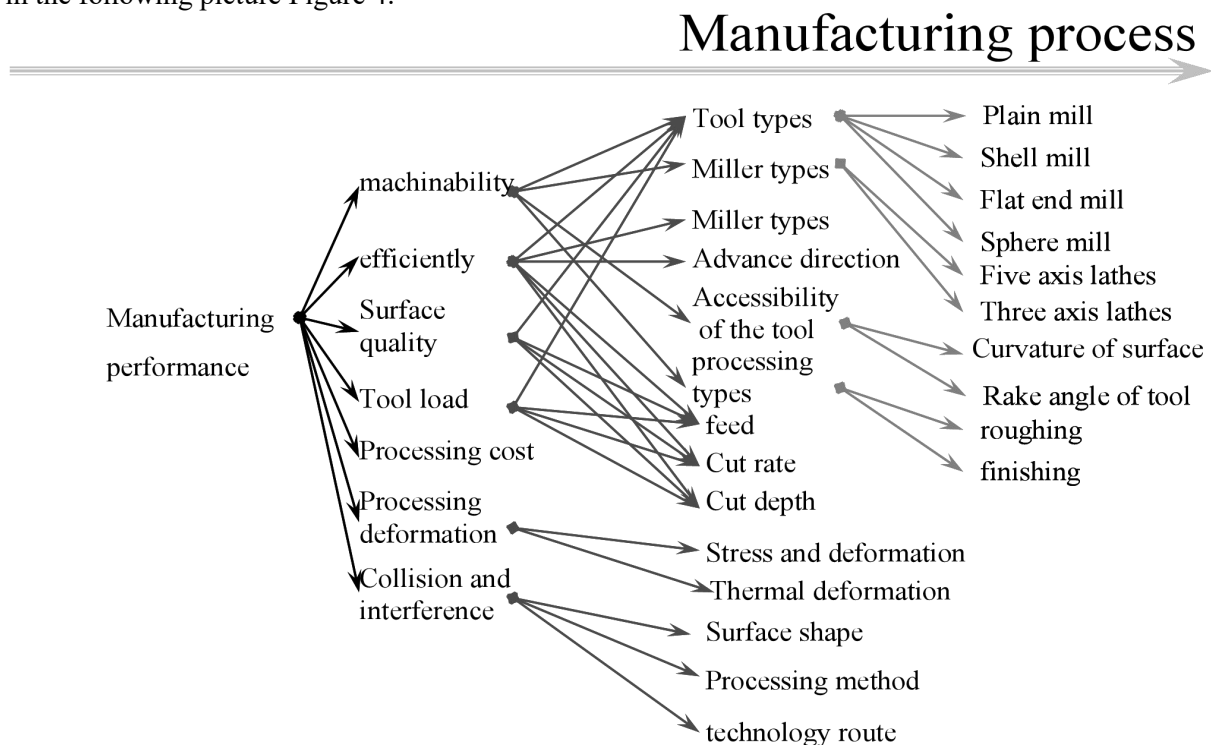


Figure 4. Criteria for manufacturing process.

The multi-level structured graph is shown in the following paragraph Figure 5.

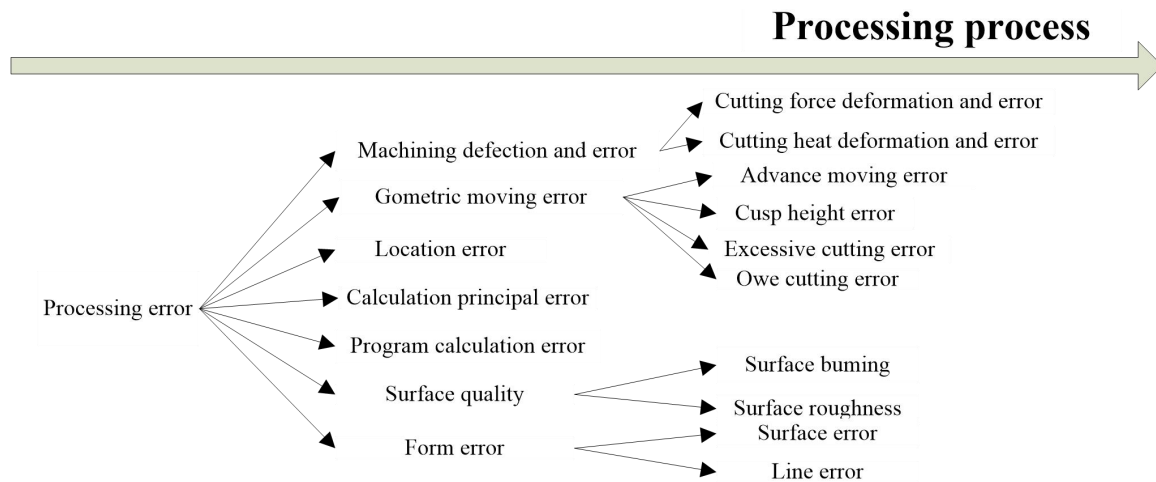


Figure 5. Criteria for processing error.

