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Decision-Making Framework for Medical Equipment Maintenance and Replacement in Private Hospitals

Siti Hajar Salim[1], Siti Aisyah Salim[2*]

[1]VAMED Engineering (M) Sdn Bhd, Plaza Flamingo,
Jalan Hulu Kelang, 68000 Ampang Jaya, Selangor, MALAYSIA

[2]Faculty of Technology Management and Business,
Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, MALAYSIA

*Corresponding Author

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Abstract: The process for medical equipment maintenance and replacement in hospitals is a challenging and demanding procedure. Further, the topic of making decisions to maintain or replace or upgrade medical equipment has been debated for a long time since errors equipment maintenance will increase equipment failure at undesirable times; or if early equipment replacement will result in high investment costs and premature disposal. Therefore, standard operating procedures or guidelines need to be in place to help healthcare facilities conduct a more organized and planned maintenance and replacement process. Many hospitals may already have established replacement guidelines or have implemented asset monitoring systems for this purpose. However, the effectiveness of this system has not yet been systematically evaluated. Several studies have been conducted on the same research topic, but most of the findings emphasize the replacement method rather than the criteria that contributed to the decision. Criteria for replacing medical equipment play an important role in ensuring that the equipment can be used cost-effectively. Thus, this research aims to identify important criteria that need to be considered for medical equipment maintenance and replacement focusing on private hospitals. This research was conducted in three phases: (1) a structured literature review; (2) semi-structured interviews with eleven (11) healthcare experts; and (3) a pairwise comparison survey with 50 biomedical engineers. A decision-making framework was developed based on the findings of these three research phases. The framework developed will provide guidelines for practitioners and academics to understand and make better decisions for medical equipment maintenance and replacement in the context of private hospitals.

Keywords: Decision-making, medical equipment, private hospitals, maintenance, criteria

1. Introduction

The healthcare industry is one of the fastest-growing industries in the world (Moses & Sharma, 2020) which also contributes almost 15% of gross domestic product of most countries (Attaran, 2022). This has created a lot of competition among the private hospitals, especially to provide the best services to their patients (Asnawi et al., 2019). Therefore, it is a priority for every hospital to provide the best medical equipment (Moons et al., 2019). This is to ensure that the level of medical equipment is always in excellent condition and the quality of hospital services is always in the best condition (Udroiu, 2021). Having a proper maintenance plan can minimize the hospital's financial expenses and avoid hazards associated with the use of medical equipment (MacNeill et al., 2020). It has become customary in hospitals where the maintenance of medical equipment is based on the age and functionality of the equipment rather

*Corresponding author: aisyahs@uthm.edu.my

than on a systematic and organized mechanism to help the maintenance decision-making process (Govindan et al., 2020). In most cases, hospitals prefer to use regular service calls, which are usually based on pre-established arrangements between the service provider and the hospital (Iadanza et al., 2019). This makes it difficult for hospitals to decide whether to maintain or dispose of the equipment, especially when the equipment has reached its maximum lifespan and the cost of repair is extremely high (Sherman et al., 2018).

From a research perspective, there is still a lack of scientific and comprehensive studies especially in the context of making decisions whether to maintain or replace medical equipment (Papa et al., 2020). This situation occurs because there is still a lack of awareness of the importance of managing the maintenance of medical equipment systematically, which results in the quality of medical equipment not being in the best condition (Moons et al., 2019). Wrong decisions in the maintenance of medical equipment can lead to premature replacement or excessive maintenance (Al-Turjman et al., 2020). Excessive maintenance means carrying out maintenance of medical equipment even though the equipment has reached the end of its life and often breaks down. While premature replacement is replacing medical equipment that is not damaged or equipment that has just been purchased. Both conditions are impractical because the cost required is extremely high and the probability of error is also high. Therefore, it is a priority for the hospital to have an asset management mechanism, so that medical equipment is well maintained. The quality of maintenance will be severe, premature, and extreme failure and the overall cost of equipment will increase in the long term if these issues are not addressed and affect the quality of health services. Furthermore, the safety of the patient and the smoothness of the intervention depend on the perfect functioning of the equipment. This research has two research questions: (1) What are the important criteria in making decisions on medical equipment maintenance in Malaysian private hospitals? and (2) How can these criteria be ranked?

