

*Review*

## MULTICRITERIA DECISION ANALYSIS: A MULTIFACETED APPROACH TO MEDICAL EQUIPMENT MANAGEMENT

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**Abstract.** Selecting medical equipment is a complex multidisciplinary task requiring mathematical tools, considering associated uncertainties. This paper offers an in-depth study of multiple-criteria decision analysis (MCDA) methods to identify the most appropriate ones for performing management tasks in resource-limited settings. The chosen articles were divided into three topics: evaluation of projects and equipment, selection of projects and equipment, and development of medical devices. Three methods (analytic hierarchy process [AHP], multi-attribute utility theory and elimination and choice expressing reality) were selected for detailed analyses of their application for medical equipment management. Twenty-one work using MCDA, artificial neural networks, human factors engineering, and value analysis were analysed in the framework of medical equipment management. The important aspects of the procedure were described, highlighting their advantages and disadvantages. It was determined that the AHP approach corresponds to all defined criteria for selecting large medical equipment. Managing large medical equipment using MCDA will reduce uncertainties, and provide a rational selection and purchase of the most efficient equipment in resource-limited settings. The direction for improving the AHP method was determined.

**Keywords:** analytic hierarchy process, decision theory, multi-criteria decision making, operations research, procurement, medical technologies.

**JEL Classification:** C44, C65, D81, H57.

### Introduction

Technological progress and innovation are generally considered to be the main drivers of economic growth in advanced economies. In addition, medical technology is specifically credited for raising the expectancy and quality of life (Willemé, Dumont 2013). At the same time, it is also commonly considered to explain the surge in health expenditures in recent decades (Willemé, Dumont 2013).

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In general, health spending in OECD (Organisation for Economic Co-operation and Development) countries grew on average by close to 5% year-on-year from 2000 to 2009; this has since been followed by a sluggish growth of around 0.5% in 2010 and 2011. Current expenditure on health (i.e. excluding capital expenditure) grew by 0.7% in both years. Preliminary figures for some countries suggest a continuation of this trend in 2012. Health spending accounted for 9.3% of GDP on average across OECD countries in 2011, compared with 9.5% in 2010. Excluding capital spending, current expenditure on health as a share of GDP dropped from 9.1% on average in 2010 to 9.0% in 2011 (OECD 2013).

According to Willemé and Dumont calculations based on 18 OECD countries data from 1981 to 2009, medical technological change accounted for as much as 69% of the explained growth of total real per capita health expenditures over the 1981–2009 period (Willemé, Dumont 2013). Since they did not attempt to correct for medical price inflation, this estimate is probably biased upward. There is ongoing discussion in the literature to this issue. The overview of the estimated impact of the expenditures drivers is presented in the Table 1. There is a commitment that the technologies accounting the highest share but the assumptions varied considerably.

Table 1. Contributions of selected factors to growth in health care spending in %

Author/s	Di Matteo, L.	Jones, C. I.	Pricewaterhousecoopers	Smith, S. D., et al.	Peden, E. A., et al.	Cutler, D. M.	Newhouse, J.
<b>Technology</b>	~65	50–75	25	38–62	70–75	49	>65
Administrative costs	*	*	15***	3–10	*	13%	*
Changes in financing	*	*	*	10	4–5	10	10
Health care prices	*	*	18	11–22	*	19%	*
Life expectancy/aging	~9	*	15**	2	6–7	2	2
Personal income growth	9–20	*	*	11–18	14–18	5	<23

Notes: \*Not estimated; \*\*included aging, but also “front page treatments” (i.e. media coverage drives demand for expensive treatment), increased preventive and diagnostic activity, and consumers moving away from less expensive managed care products; \*\*\*included government mandates (including new mandated benefits) and federal and state regulatory requirements.

Source: Sorenson et al. 2013.

Reports published by the World Health Organization (WHO) indicate that the rising financial costs in the global system of public health are caused by mistakes in the control system and misuse of funds (World Health... 2010b). The paramount reasons for financial losses, as stated by WHO, are the malfunction of the acquisition system, and misuse and poor control of technical resources (World Health... 2010b).

