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A decision approach with multiple interactive qualitative objectives for product conceptual schemes based on noncooperative-cooperative game theory

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ABSTRACT

Product development based on a morphological matrix involves the process of decision-based design. Although the decision process can generate conceptual schemes under the guidance of qualitative decision objectives, analysis of the interactions among the qualitative objectives is seldom considered, which can lead to unreliable optimal solutions by combining conflicting principle solutions. In addition, due to the ambiguity of the constraints among the qualitative objectives, multiple feasible schemes with equilibrium states are not considered in the concept decision stage. To solve these problems, a decision approach with multiple interactive qualitative objectives is developed for conceptual schemes based on noncooperative-cooperative game theory to consider the tradeoffs among objectives (e.g., cost, quality and operability) using discrete principle solution evaluation data. First, the morphological analysis method can obtain feasible schemes and determine the principle solutions for each subfunction. Second, the principle solutions are quantified using linguistic terms. Then, the subfunctions are categorized through cluster analysis to determine the suitable principle solution. Third, based on the clustering results, a noncooperative game decision model is constructed to identify multiple Nash equilibrium solutions that satisfy the constraints among the objectives. Fourth, a cooperative game decision model is constructed to obtain the optimal scheme as screened by the noncooperative game model. The case study proves that this approach can choose a relatively superior scheme under the existing technical conditions, thereby preventing inconsistency with the actual design expectations.

1. Introduction

In the conceptual design process, it is necessary to analyze the product subfunctions and choose an appropriate principle solution for each subfunction. Then, the design scheme can be obtained by combining all the subfunction principle solutions [1,2]. In the process of designing complex products, principle solutions can be effectively obtained to meet the design requirements and generate more combined schemes. Developing a morphological matrix is a simple and effective method of generating conceptual schemes, and it was first developed by Zwicky [3]. Conceptual design based on the morphological matrix is a multi-objective decision problem that must consider different combinations of contradictions to principle solutions and the impacts of the decision objectives [4]. Identifying the best scheme, however, is a challenge in the conceptual product design process [5,6].

Determining how to sort the conceptual schemes according to decision objectives is a common problem in the decision process [7]. Decision objectives are often derived from product function requirements that are established to meet the requirements of different customers and engineers in the conceptual design process [5,8]. If the above requirements are vague with limited information, some decision objectives are qualitative [9,10], such as 'reduce energy loss' and 'increase vibration stability'. Based on the existing design experience, these objectives have a certain involvement in the decision process [11]. For example, there are two decision objectives of 'cost' and 'quality' in the decision process associated with clothes hangers in our case study. The two objectives describe the manufacturing cost and transmission precision of clothes hangers. Cost and quality are positively correlated, and as the quality improves, the cost increases. The above situation will lead to the existence of links among the decision data for principle solutions. Determining how to quantitatively analyze

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the interactions among objectives and address the combined contradictions of principle solutions is a problem that must be solved.

Decision methods include the analytical network process [12], analytic hierarchy process [13], utility value analysis [14] and order of preference by similarity to the ideal solution [15] methods. In the above methods, it is necessary to determine the relative importance of the objectives, and the scheme is scored by experts and used in the ranking schemes. When conflicts exist among the qualitative objectives, it is difficult to describe the impacts of the objectives with a single-weight ranking for the schemes because this approach cannot ensure that the global optimal scheme is effective. Some approaches have been developed to identify the best scheme considering conflicting objectives in the conceptual design stage [16]. Such methods include the normal constraint method [17,18] and evolutionary multiobjective optimization [19]. Among these methods, multiple objective optimization is generally transformed into single objective optimization with new objective constraints, and single objective optimization is performed in the new constraint space to solve the conflicting problem between objectives. However, these methods are more often applied to quantitative objectives that have a clear constraint space. In such cases, it is necessary to determine whether the distribution of benefits under each objective meets the qualification constraints. The decision process should balance the interests of each objective, and the process cannot focus solely on the overall design expectations. This decision process is similar to a game decision, which is a process of multiple objective tradeoffs through the coordination of different objectives among the contradictions to obtain a balanced solution [20]. Noncooperative game theory, which incorporates rational game analysis, has been applied to solve the above decision problem [21]. When the interactions among qualitative objectives are qualitative, it is impossible to accurately describe the relationships between objectives and determine the best scheme. Avoiding design conflicts by balancing the benefits of various objectives is a viable way to ensure that the benefits of each objective are achieved. Moreover, as a decision regarding conceptual schemes, the principle solution evaluation data in each scheme are associated with a discrete point, and this approach will result in discrepancies among scheme decision results. To avoid the resulting error caused by unclear constraints among objectives, other discrete solutions around the optimal solution are selected by determining a feasible interval to improve the reliability of the game decision process for the decision makers. Then, all the combined schemes in a certain equilibrium state are treated as similar multiple feasible solutions in a noncooperative game. According to the overall goal of product design, it is possible to ensure the uniqueness and reliability of the decision result. In the cooperative game process, benefits can be allocated based on the design requirements considered by the customers to obtain the optimal scheme [22]. This optimal scheme satisfies not only the distribution of interests for each decision objective but also the overall interest distribution for the important objective decision.