This research is beneficial for three reasons. First, this research suggests important criteria that need to be emphasized in the process of maintaining or disposing of medical equipment in the context of a private hospital; while past studies have focused only on examining the criteria for medical equipment maintenance in public hospitals or hospitals in general (Wong et al., 2021). Research that focuses on private hospitals is still lacking and less implemented. This research could also be used by the hospital management to forecast the right budget for equipment maintenance, which leads to better service quality. Findings from this research serve as a guideline for new researchers or existing researchers to understand more clearly the important criteria that need to be considered when deciding whether to maintain or dispose of medical equipment. The discussion of this research is organized as follows. Section 2 discusses the research methodology of the study. Section 3 discusses the three research phases, namely: (1) structured literature review (SLR); (2) findings from qualitative interviews; and (3) presents the quantitative findings from pairwise comparison surveys. Finally, the paper will elaborate more on the three phases of the research in the discussion and conclusion section.

2. Phase 1: Structured Literature Review

This research has been conducted in three phases namely: (phase 1) structured literature review (SLR); (phase 2) expert interview with 11 biomedical expert and (phase3) analytic hierarchy process (AHP) approach through pairwise survey. This section will focus on elaborating the first phase which is getting the preliminary set of criteria for decision makers during the medical equipment maintenance process through SLR.

2.1 SLR Process

The first step is to start with SLR where a list of criteria that need to be considered when deciding whether to maintain or replace medical equipment in the hospital. The procedure starts with findings the keywords which in this case we have used the mix of "medical equipment", "medical device", "health equipment." Boolean operators including OR and AND were used together with the above keywords which represent as follows: (criteria OR attribute OR variable OR factor) AND (selection OR decision) AND (replace OR maintain OR maintenance OR disposal OR condemn). Three databases were used to perform the keyword search, including: (1) Web of Science, the top databases that provide criteria from multidisciplinary content (in the area of IT (Information Technology), medical, sciences and etc); (2) ScienceDirect, which one of the important sources for information in the field lie medical, sciences, management and education; and (3) IEEE Xplore or known as Institute of Electrical and Electronics Engineers, this database delivers the best access towards research field like computer science, IT, applied physics, electrical engineering and other technical area. The three databases selected sufficiently cover for us the find related paper in medical equipment maintenance (Vora et al., 2021).

In the first phase of SLR, it is important to remove less relevant papers related to this study. Thus, the process of filtering and scanning treatment were done by the researcher. Then, duplicate articles were removed during the initial process of SLR. All articles that are unrelated to the title or research abstract will be excluded from use. Next in the second phase of SLR, the researcher collected all the articles related to the maintenance of medical equipment in one folder and numbered each article. A full reading of the articles was then carried out to ensure that only relevant articles were used. The articles are then categorized according to several themes that correspond to the needs and requirements of the research. For example, for this research to know the important criteria in deciding whether to dispose of or maintain medical equipment. So, the data related to these criteria will be extracted. This important data will be stored in Microsoft Word and Excel files. All articles have been analyzed in depth. Please refer Figure 1 for a comprehensive overview of the SLR process.