The need to create a system for the rational management of large medical equipment at medical institutions worldwide has become of prime importance. This is due to several reasons, including the undeveloped management systems for large medical equipment, the rapid growth of large medical equipment markets and financial markets (Skinner 2013; World Health... 2013), and the high volume of medical equipment that is partially or fully unfit for use, accounting for 50% globally, and as high as 80% in some countries (Voronin 2003). One of the most crucial questions in creating the management system for medical equipment concerns the identification of the appropriate method.

The purpose of this paper is to identify multiple-criteria decision analysis (MCDA) methods which can be applied to the task of medical equipment selection. The article identifies advantages and weaknesses of some of the MCDA methods and suggests methods for improving the most appropriate methods.

A search of the literature was conducted using the following databases: CINAL, IEEE Explore, MEDLINE, PsycINFO, PubMed, ScienceDirect, SpringerLink, and Wiley Online Library. A combination of the following key words and phrases were inputted into these databases: Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Elimination and Choice Expressing REality (ELECTRE), Goal programming, Grey relation analysis, Markov process, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VIseKriterijumska Optimizacija (VIKOR), and related words. The Medical Subject Headings controlled vocabulary thesaurus was used.

## **1. MCDA: applications in medical equipment management**

Multicriteria decision analysis (MCDA) is widely used in economics (Zavadskas, Turskis 2011). MCDA has been used to support decision making in healthcare management (Table 2) and also in many others fields like road networks planning (Zolfani *et al.* 2011), portfolio management (Fotr *et al.* 2013), creative industries analysis (Slach *et al.* 2013). Steps are being taken to identify the main parameters and to issue recommendations, as well as to create various models to reduce the risks in making managerial decisions in healthcare (World Health... 2010b). On one hand, modern materials describing decision making (World Health... 2010a) do not go beyond defining the need for the new equipment, replacement of the old one, and the abilities of a medical institution. On the other hand, some tools reveal the most critical technical parameters (Lerski *et al.* 2010) that are sufficient for the equipment to fulfil its clinical tasks.

### **1.1. Selection of projects and equipment**

The methodological recommendations for the purchase of medical equipment (Angelo 2009) include a range of organizational and technical questions that the decision maker (DM) needs to answer in the process of choosing the equipment.

The MCDA techniques have been used (Table 1) in both evaluation and selection of projects and equipment. Balestra *et al.* (2007) applied the analytic hierarchy process (AHP) to support the acquisition of pacemakers and implantable defibrillators. Chatburn and

Table 2. MCDA applications for medical equipment management

Field of application	Author/s / Year	The method	The decision-making framework
Selection of projects and equipment	Balestra <i>et al.</i> 2007	AHP	evaluation of the quality and selection of cardiac pacemaker
	Chatburn, Primiano 2001		selection of a medical ventilator
	Cho, Kim 2003		selection of consumables and medical devices
	Pecchia <i>et al.</i> 2013		selection of a CT
	Montevechi <i>et al.</i> 2010		selection of an ultrasound imaging device
	Sloane 2004		selection of a neonatal ventilator
	Hummel 2001		evaluation of an artificial cardiac valve
	Mundzhed 2008		selection of electrocardiographs for first-aid stations
	Arikan, Kucukce 2012	AHP, PROMETHEE II	evaluation and selection of suppliers
	Velmurugan, Selvamuthukumar 2012	ANP	selection of the most suitable procedure for preparing nanoparticles
	Santos, Garcia 2010	AHP, MAFMA, ELECTRE	creation of a decision-making model for acquiring medical equipment
	Ferreira Ramírez, Calil 2007	Artificial neural networks	medical equipment purchasing
	Ginsburg 2005	Human factors engineering	selection of a general-purpose infusion pump
	Feldstein, Brooks 2010	Value analysis	optimized purchase of laparoscopic equipment
Evaluation of projects and equipment	Rocha <i>et al.</i> 2005	AHP	selection of services for medical devices
	Sloane 2004		healthcare technology assessment
	Büyüközkan <i>et al.</i> 2011		evaluation of healthcare service quality
	Wollmann <i>et al.</i> 2012		assessment of healthcare services by consumers
	Topacan <i>et al.</i> 2009		evaluation of users' preference about health service
	Ni <i>et al.</i> 2002	PROMETHEE, GAIA	evaluation of nanoparticles enrichment
Development of medical devices	Li <i>et al.</i> 2011	AHP	procedure for developing the design of medical devices

Source: Own compilation based on the literature review.