Unlike previous decision methods used to evaluate the principle solutions based on a morphological matrix, a decision approach based on game theory is proposed in this study to analyze the discrete evaluation data of principle solutions and improve the interest conflicts among objectives and the reliability of the principle solution combinations. The proposed quantification subfunction and clustering analysis aim to clarify the interrelationships among decision objectives and the principle solutions. Then, an equilibrium solution model based on noncooperative game theory is used to select the suitable principle solution combinations that satisfy the relative constraints among the various interactive qualitative objectives. Cooperative game theory is used to seek a relatively superior scheme closest to the overall design desirability. The decision model is a compromise decision idea that considers how to avoid design conflicts given the existing design requirements. The remaining sections in this paper are as follows. Section 2 presents a brief review of the related work. Section 3 describes the implementation of the noncooperative-cooperative game decision model. Section 4 is a case study of a conceptual scheme decision process for clothes hangers. Section 5 presents the discussion and conclusions.

2. Related work

Conceptual scheme evaluation is a multicriteria decision making (MCDM) process that considers many different design factors [23]. Various methods, such as the Analytic Hierarchy Process (AHP) method [23,24], Principal Component Analysis (PCA) [25], Delphi method [26] and Simple Multi-attribute rating Technique (SMART) [27], can be used to effectively determine the weights of decision criteria. The AHP decomposes decision problems, and the weight of each objective is calculated to identify the scheme that satisfies the relevant requirements. PCA is mainly based on the concept of dimensionality reduction to convert multiple indicators into a few comprehensive indicators and determine the associated indicator weights. The SMART method is based on a decision support system that is applied by assigning weight values for each criterion. The above methods involve the processing of decision data to assess the relative weights assigned to various objectives. In general, according to the predetermined linguistic variables, the expert judgment information for each scheme under the decision objectives is analyzed to quantify the data [28,29].

Because conceptual schemes often include qualitative information, many methods have been applied to rank schemes, such as the simple additive weighting method (SAW) [30], the Višekriterijumska Optimizacija I kompromisno Rešenje (VIKOR) method [31], the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) [32], ELimination Et Choix Traduisant la Realité (ELECTRE) [33], and others. The SAW method ranks schemes by determining the multicriterion weight, which is easily influenced by decision maker preferences. In the TOPSIS and VIKOR methods, it is necessary to find an ideal solution, which is generally referred to as the highest assignment for each decision objective. To improve the reliability of the ideal solution, Zhang and Gong [34] proposed data-driven performance prediction that sequenced multiple attributes through the VIKOR method to obtain a ranking of design alternatives. Chen and Lin [35] evaluated the importance of an electronic product function menu through the AHP and the similarity between the scheme solution and ideal solution based on TOPSIS to rank design alternatives. ELECTRE is a decision method based on a precedence relation; it defines the ordering of the scheme by defining different values of the harmony threshold to meet customer needs [36]. To improve the credibility of the evaluation result, improve data effectiveness and precisely capture the perspective of decision makers, many hybrid methods have been developed [37]. For example, Huang et al. [38] analyzed the hierarchical design problem based on both fuzzy theory and the computational intelligence technique to obtain an optimal design scheme. Zhu et al. [39] proposed a method for concept evaluation based on rough numbers in a fuzzy environment. The above integrated decision techniques can reduce the ambiguity and inaccuracy of the decision results of a scheme.

During the conceptual design process based on the morphological matrix, choosing the right principle solution for each subfunction is the core of scheme decision making. Multiple design objectives (e.g., low costs, high quality, and other factors) should be considered, and the evaluation process of the scheme is also a strategy selection problem [40]. When qualitative objectives are interconnected, each objective cannot have a principle solution that only meets its own interests and neglects the constraint relationships of other objectives. Therefore, the application of game theory to the above situation provides a method for guiding the principle solution selection process among decision objectives. That is, objectives act as players in a game and seek a compromise through negotiation to maximize each interest as much as possible [41].

Game method has been commonly applied to address multi-objective engineering problems. Rao and Freiheit [42] first proposed the application of game theory to mechanical product multi-objective decisions for ambiguous multiobjective design optimization. Vincent [43]