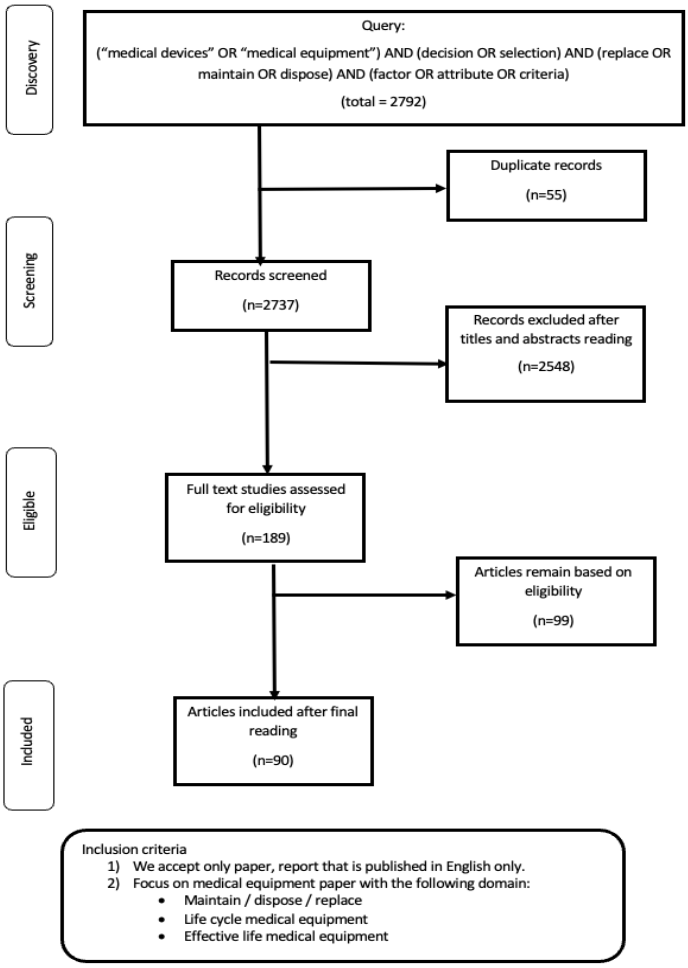


Fig. 1 - SLR protocol and inclusion criteria

2.2 Findings from SLR

This section will tell the findings from SLR starting with the number of articles obtained at the initial stage which is 2792 articles. Then as many as 55 articles were removed from the collection because these duplicates led to 2737 articles. After that, a full reading was carried out which finally left only 90 articles that could be used for this research. Figure 2 gives an overview of the articles that have been analyzed. From these 90 articles, we have then detailed, tabulated, and summarized the preliminary findings of the research. Although the main purpose of this SLR is to extract criteria related to making decisions whether to dispose of or repair medical equipment, we also extract some essential information such as popular methods used to make decisions, types of respondents, data collection methods and so on. To make the narration of this paper more organized and clearer, we will only focus on the data related to the criteria that are narrated. From these 90 articles, we have identified forty-six (46) criteria at the early stage. However, after examining these criteria one by one, there are criteria that can be combined or have the same meaning. Thus, we have combined some of the criteria and made it to only 15 criteria. The grouping process is complicated because some criteria appear similar but differ across a broader spectrum; therefore, the categorization process is carried out with careful attention and detail. It is also found out that some of the criteria are independent and stand out as a single criteria, other criteria need to be grouped together. For example, usage is one of the criteria that stands out in itself; however, failure and risk are combined as one criteria because risk can cause equipment to fail, and equipment failure itself is a risk. These 15 final criteria are also strongly emphasized in all sources that we have used to retrieve the information.

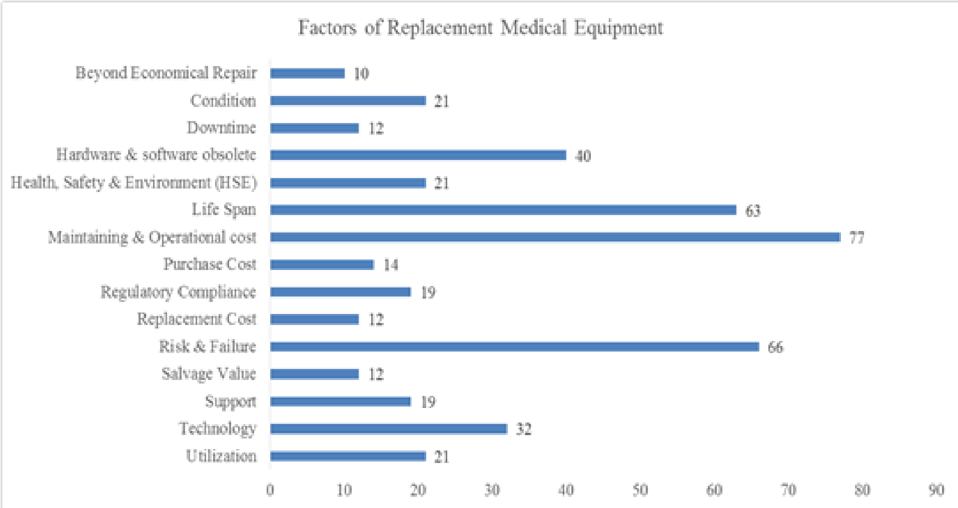


Fig. 2 - Final 15 decision-making criteria

Identifying the 15 criteria is important because the process of deciding whether to maintain and replace the equipment should be based on accurate criteria such as economics rather than estimates or expectations (Shneiderman, 2020). The 15 criteria identified through SLR are: (1) beyond economical repair, (2) condition, (3) downtime, (4) hardware and software obsolete,(5) health, safety, and environment, (6) lifespan, (7) maintenance and operational cost, (8) purchase cost, (9) regulatory compliance, (10) replacement cost, (11) risk and failure, (12) salvage value, (13) support, (14) technology and (15) utilization. After identifying these 15 criteria through the SLR process, the next process is to double compare these criteria with experts. The next phase is to confirm and identify if there are criteria that were not included during the SLR process. The next phase, which is the second phase, involves an expert interview that takes place as a semi-structured interview (Van Audenhove & Donders, 2019). The objective of expert interview is to validate the criteria identified through SLR, and to develop an initial framework for managing the maintenance and replacement of medical equipment in the context of private hospitals in Malaysia.