Primiano (2001) used AHP for selecting and purchasing intensive care ventilators. Cho and Kim (2003) employed AHP for selecting 88 medical products and materials for development in Korea. Pecchia *et al.* (2013) designed a CT scanner selection based on 12 specifications. Montevechi *et al.* (2010) used AHP for ultrasonic scanning system selection in private hospitals in Brazil. Sloane (2004) showed how to build a neonatal ventilator evaluation model. Arikian and Kucukce (2012) applied AHP and the preference ranking organization method for enrichment evaluation (PROMETHEE II) for evaluating criteria and suppliers to minimize economic losses from the inadequate assessment of suppliers. Santos and Garcia (2010) used AHP, Multi-Attribute Failure Mode Analysis (MAFMA) and ELECTRE to demonstrate a decision model for incorporating indicators in the acquisition of hospital medical equipment. Velmurugan and Selvamuthukumar (2012) employed the ANP to assess and select the most appropriate procedure for preparing nanoparticles.

Human factors engineering, which included a heuristic evaluation of instruments and was supplemented by results of end-user testing, made it possible (Ginsburg 2005) to determine the strongest and weakest points of infusion pumps. The negative side is that this method cannot be used for evaluating all types of equipment due to its prohibitive use of time, and human and financial resources. The data obtained could be used as a guide for design changes and modifications of medical devices.

The paper (Ferreyra Ramírez, Calil 2007) described the possibility of using neural networks as the means of artificial intelligence to provide knowledge to experts (clinical engineers) for evaluating offers of medical equipment. The disadvantages of this method are twofold. First, this model only has an 85% reliability (Ferreyra Ramírez, Calil 2007). Second, in the real world, this model requires numerous iterations and the cooperation of consultants experienced in dealing with such tasks, such as doctors, nurses and managers. The experts' competence was not evaluated in the paper, and therefore the value of opinions expressed by the authors could not be taken into account.

This fact can influence the reliability of the final selection results. Value analysis to optimize the purchase of medical equipment (laparoscopic equipment) was also applied (Feldstein, Brooks 2010). This paper demonstrates that value analysis can be used to develop a model of comparing equipment to be purchased. The model is based on complex costs and known results of deployment of the instrument in clinical practice, and takes into account the economical parameters of healthcare institutions and medical service providers. The limitations of applying this model stem from the disadvantages of the method in question: the process of describing functions can prove excessively detailed; the model is oftentimes too complicated and difficult to support; a quality realization of the model requires special software; and organizational changes often render the model obsolete. The possibility of applying methods of multicriteria analysis to the evaluation and selection of medical equipment and instruments was illustrated in the evaluation of the artificial cardiac valve using AHP (Hummel 2001). The evaluation was based on clinical, economical, social and technical parameters of cardiac valves. Specialists, namely, developers, manufacturers and doctors (cardiologists and thoracic surgeons) have been chosen as experts for the sake of the interdisciplinary task. The research result was a ranked list of cardiac valves, headed by the valve that proved the most