5. Hybrid ANP Structure for FSP Evaluation

This hierarchical system simply and intuitively describes the relationship of various indicators (factors in the lower classes dominated by the upper classes). It does not reflect interactions and interdependencies in the same class. ANP is an effective method to show the interdependence among criteria [19].

The ANP provides a more generalized model in decision-making without making assumptions about the independency of the elements within their own level. However, to evaluate the FSP, there are sixty-two criterions. Thus, ANP reduces the efficiency of the evaluation. Therefore, it is necessary to adjust the hierarchical system of the FSP and establish a mixed-network model according to the typical structure of ANP.

In this paper, according to the factors discussed in section 3, we treated the second layer criteria as the network layer, while the third layer and fourth layer were still in a hierarchical structure. We then set up a hybrid ANP structure.

5.1. Criteria and criteria clusters in the network

The control layer includes three criterion clusters: P_1 , P_2 , and P_3 . P_1 is the design performance of the free-formed surface. P_2 is the manufacturing performance. P_3 is the testing performance. The criteria in the paper are mainly the elements dominated by the control layer in the three processes of free-formed surface design, process, and test, which are classified into three groups according to the elements. The three element groups are: C_1 , C_2 , and C_3 . C_1 includes e_{11} hydromechanics, e_{12} aesthetics, e_{13} kinetics, e_{14} intensity, e_{15} other performance, and e_{16} fairing. C_2 includes, e_{21} machinability, e_{22} processing efficiency, e_{23} surface quality, e_{24} tool load, e_{25} processing cost, e_{26} processing deformation, and e_{27} collision and interference. C_3 includes e_{31} machining defection and error, e_{32} geometric moving error, e_{33} programs calculation error, e_{34} calculation principal error, e_{35} surface quality, e_{36} location error, and e_{37} form error.

5.1.1. The hybrid network modelling evaluation system on the basis of hybrid -ANP.

As shown in Figure 6, the satisfaction of the CSP is the overall object. The three criteria are: design performance, manufacturing performance, and testing performance. The control layer is formed by these three criteria.

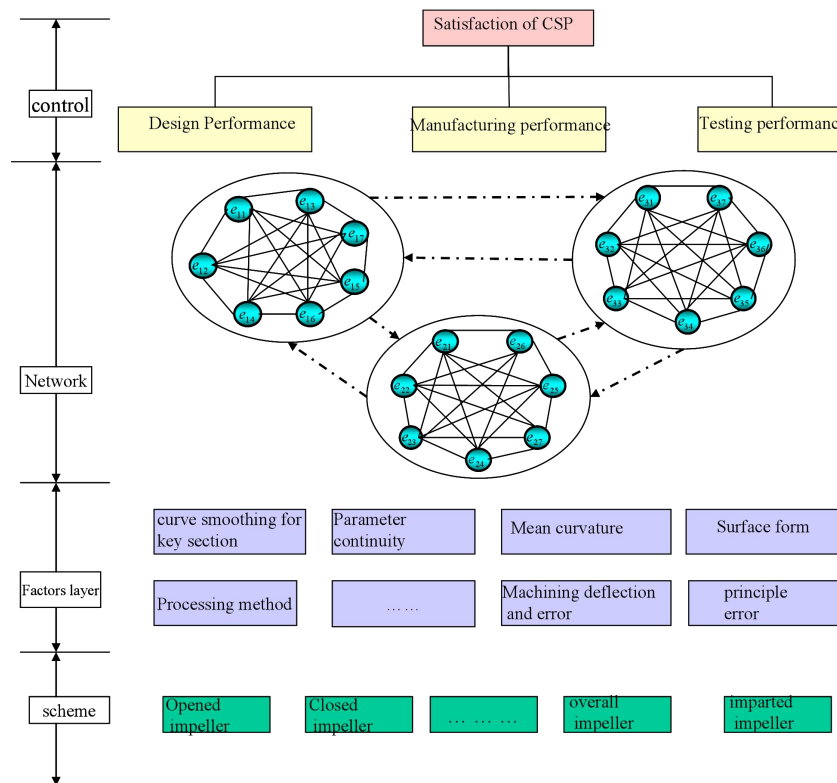


Figure 6. Hybrid ANP structure.

The three criterion clusters are formed by the elements of the second layer (design, process, and test). In the third and fourth layer, design, manufacturing, and test are named as factor levels. The framework of the factor level is still the hierarchical structure. The schemes are treated as the fourth layer, where mixed evaluation architecture is established.