3. Phase 2: Expert Interviews

3.1 Expert Interviews Process

The second phase of this research is expert interviews using semi-structured interview approach. Semi-structured interviews were conducted to gather information and experience from the expert directly and as a basis to develop a framework for medical equipment maintenance and replacement in private hospitals. Another reason for conducting semi-structured interviews is to validate the criteria that were identified through SLR in phase 1. The sampling technique used for this research is purposive and snowball which is non-probabilistic technique (Omona, 2013). For this research, the participants selected are experts in the healthcare industry who mostly work in hospitals with more than five years of experience. Eleven (11) semi-structured interviews were conducted involving selected participants with each taking 50-60 minutes. Additional notes were taken to supplement the findings and all interviews were audio-recorded for subsequent analysis.

The aim of the interview with the expert is to confirm the 15 criteria that have been identified through the SLR process as well as to explore if there are criteria that are particularly important but are not in the list of 15. The process implemented in phase 2 is identified as a deductive approach (Azungah, 2018) which is then followed by a data analysis process. The use of the Framework method implemented in this study includes the following steps: (1) transcription - it is implemented by transcribing interviews that have been implemented with expert; (2) familiarization - the meaning of familiarization is where the research team understands the data that has been transcribed by listening several times to the recording and writing of the data that has been transcribed; (3) coding – this process is carried out by analyzing the data that has been transcribed according to the codes and categories that have been set during the SLR phase; (4) develop a functional analysis framework - it was developed based on the findings and themes that emerged from the SLR; (5) applying analytical framework in research – an existing analytical framework was applied to the transcripts using codes and categories; (6) plot the data into a framework matrix - where transcript data is summarized with labelled into categories; and (7) assess the data (Gale et al., 2019).

3.2 Findings from Expert Interviews

The purpose of the semi-structured interviews is to derive and validate important criteria for replacing medical equipment in private hospitals. Some of the points coined by experts including E#1 states, *"It is important to avoid unnecessary expenses, wrong equipment purchases and equipment failures that can cause safety issues for patients and users; thus, the disposal process is important in hospitals".* According to E#2, *"It is important for the hospital to have the correct medical equipment replacement process to avoid loss, image is doubted by patients which ultimately leads to unwanted incidents".* The experts were also asked questions on how to improve the medical equipment replacement process. E#1 suggests *"in managing medical equipment, it is important to be flexible and allow medical equipment to be replaced if it is needed".* Experts also think it is important to have an organized and constantly updated database system that stores all information about medical equipment. For example, E#2 suggests*: "a comprehensive database needs to be developed that saves information current and past of the medical equipment.* E#3 mentions: *"Make sure that the system that stores medical equipment information is always updated and complete, especially involving information on the maintenance of medical equipment such as cost information, frequency of equipment failure, disposal date if any etc.* In addition, respondents focused on the importance of standardizing medical equipment, implementing asset management systems and disposal processes. EA9 mentions: *"Legal acts or regulations in the disposal of medical equipment should be established in every hospital".* EA7 states: *"a complete and stable asset management system needs to be developed".*

The list of criteria derived from the expert interviews was mapped to the same criteria that had been initiated through the SLR process. This process helps the researcher to observe whether the decision-making criteria initiated from the interviews have similarities with any criteria identified through the SLR. The comparison between criteria identified through SLR and semi-structured interviews is demonstrated in Table 1.

Table 1 - Criteria of decision-making from SLR and semi-structured interviews

No.	Criteria from SLR	**No**	Criteria from semi-structured interviews
1	Beyond economical repair	1	Net depreciation value
2	Condition	2	Failure risk
3	Downtime	3	Lifespan
4	Utilization	4	Life cycle cost
5	Support	5	Regulatory compliance
6	Salvage value	6	Technology
7	Hardware & software obsolete	7	Beyond economical repair
8	Lifespan	8	Condition
9	Technology	9	Hardware & software obsolete
10	Disposal cost	10	Health, safety, and environment
11	Health, safety, and environment	11	Support
12	Maintaining & operational cost		
13	Failure risk		
14	Purchase cost		
15	Regulatory compliance		

From the expert interviews, it can be concluded that nine (9) criteria similar to criteria extracted in SLR including: (1) condition, (2) outdated hardware and software, (3) health, safety, and environment, (4) beyond economic repair, (5) lifespan, (6) regulatory compliance, (7) risk of failure, (8) support, (9 technology. Further, two new criteria that emerged from the interviews are: (1) net of depreciated value and (2) life cycle cost. These two additional criteria have been included since it has been mentioned four times by the expert during the interviews.

