

3/2026,
may-
iyun
(№ 00083)



HIERARCHICAL EXPERT-BASED ASSESSMENT OF FACTORS AFFECTING THE OPERATIONAL EFFICIENCY OF MEDICAL EQUIPMENT

Talat Magrupov

Department of Biomedical Engineering. Tashkent State Technical University named after Islam Karimov. Tashkent, Uzbekistan

Email: talatmt@rambler.ru

Maloxat Magrupova

Department of Biomedical Engineering. Tashkent State Technical University named after Islam Karimov. Tashkent, Uzbekistan

Email: maloxatmagrupova@gmail.com

Seit Abdihalikov

Department of Intellectual Systems. Joint Belarusian-Uzbek Intersectoral Institute of Applied Technical Qualifications in Tashkent. Tashkent, Uzbekistan

Email: seit-abdihalikov@rambler.ru

Abstract

This study presents a comprehensive methodology for evaluating the operational efficiency of medical equipment based on a hierarchical expert model and the Analytic Hierarchy Process (AHP). The proposed approach integrates technical, operational, and organizational factors into a unified quantitative indicator. A structured algorithm for expert assessment, consistency control, and weight coefficient calculation is developed. The methodology is validated using computed tomography (CT) systems as a case study. The results demonstrate that equipment reliability and technical condition exert dominant influence on operational efficiency. The proposed framework provides a systematic and reproducible tool for supporting technical management decisions in healthcare institutions.

Keywords: medical equipment, operational efficiency, expert evaluation, analytic hierarchy process, reliability, computed tomography.

ИЕРАРХИЧЕСКАЯ ЭКСПЕРТНАЯ ОЦЕНКА ФАКТОРОВ, ВЛИЯЮЩИХ НА ЭКСПЛУАТАЦИОННУЮ ЭФФЕКТИВНОСТЬ МЕДИЦИНСКОГО ОБОРУДОВАНИЯ

Аннотация В данном исследовании представлена комплексная методология оценки эксплуатационной эффективности медицинского оборудования, основанная на иерархической экспертной модели и методе анализа иерархий (АНР). Предлагаемый подход

интегрирует технические, эксплуатационные и организационные факторы в единый количественный показатель. Разработан структурированный алгоритм экспертной оценки, контроля согласованности и расчета весовых коэффициентов. Методология апробирована на примере систем компьютерной томографии (КТ). Результаты показывают, что надежность и техническое состояние оборудования оказывают определяющее влияние на эксплуатационную эффективность. Предлагаемая модель представляет собой систематический и воспроизводимый инструмент для поддержки решений по техническому менеджменту в медицинских учреждениях.

Ключевые слова: медицинское оборудование, эксплуатационная эффективность, экспертная оценка, метод анализа иерархий, надежность, компьютерная томография.

Introduction

The operational efficiency of medical equipment is a critical determinant of healthcare quality, safety, and accessibility. Modern diagnostic and therapeutic processes heavily rely on advanced medical devices, including computed tomography (CT), magnetic resonance imaging (MRI), angiographic systems, and clinical laboratory analyzers. Any disruption in equipment performance leads to increased diagnostic delays, elevated operational costs, and potential clinical risks [1–3].

Recent studies indicate that up to 40–60% of medical devices in developing healthcare systems operate below optimal performance levels due to inadequate maintenance strategies, limited technical expertise, and insufficient management frameworks [4,5]. The operational efficiency of medical equipment is governed by a multifactorial system involving reliability, technical condition, preventive maintenance quality, personnel competence, metrological control, and infrastructure compatibility [6–9].

Several authors have emphasized the critical role of preventive maintenance and reliability-centered management in reducing downtime and improving equipment availability [10–12]. Bahreini et al. identified more than 80 influencing factors grouped into seven principal categories, demonstrating that managerial and organizational aspects significantly affect maintenance outcomes [6]. Kutor et al. reported that nearly 70% of medical equipment failures are attributed to deficiencies in preventive maintenance systems and staff training [7].

Despite extensive research, existing methodologies often focus on isolated parameters and lack integrated evaluation frameworks. Multi-criteria decision-making methods have therefore gained increasing popularity. Among these, the Analytic Hierarchy Process (AHP), introduced by Saaty, provides a robust theoretical basis for combining expert judgment with quantitative analysis [13–15]. AHP has demonstrated high effectiveness in engineering diagnostics, asset management, and healthcare decision support.