5.2. Determining the total sort eigenvector

Table 1 is the sort eigenvector that is calculated according to the limit relative sort eigenvector in the criteria of the control layer and the criteria of the Network layer. In order to compare the evaluation results, the sort eigenvector is calculated by AHP in the table at the same time.

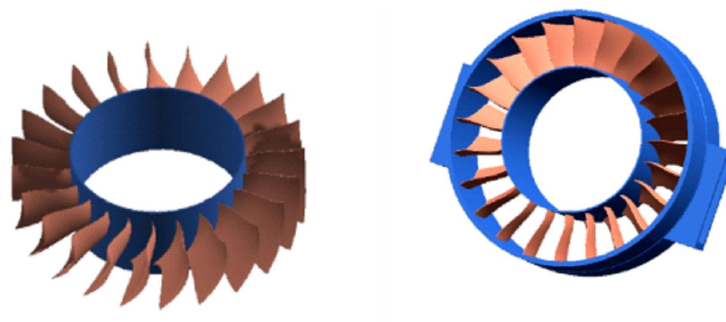
Table 1. Total sort eigenvector.

Sort eigenvector		Sort eigenvector on the criteria						Overall sort eigenvector	
Elements in the network layer	criteria	P ₁ W ₁ =0.4819		P ₂ W ₂ =0.4462		P ₃ W ₃ =0.0719		Project	
		ANP	AHP	ANP	AHP	ANP	AHP	ANP	AHP
C ₁	e ₁₁	0.0574	0.1146	0.0574		0.0542		0.0572	0.0552
	e ₁₂	0.0577	0.1126	0.0537		0.0785		0.0574	0.0543
	e ₁₃	0.0572	0.1795	0.0546		0.0761		0.0574	0.0865
	e ₁₄	0.0627	0.2027	0.0637		0.0707		0.0637	0.0977
	e ₁₅	0.0575	0.0478	0.0375		0.0425		0.0475	0.0230
	e ₁₆	0.0481	0.3428	0.0481		0.0481		0.0481	0.1652

C_2	e_{21}	0.0571	0.0571	0.2621	0.0571	0.0571	0.1169
	e_{22}	0.0509	0.0479	0.0899	0.0695	0.0509	0.0401
	e_{23}	0.0572	0.0602	0.2654	0.0386	0.0572	0.1184
	e_{24}	0.0412	0.0442	0.1160	0.0226	0.0412	0.0518
	e_{25}	0.0579	0.0429	0.0561	0.0119	0.0479	0.0250
	e_{26}	0.0445	0.0495	0.1104	0.0134	0.0445	0.0493
	e_{27}	0.0345	0.0305	0.1001	0.0593	0.0345	0.0447
C_3	e_{31}	0.0391	0.0391		0.0391	0.1156	0.0391
	e_{32}	0.0473	0.0753		0.1507	0.1395	0.0673
	e_{33}	0.0453	0.0403		0.0068	0.0539	0.0403
	e_{34}	0.0472	0.0602		0.0361	0.0779	0.0522

6. Real World Case Study

The impeller is a complex product with free-formed surface parts. Figure 7 shows two impeller schemes for one company. According to the ability in design, manufacturing and testing of the company, the performance of the opened impeller and closed impeller are comprehensively evaluated in accordance with the comprehensive sort eigenvector in table 1. The overall scores are calculated by ANP and AHP. If the dependency is omitted, the ANP model becomes an AHP model. The opened impeller scheme scores 5.1971441 by the ANP method and 5.521217 by the AHP method. The closed impeller scheme scores 5.388804 by the ANP method and 5.53628 by the AHP method. The ANP method is more distinct than the AHP. Furthermore, the ANP method takes the dependence of the element in the same layer into account. It is also reasonable at distributing the weight among criteria. The scores level is lower than the analytical method in evaluating the same scheme.



(a) Closed loop impeller

(b) Open loop impeller

Figure 7. Two kinds of impeller.

7. Conclusion

This paper presented various evaluation criteria for the design, manufacturing and testing of an FSP. According to the dominance relations and interdependence among the criteria, we established a hybrid Network evaluation system based on HANP and gave a comprehensive evaluation for the impeller scheme. Compared with the traditional method AHP, HANP considered the interdependence among the criteria in same layer, making the evaluation results more reasonable and the scheme easier to distinguish. In the evaluation system, the scoring system still uses a decimalist, which is constitutionally based on the score of specialists from different areas. This scoring system is difficult and inefficient at avoiding of subjectivism of specialists. Thus, the scoring system for design, manufacturing, and testing is the focus of further study.

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