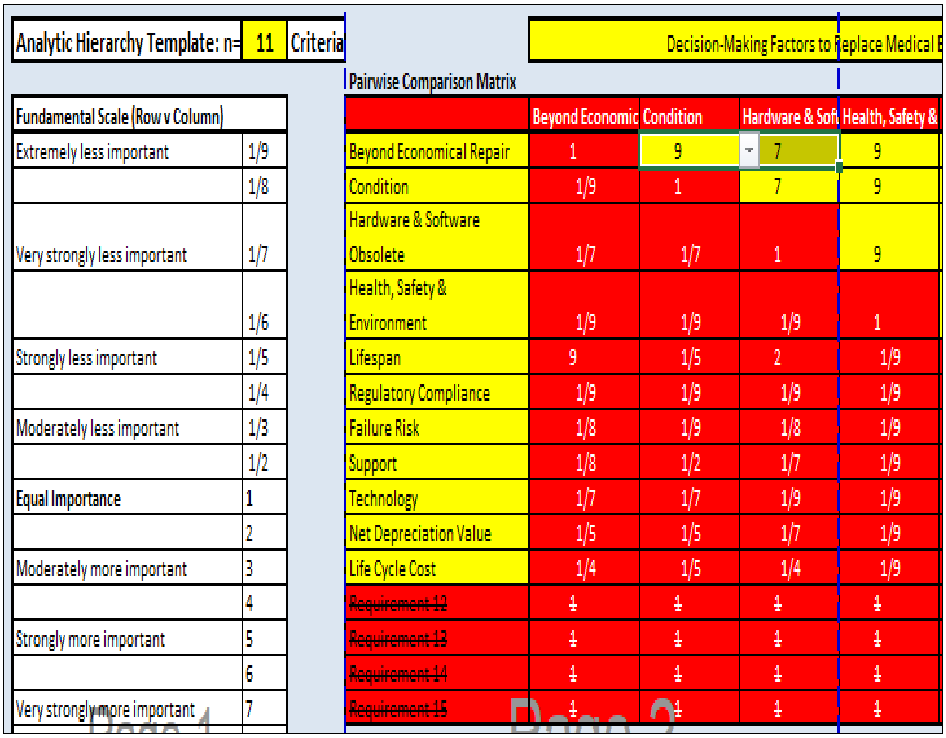
In this study, net of depreciated value (NDV) can be defined as depreciated value of the equipment from one year to another year and the depreciation of the asset happens over a period due to certain reasons such as wear and tear. Another criteria that could be considered as depreciation value is salvage value; nevertheless, salvage value excluded in phase 2 findings since most of the experts think this criteria is not important especially for resale of the medical equipment. The second new added criteria is lifetime cycle cost (LCC) equipment. According to Cui and Gao (2015), LCC is defined as the process of estimating the amount of budget that the company will use on an equipment over its lifetime. Some other similar criteria like maintenance cost, purchase price and replacement cost have also been included as sub-criteria of LCC. Other replacement criteria like maintenance and operation cost that were identified through SLR were also categorized as sub-criteria of LCC as suggested by experts during the interview. The reason to emerge and combine some of the criteria is to avoid confusion and overload data especially when conducting the pairwise survey in the next phase of the research. Some of the criteria recognized through SLR were omitted from the final list of phases 2 (expert interviews). This happened based on expert feedback as they were saying the criteria were not that important during the decision-making process. After these eleven (11) criteria were validated in expert interview phase, the next step is to conduct the AHP analysis which will be discussed further in section 4.

4. Phase 3: Pairwise Comparison Survey

4.1 Pairwise Comparison Survey Process

Phase 3 is the phase where we are going to prioritize and rank the criteria. Pairwise comparison surveys were used to collect the data while AHP analysis were used to analyze the data. Thus, this section will discuss the process of these two procedures. The process in this third phase begins by using the eleven (11) criteria that have been finalized through expert interviews as a reference to construct the pairwise comparison survey questions; that commonly used for analytic hierarchy process (AHP) analysis.

In conducting the pairwise comparison survey, the participants will need to determine the scale for each of the criteria (Spires, 1991). The goal of determining the scale is to find the most important criteria based on the priority vector which in turn determines the consensus and consistency results. Further, the decision to determine the rank criteria is made using degree of uncertainty values instead of accurate assessment, which makes the results from pairwise comparisons more flexible and realistic (Chen & Yu, 2013). Let us understand the purpose of using priority vectors in AHP analysis, particularly in this study. Priority vector was used in this study to infer weights for each decision-making criteria. According to Srdevic et al. (2011), the priority vector is a process to rank the criteria according to their weights and to conclude the priority on each criteria. The weight of each criteria can be measured using various methods. For this study, we have used two methods which are (1) the method proposed by SCB Association Ltd (Ltd, 2016) and (2) BPMSG diversity analysis–Shannon alpha and beta distribution method (Goepel, 2013) using Microsoft Office Excel templates, and which have been illustrated in Figures 3 and 4, respectively. Using AHP, it helps the researcher obtain the consistency ratio (CR) and consensus indicator (CI) of the survey.