However, comprehensive hierarchical models tailored to the operational characteristics of medical equipment remain insufficiently explored. This study aims to fill this gap by developing a structured methodology for the integrated assessment of medical equipment operational efficiency using hierarchical expert modeling.

The objective of this study is to design, formalize, and validate a hierarchical evaluation framework capable of generating a reliable quantitative indicator of medical equipment operational efficiency.

Materials and Methods

2.1. Conceptual Framework

The proposed methodology is based on hierarchical decomposition of operational efficiency into a structured system of factors, followed by expert evaluation using AHP. The general algorithm is presented in Figure 1.

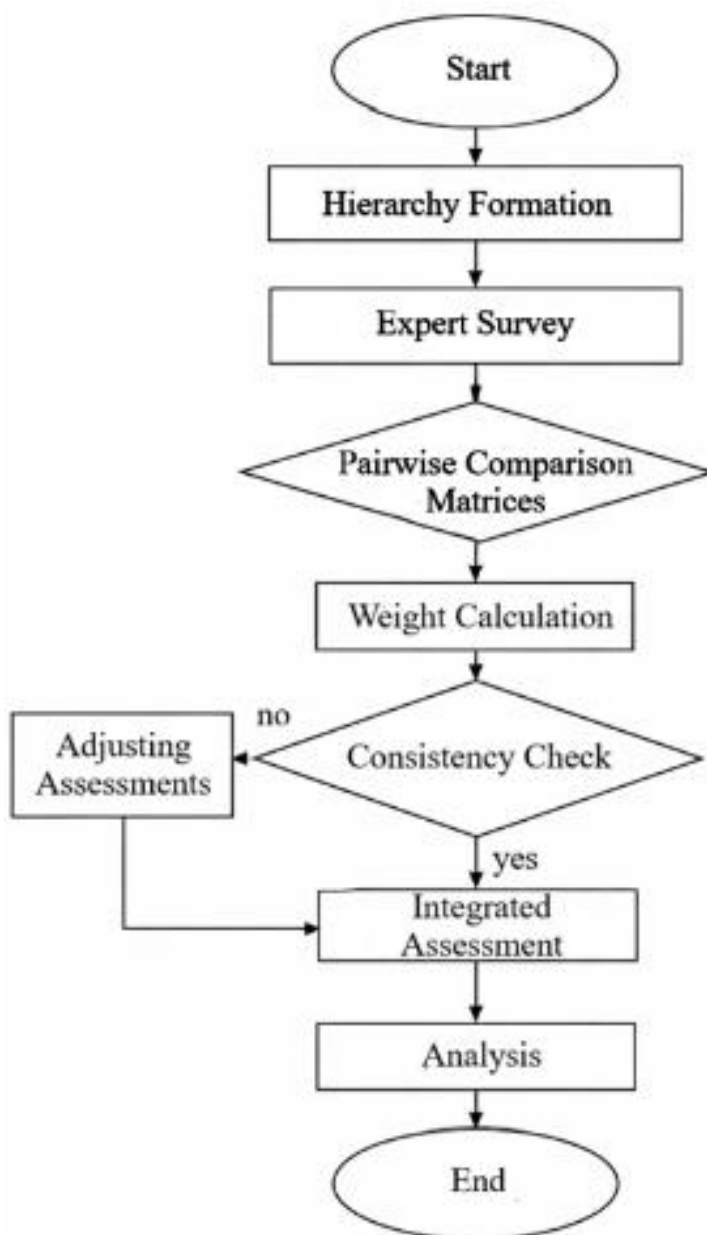


Figure 1. Flowchart of the operational efficiency assessment algorithm.

Figure 1 presents the flowchart of the comprehensive evaluation algorithm for assessing the operational efficiency of medical equipment based on a hierarchical expert model and the Analytic Hierarchy Process.

The algorithm begins with defining the evaluation objective and selecting the medical equipment type. This is followed by identification of key efficiency criteria through literature review and expert consultations. Subsequently, an expert panel is formed and a structured questionnaire is designed for conducting pairwise comparisons.

The collected expert judgments are used to construct pairwise comparison matrices, from which local and global priority vectors are derived. Consistency of expert evaluations is

verified by calculating the consistency ratio. If the obtained value exceeds the acceptable threshold, expert judgments are revised and the assessment procedure is repeated.

The final stage involves computation of the integral efficiency index, ranking of influencing factors, and interpretation of the results to support evidence-based management decisions.