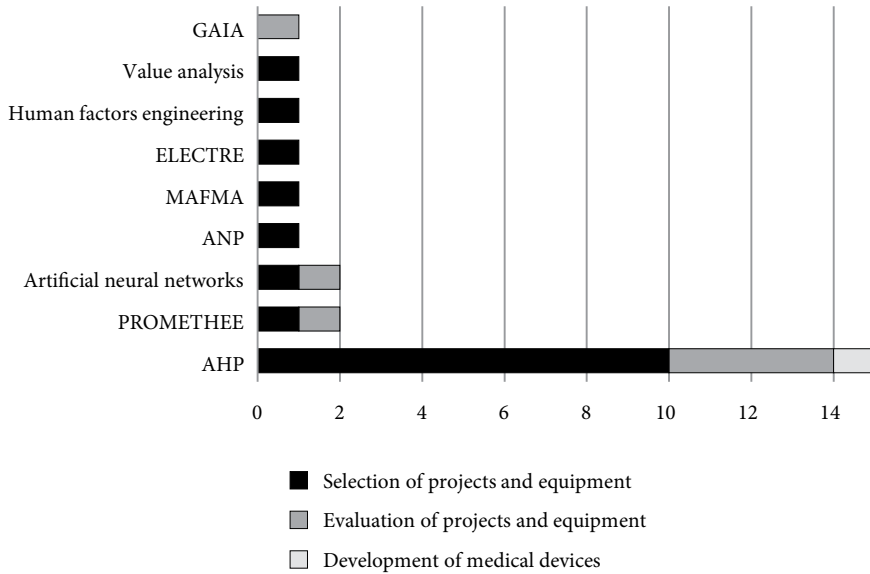


Fig. Use of MCDA methods for management of medical equipment

rational choice within the framework of the given task. Another paper (Mundzhed 2008) that followed a similar logic studied the issue of rational selection of electrocardiographs for first-aid stations.

The application of AHP offered the option that conformed to the technical specifications put forward by experts. The Figure presents the use of MCDA methods for management of medical equipment.

### 1.2. Evaluation of projects and equipment

Attempts have been made (Feldstein, Brooks 2010; Ferreyra Ramírez, Calil 2007; Ginsburg 2005; Hummel 2001) to apply well-known methods to evaluate and select various kinds of medical products.

The AHP has often been applied to the evaluation of projects and medical equipment. Sloane (2004) described a framework to evaluate maintenance service modalities for medical equipment within the decision support system based on AHP. Büyüközkan *et al.* (2011) applied a fuzzy AHP to develop a decision-making model that can help evaluate the perceived service quality in some pioneer Turkish hospitals. Wollmann *et al.* (2012) used AHP to assess the quality of services offered by health service providers, according to consumers' perceptions. Topacan *et al.* (2009) used AHP to evaluate users' preferences about health service. Ni *et al.* (2002) applied PROMETHEE and geometrical analysis for interactive aid (GAIA) for ranking of computational methods, accompanied by a first derivative pre-treatment of the spectral data matrix as the preferred performing method.

## 2. Criteria for choosing MCDA methods

Initially, in selecting an MCDA method, the number of choices under evaluation is very important. Certain tasks, especially in design and engineering, can have an unlimited number of options. Provided the number of choices is finite, in principle, the magnitude of this number is irrelevant. However, it is essential to bear in mind that each option to be considered must be evaluated to determine how it corresponds to the criteria. While selecting an MCDA method, it should be understood that the resources spent on data processing depend on their volume.

The following can be used as criteria for selecting an MCDA method: internal conformity and logical validity; transparency; user-friendliness; data requirements that do not contradict the importance of the issue under examination; correlation among available time, human resources, and resources needed for given methods; possibility to perform check analysis; and software availability, if needed (Dodgson *et al.* 2009). Besides, the method should be as close as possible to the natural, intuitive process typical of humans (Linkov *et al.* 2006b).

## 3. General comparison of MCDA methods

Table 3 and Table 4 describe the methods used for performing multicriteria tasks in decision-making. These tables show that multi-attribute utility theory (MAUT) and AHP are the most complex. This is due to the use of optimization algorithms, which are not present in outranking methods. Methods applying optimizing approaches use numerical evaluations to determine the advantages of each choice (alternative) on the same scale. Eventually, the derived sets are the result of evaluations combined into a cumulative score of choices and individual criteria. Individual evaluations are summed or averaged; a weighting mechanism can also be introduced to bring out the greater significance of certain criteria against others.

The advantage of MAUT is that it is based on a utilitarian theory, as well as a mathematical theory that enables validating an exact form of general utility function, depending on the DM's preferences (Larichev 2002). In return, utility maximization need not be important for the DM and can be considered as a drawback of MAUT. The aim of MAUT is to find a simple expression to determine the most beneficial solution. At the same time, identifying the strict preferences of the parties concerned takes a long time and financial losses. A significant disadvantage (Dodgson *et al.* 2009; Linkov *et al.* 2006b) of the method is a presumption that the DM is capable of performing precise quantitative measurements of quality. The DM's goal in MAUT lies in utility maximization. It is associated with the fact that certain low-evaluated criteria can be compensated for by the high estimation of the other criteria. Therefore, MAUT belongs to the group of multicriteria decision-making methods known as "compensational" (Linkov *et al.* 2006b).