Analytic Hierarchy Template: n= 11 Criteria

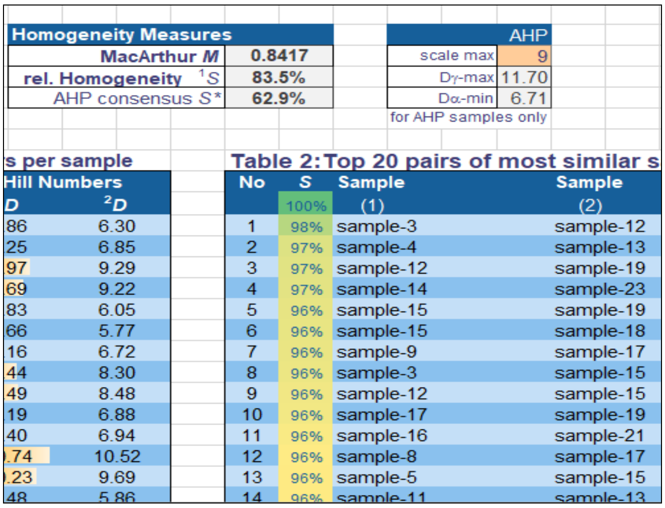
Decision-Making Factors to Replace Medical E

Fundamental Scale (Row v Column)	
Extremely less important	1/9
	1/8
Very strongly less important	1/7
	1/6
Strongly less important	1/5
	1/4
Moderately less important	1/3
	1/2
Equal Importance	1
	2
Moderately more important	3
	4
Strongly more important	5
	6
Very strongly more important	7

Pairwise Comparison Matrix

	Beyond Economic	Condition	Hardware & Soft	Health, Safety &
Beyond Economical Repair	1	9	7	9
Condition	1/9	1	7	9
Hardware & Software Obsolete	1/7	1/7	1	9
Health, Safety & Environment	1/9	1/9	1/9	1
Lifespan	9	1/5	2	1/9
Regulatory Compliance	1/9	1/9	1/9	1/9
Failure Risk	1/8	1/9	1/8	1/9
Support	1/8	1/2	1/7	1/9
Technology	1/7	1/7	1/9	1/9
Net Depreciation Value	1/5	1/5	1/7	1/9
Life Cycle Cost	1/4	1/5	1/4	1/9
~~Requirement 12~~	~~1~~	~~1~~	~~1~~	~~1~~
~~Requirement 13~~	~~1~~	~~1~~	~~1~~	~~1~~
~~Requirement 14~~	~~1~~	~~1~~	~~1~~	~~1~~
~~Requirement 15~~	~~1~~	~~1~~	~~1~~	~~1~~

Fig. 3 - AHP analysis using SCB Associates Ltd



Homogeneity Measures	
MacArthur *M*	0.8417
rel. Homogeneity ¹S	83.5%
AHP consensus *S**	62.9%

AHP	
scale max	9
Dγ-max	11.70
Dα-min	6.71
for AHP samples only	

s per sample

Hill Numbers	
D	²D
86	6.30
25	6.85
97	9.29
69	9.22
83	6.05
66	5.77
16	6.72
44	8.30
49	8.48
19	6.88
40	6.94
.74	10.52
.23	9.69
48	5.86

Table 2: Top 20 pairs of most similar s

No	S	Sample (1)	Sample (2)
	100%		
1	98%	sample-3	sample-12
2	97%	sample-4	sample-13
3	97%	sample-12	sample-19
4	97%	sample-14	sample-23
5	96%	sample-15	sample-19
6	96%	sample-15	sample-18
7	96%	sample-9	sample-17
8	96%	sample-3	sample-15
9	96%	sample-12	sample-15
10	96%	sample-17	sample-19
11	96%	sample-16	sample-21
12	96%	sample-8	sample-17
13	96%	sample-5	sample-15
14	96%	sample-11	sample-13

Fig. 4 - AHP analysis by BPMSG diversity–Shannon alpha and beta

After understanding the steps that need to be done in AHP analysis in general, we will now explain each step of the AHP step in detail that is implemented in this study. The AHP analysis process began by extracting and tabulating data from a questionnaire survey conducted with 50 experts. Data were transferred into an AHP Excel template to determine weights, consensus, and consistency. Pairwise comparisons were constructed to determine the relative importance of each criterion. Participants had to state their judgment of the value of each pairwise comparison one at a time. An 11 x 11 reciprocal comparison matrix was developed to show the 11 decision-making criteria. This matrix is then translated into a scale that can measure the verbal preference selected by the expert during the evaluation. This research uses the Saaty 1–9 scale to determine the weight of the criteria for each level. Table 2 illustrates the scale proposed by Saaty (1980). Based in Table 2 scale, respondent will need to rank all the eleven (11) criteria based on the survey that could be referred in Appendix A.