2.2. Hierarchical Model Construction

Based on literature analysis [1–12] and expert consultations, a three-level hierarchical model was developed:

Level 1: Overall operational efficiency.

Level 2: Groups of influencing factors.

Level 3: Individual technical and organizational indicators.

The selected key factors are presented in Table 1.

Table 1.

Factors affecting medical equipment operational efficiency

Code	Factor
F1	Equipment reliability
F2	Technical condition
F3	Maintenance quality
F4	Metrological control
F5	Software reliability and updates
F6	Spare parts availability
F7	Engineering infrastructure compatibility

The hierarchical structure of the model is illustrated in Figure 2.

Figure 2 illustrates the hierarchical structure of factors influencing the operational efficiency of medical equipment.

At the top level, the model defines the overall objective, namely, the integral assessment of equipment operational efficiency. The second level comprises major groups of criteria, including technical reliability, diagnostic performance, operational safety, economic efficiency, and human factors.

The third level consists of detailed subcriteria that quantify each group of factors. This hierarchical decomposition enables systematic analysis, ensures logical consistency of expert evaluations, and enhances the objectivity and interpretability of the results.

The proposed hierarchical model is adaptable to various categories of medical equipment and operational conditions, thereby providing a versatile decision-support tool for healthcare engineering management.

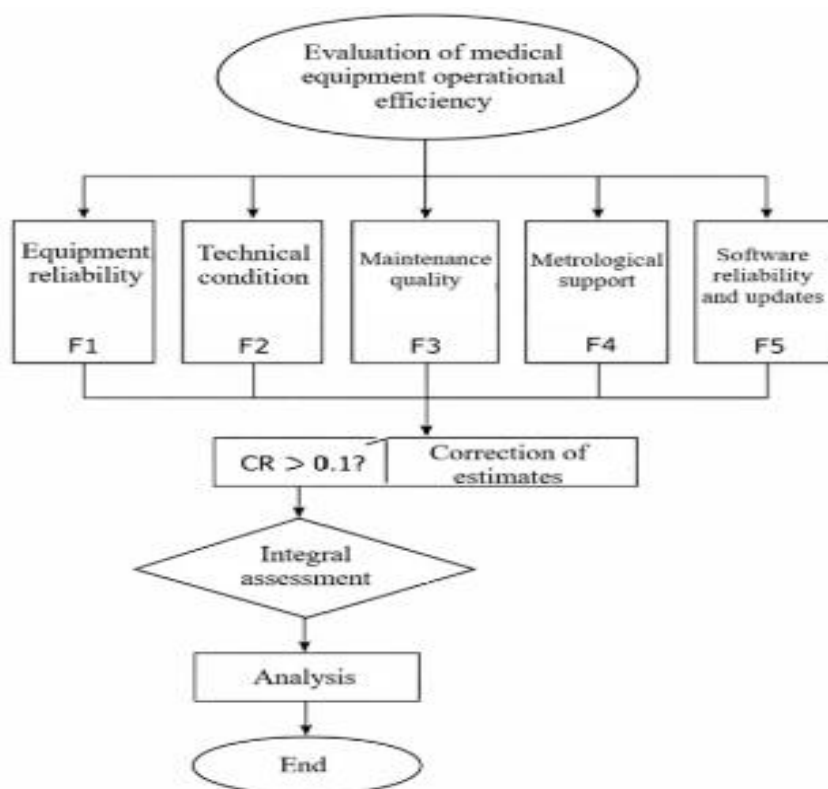


Figure 2. Hierarchical model of operational efficiency assessment.

2.3. Expert Evaluation and Pairwise Comparison

Expert assessment was conducted by a panel of 12 specialists with at least 7 years of experience in biomedical engineering and medical equipment maintenance. Pairwise comparisons were performed using Saaty's fundamental 1–9 scale.

The pairwise comparison matrix is defined as:

$$A = [a_{ij}], \quad a_{ij} = \frac{w_i}{w_j}$$

The priority vector is obtained by solving:

$$A \cdot w = \lambda_{\max} \cdot w$$

The normalized eigenvector yields weight coefficients.

The normalized priority vector was computed using the geometric mean method:

$$w_i = \frac{(\prod_{j=1}^n a_{ij})^{1/n}}{\sum_{k=1}^n (\prod_{j=1}^n a_{kj})^{1/n}}$$

2.4. Consistency Verification

Consistency of expert judgments was evaluated using the consistency ratio (CR):

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

RI is the random index (Table 2). Acceptable consistency requires $CR \leq 0.10$.