The method's advantage is its application in the presence of a large number of choices, achieved with the ease of carrying out the comparison procedure. In turn, the result of applying the method (Larichev 2002) enables the evaluation of any choices (including newly emerged ones).

Table 3. Comparison of MCDA Methods

Method	Important elements	Advantages	Disadvantages
AHP	Values of weight-coefficients and general evaluation result from paired comparisons of criteria and choices (Linkov <i>et al.</i> 2006b).	User-friendliness of the application (Formav, Gass 2001; Charouz, Ramík 2010). Paired comparisons are easy to perform (Charouz, Ramík 2010; Linkov <i>et al.</i> 2006b). Targeted at comparison of real choices (Santos, Garcia 2010). Axiom of homogeneity and hierarchical decomposition principle bring into accord the problem of receiving evaluations with human psychometric abilities (Linkov <i>et al.</i> 2006b; Wollmann <i>et al.</i> 2012). Determines the quality index quantitatively (Larichev 2002). Provides for checking expert information for lack of contradictions (Saaty 2000). Does not require mathematical models (Brauers, Zavadskas 2012; Linkov <i>et al.</i> 2006b).	Critics point out that weight-coefficients obtained through paired comparisons do not necessarily reflect a DM's real preferences (Linkov <i>et al.</i> 2006b). Mathematical procedures can produce illogical results (Brauers, Zavadskas 2012; Linkov <i>et al.</i> 2006b; Saaty 2000). This is a heuristic approach and does not guarantee that a DM's preferences are presented correctly (Larichev 2002; Linkov <i>et al.</i> 2006b).
MAUT	Weight-coefficients are often determined by direct evaluation of choices against an absolute scale (Linkov <i>et al.</i> 2006b). A utility function is constructed which is axiomatically (purely mathematically) based (Larichev 2002). Usually, tasks from the second group are solved and the results are used for evaluation of given choices (Larichev 2002).	Scientific proof is based on a utilitarian theory (Linkov <i>et al.</i> 2006b). The presence of a mathematical theory can validate a specific view of general utility function, depending on a DM's preferences (Larichev 2002). Applying the method enables the evaluation of any choices (including newly emerged ones) (Larichev 2002). Can be applied to many choices (Larichev 2002).	Utility maximization does not have to be important for a DM (Formav, Gass 2001). Weight-coefficients of criteria provided during a survey by persons with a low interest can result in discrepancy with participants with a high interest (Linkov <i>et al.</i> 2006b). Determining strict preferences of interested parties leads to high expenses (Linkov <i>et al.</i> 2006b). The method presumes that a human can perform precise quantitative measurements of quality indexes (Larichev 2002; Linkov <i>et al.</i> 2006b). Requires much time and effort from a DM (Linkov <i>et al.</i> 2006b).



Continued Table 3

Method	Important elements	Advantages	Disadvantages
OUTRAKING (ELECTRE)	One option over another if: "it outperforms the other on enough criteria of sufficient importance (as reflected by the sum of criteria weights)" and it "is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion" (Linkov et al. 2006b). Allows for classification of choices as "disparate" (Linkov et al. 2006b).	A staged discovery of a DM's preferences (Larichev 2002). The decision rule is not defined beforehand but is changed during the process to take into account a DM's opinion (Larichev 2002). Does not require all criteria to be combined into one block (Linkov et al. 2006b). An explicit examination of a situation in which a very low effectiveness of one criterion can exclude a choice, even if this low value is compensated for by very good indexes for other criteria (Linkov et al. 2006b).	Only a condition of supremacy of one choice over another is established (Larichev 2002). The fact that a high weight of one criterion can compensate for a low weight of another one is not always considered (Linkov et al. 2006b). The algorithm does not have to reflect a DM's true preferences (Linkov et al. 2006b). Results are difficult to interpret (Brauers, Zavadskas 2012; Larichev 2002; Linkov et al. 2006b).

Source: Own compilation based on the literature review.