Table 2 - Scales of AHP by Saaty (1980)

Level of importance	Definition	Explanation
1	Equivalent importance	Two activities are equally important to the objective
3	Lower importance of one over another	Understanding and opinion slightly favor one activity over another
5	Important or significant importance	Understanding and opinion favor one activity over another
7	Proven importance	Activity is favored, and its dominance displayed in practice
9	Utter importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above non-zero	If activity i has one of the above on non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	

Building normalized decision matrix is the next step where the component in the matrix A will be normalized. The normalized pairwise comparison matrix is called *Anorm* matrix. Figure 5 illustrates the *Anorm* matrix equation where A (*xi*) is given by Equation (b) and *Anorm* (a*ij*). The sum of all the components will be normalized to eigen vector or also called priority vector 1, which means the elements from the eigen vector will be summed to 1.

$$a_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}$$

$$A_{norm} = \begin{pmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & \cdots & a_{nn} \end{pmatrix}$$

Fig. 5 - Anorm (aij) equation

Once the eigen vector is summed, the calculation of priority vector needs to be done by multiplying the priority vector value to produce an n x 1 matrix. To get the unit vector, the matrix will be divided with the priority vector. This unit vector is used to get the maximum eigenvalue (Kumar & Ganesh, 1996) which represent as follows $\boldsymbol{\lambda max}$. Next is to find the consensus indicator (CI) which gives the level of agreement between all the respondents (Wu & Xu, 2012), in this research is the experts who made decision whether to replace or maintain the medical equipment. Shannon alpha and beta entropy (Goepel, 2013; Shannon, 1948) were used for calculating the consensus since it measures the priorities between the respondents. We get the consensus from the level of priority of agreement from the respondents where the measures are between 0% to 100%. The illustration of the equation that we used for the equation is shown in Figure 6, where three unusual types of categories can be selected namely high, moderate, and low as shown in Table 3.

$$S^* = (1/D_{\beta} - D^*_{\alpha\ min} D^*_{\gamma\ max}\ )/(1 - D^*_{\alpha\ min}/D^*_{\gamma\ max}\ )$$

where $D_{\alpha,\beta,\gamma}$ is the diversity of order one

Fig. 6 - Priority agreement equation

Table 3 - Level of consensus

Consensus indicator	Description
less than 50%	Consensus is exceptionally low
50% to 65%	Consensus is low
65% to 75%	Consensus is moderate
75% to 85%	Consensus is high
more than 85%	Consensus is extremely high

Checking the consistency ratio (CR) is the last step in AHP analysis (Taherdoost, 2017). The CR could be achieved by estimating the CI (Yeh et al., 2001) and the result of CR is considered adequate if the score is less than 10% (Saaty, 1980). The process of getting the CR value is by summarizing the column in the matrix and multiplying with the result of priority vector that we achieved earlier. Finally, the approximation of the maximum eigen value that represented by λ_{max}. Will be produced.

$$CI = \frac{\lambda\, max - n}{n-1} \qquad\qquad CR = \frac{CI}{RI}$$

Fig. 7 - Equations for CI and CR

The CI value was determined by the random consistency index (RCI) as shown in Table 4 and by using the equation illustrated in Figure 7.

Table 4 - The RCI values

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

4.2 Findings from Pairwise Comparison Survey and AHP Analysis

Section 4.2 will focus solely on the results from the AHP analysis which were obtained from pairwise comparison survey. In this research, the aim of AHP analysis is to compute the vector of criteria weight then to prioritize it. Thus, it requires to decompose a general hierarchical decision problem into sub-problems that can be easily comprehended and evaluated (Rajput et al., 2018). This research focusing on the criteria for decision making medical equipment maintenance and replacement in Malaysian private hospitals. The final list of decision-making criteria is illustrated as in Figure 8 where the upper level of hierarchy represents the goal of the research whilst the lower level represents the decision-making criteria for medical equipment maintenance and replacement in Malaysia private hospitals.