Table 2.

Random Index (RI) values.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.5. Integral Efficiency Indicator

The overall operational efficiency index was calculated as:

$$E = \sum_{i=1}^n w_i \cdot s_i$$

where: w_i – weight coefficient of factor i ;

s_i – normalized performance score of factor i .

3. Results

The expert evaluation produced the weight coefficients shown in Table 3.

Table 3.

Weight coefficients of efficiency factors.

Factor	Weight
Reliability (F1)	0.26
Technical condition (F2)	0.22
Maintenance quality (F3)	0.18
Metrological control (F4)	0.11
Software reliability (F5)	0.09
Spare parts availability (F6)	0.08
Infrastructure compatibility (F7)	0.06

The calculated consistency ratio was $CR = 0.047$, indicating high consistency.

The computed integral efficiency index for the investigated CT systems ranged from 0.68 to 0.87, corresponding to satisfactory to high operational efficiency levels.

Discussion

The results indicate that reliability and technical condition are the most significant determinants of medical equipment operational efficiency. This finding aligns with previous studies emphasizing reliability-centered maintenance as a cornerstone of effective healthcare technology management [6,7,10].

Maintenance quality and metrological control also exert considerable influence, confirming the necessity of systematic preventive maintenance programs and periodic calibration. Software reliability is increasingly important due to the growing complexity of diagnostic algorithms and system integration.

The proposed hierarchical model allows transparent prioritization of resource allocation and supports evidence-based decision-making in healthcare engineering management. Compared to conventional single-parameter evaluation methods, the developed approach provides a more comprehensive and objective assessment.

Conclusion

A hierarchical expert-based methodology for assessing the operational efficiency of medical equipment has been developed and validated. The proposed framework integrates technical, operational, and organizational factors into a unified quantitative index.

The methodology demonstrates high reliability, consistency, and adaptability to different categories of medical devices. Its application can enhance maintenance planning, improve resource utilization, and reduce operational risks. Future research will focus on extending the model to predictive maintenance and digital twin-based monitoring systems

List of used literature

1. World Health Organization. Medical equipment maintenance programme overview. Geneva: WHO; 2011.
2. Taghipour S, Banjevic D, Jardine AKS. Reliability analysis of medical equipment. *Reliability Engineering & System Safety*. 2011;96(10):1335–1345.
3. Wang B, Levenson A. Equipment management strategies. *Journal of Clinical Engineering*. 2013;38(3):147–153.
4. Perry L, Malkin R. Effectiveness of medical equipment maintenance. *Medical Engineering & Physics*. 2011;33(5):580–587.
5. Temple-Bird C, et al. How to manage medical equipment. *Health Policy and Planning*. 2005;20(1):30–38.
6. Bahreini R, et al. Factors affecting medical equipment maintenance. *Health Policy and Technology*. 2019;8(4):333–344.
7. Kutor J.K, et al. Maintenance challenges in medical devices. *Frontiers in Public Health*. 2021;9:782203.
8. M.T. Magrupova, P.M. Matyakubova, T.M. Magrupov and S.P. Abdihalikov, "Methods for Increasing and Assessing Reliability of Medical Equipment," 2020 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, – 2020. – P. 1-3, doi: 10.1109/ICISCT50599.2020.9351382.
9. T. Magrupov, S. Yusupov, Y. Talatov and M. Magrupova, "Intelligent Medical System of Designing Medical Technics and Technology," 2020 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, – 2020. – P. 1-4, doi: 10.1109/ICISCT50599.2020.9351375..
10. Swanson L. Linking maintenance strategies to performance. *International Journal of Production Economics*. 2001;70(3):237–244.
11. Alsayouf I. Cost effective maintenance. *Journal of Quality in Maintenance Engineering*. 2007;13(3):252–270.
12. Ben-Daya M, et al. *Handbook of Maintenance Management and Engineering*. London: Springer; 2009.
13. Saaty T.L. *The Analytic Hierarchy Process*. New York: McGraw-Hill; 1980.
14. Saaty T.L. Decision making with the AHP. *International Journal of Services Sciences*. 2008;1(1):83–98.
15. Ishizaka A, Labib A. Review of the AHP. *Expert Systems with Applications*. 2011;38(11):14336–14345.