Both MAUT and AHP methods aggregate different aspects of solving the optimization function, i.e. the target function (Angular 2009). The goal of AHP is to select the best choice that exhibits the highest values of the target function. Both AHP and MAUT are used in the compensational optimization approaches. However, unlike MAUT, which is based on evaluations of usefulness or weight functions, AHP uses paired comparisons of each criterion, which creates a matrix of paired comparisons. The application of AHP, as distinct from MAUT, rests on a successful assumption that a human is more capable of performing a comparative analysis (Table 4) rather than producing absolute evaluations, when experts (or DMs) cannot give absolute evaluations according to criteria and revert to weaker comparative measurements. Critics point out that weight-coefficients obtained through paired comparisons do not necessarily reflect a DM's real preferences (Linkov et al. 2006b). Notwithstanding this, the paired comparisons allow AHP to effectively solve a range of practical tasks (Hummel 2001; Linkov et al. 2006a; Mundzhed 2008). Hence, due to a rational presumption about comparative measurements (Linkov et al. 2006b) and the fact that the method does not require mathematical models (Formav, Gass 2001), AHP is a less stressful method for evaluation participants, compared to MAUT (Larichev 2002).

Unlike MAUT and AHP, methods from the outranking family, to which ELECTRE belongs, are based on a principal supposition that one choice can have a degree of supremacy over another (Formav, Gass 2001; Larichev 2002). The ELECTRE method is significantly different from the previously described methods, vis, the decision rule used to make a selection from existing choices, is not determined beforehand, but is changed based on the DM's opinion.

During this process, the DM changes the algorithm parameters, depending on the properties of the considered task, and thus reaches the most acceptable result for him/her (Larichev 2002; Lotov, Pospelova 2008).

Table 4. Comparison of MCDA methods respect to defined criteria

Criteria	AHP	MAUT	OUTRANKING (ELECTRE)
Problem decomposition	hierarchy	no	no
Evaluation criteria	obtain the mechanism for evaluation	requires an assessment of evaluation	requires an assessment of evaluation
Subjectivity	large	large	large
User-friendliness			
Organization of a research	easy	difficult	difficult
Need time period	short	long	long
Processing of an obtained result	easy	difficult	difficult
Resources needed (time)	smaller	bigger	bigger
The issue of incomparability of alternatives	no	no	yes
Closely reproduces natural, intuitive, and human typical process of defining priorities	yes	no	no
Algorithm for combining of expert groups opinions	no	no	no

Source: Own compilation.

Dominance becomes apparent when one choice is more effective than another on at least one criterion is not worse than others on all criteria. Outranking methods presume that a situation can occur in which the best choice shall not be discovered. The drawback is that it is not always taken into account that a high weight of one criterion can compensate for a low weight of another. To define and affirm the level of a certain alternative's advantages over the other one, outranking models evaluate the effectiveness of two (or more) alternatives concerning combined criteria.

Thus, these methods collect composite information about preferences for all existing criteria and determine the supremacy of one choice over another. For example, these methods can determine the best choice if it possesses a large number of outstanding criteria.

On the other hand, outranking models are known as “partially compensational”; these methods are more suitable for cases when the criteria metrics are difficult to aggregate, the measuring scales show wide variations, and the values are incommensurable or disparate (Linkov *et al.* 2006a, b). Unlike other multicriteria evaluation methods, outranking methods possess peculiarities that allow them to solve the issue of disparate choices. This feature becomes especially important when choices become disparate due to certain circumstances (Wang *et al.* 2009).

## Conclusions

Based on the analysis of the possibility of applying MCDA methods, it was determined that the AHP approach corresponds to major defined criteria for the selection of medical equipment. The AHP method closely reproduces the natural, intuitive and typically human process of defining priorities. This is achieved through the axiom of homogeneity and the hierarchical

decomposition principle, which brings the problem of receiving evaluations in line with a human's psychometric abilities. Moreover, the process and results of the AHP application are the easiest to understand, when compared to other previously discussed technologies. The AHP method can address the issue of the rational selection and purchase of medical equipment by healthcare institutions at all levels of the organization. This is because it compares real choices, which allows ranking according to priorities and selecting the best. It does not require constructing mathematical models and it can be used for solving problems under uncertain conditions, such as, undoubtedly, those posed by the selection of medical equipment. The analysis showed that all of the methods explored have a significant drawback. For example, the reviewed methods do not have a mechanism for combining the opinions of the expert groups; also, the analysed methods do not take into account the competence of experts in the task of rational selection of medical equipment. These weaknesses should be eliminated in the process of improving the AHP method.

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