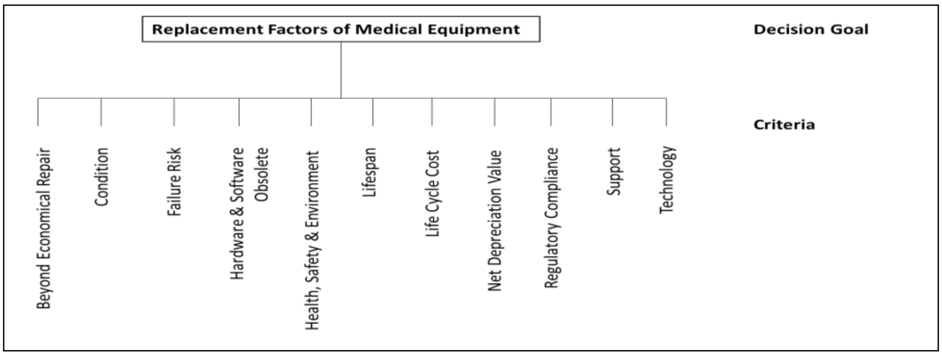


Fig. 8 - Hierarchy of decision-making criterias

Through the pairwise comparison survey, the experts who act as respondents will need to judge the criteria based on importance. The overall pairwise comparison survey which is the AHP analysis results are provided in Appendix B. In this research, we managed to get 50 responses which all of them are professionals and experts that are dealing directly in decision making process of medical equipment maintenance and replacement in Malaysian private hospitals.

The process of analysis starts with extracting the 55 comparison matrixes that we get through (11) criteria that has discussed in detail in section 4.1 The equation shown in Figure 5 were used get the number of comparison where *n* denotes as the number of criteria. While Table 5 demonstrates three different elements namely the final decision-making criteria, the result of average priority vector and the result of priority average. AHP analysis excel template by BPMSG diversity–Shannon alpha and beta as illustrated in Figure 4 and AHP analysis using SCB Associates Ltd as illustrated in Figure 3 were used to calculate the priority vector weight of each criteria from 50 respondents. To make it simplify in pairwise survey questiionniare, the following acronym were use : support (**S**), technology (**T**), lifespan (**L**), condition (**C**), failure risk (**FR)**, life cycle cost (**LCC**), regulatory compliance (**RC**), net depreciation value (**NDV**), beyond economical repair (**BER)**, health, safety & environment (**HSE**) and hardware & software obsolete (**HSO**). The design of pairwise comparison of AHP analysis is illustrated in Appendix B. The next step is to calculate the priority vector according to the score tabulated by the respondents as illustrated in Table 5. From the result, it shows that health, safety and environment criteria have the highest percentage while net depreciation value has the lowest percentage. Having health, safety and environment as the highest might give an indicator that safety is the most important aspect followed by the regulation when making the decision whether to maintain or replace the medical equipment in the private hospitals setting.

Table 5 - The result of average priority vector and priority average of criteria

No.	Decision-making criteria	Average of priority vector (%)	Average of priority
1	Health, safety & environment (HSE)	14.65	0.1465
2	Regulatory compliance (RC)	14.59	0.1459
3	Beyond economical repair (BER)	10.90	0.1090
4	Failure risk (FR)	9.91	0.0991
5	Hardware & software obsolete (HSO)	9.88	0.0988
6	Condition (C)	8.76	0.0876
7	Support (S)	7.85	0.0785
8	Life cycle cost (LCC)	6.30	0.0630
9	Technology (T)	6.22	0.0622
10	Lifespan (L)	5.62	0.0562
11	Net depreciation value (NDV)	5.11	0.0511

Consensus indicator (CI) is the next that we check in this study where the priority criteria that each respondents provide will be examined. CI is important to know the agreement level of the criteria (Bryson, 1996). Equation as illustrated in Figure 9 were used to get the result.

$$S^* = (1/D_{\beta} - D^*_{\alpha\ min} D^*_{\gamma\ \max})/(1 - D^*_{\alpha\ min}/D^*_{\gamma\ \max})$$

S^*= 67%

Fig. 9 - Equation for consensus indicator (CI)

Getting full consensus is not easy since the respondents have different priorities when making the assessment (Blagojevic et al., 2016). This is added when respondents come from different organizations and diverse backgrounds or job scopes.

This study obtained only 67% AHP consensus based on eleven criteria and a sample size of 50 respondents. The result indicates as moderate as if we follow the indicator in Table 3. Getting 67% consensus indicates that 67% of the respondents who answered the survey questions agree with "almost all" criteria (Chan & Lee, 2019). The comparison result of proportional distribution and average priority vector is shown in Table 6 where regulatory compliance and health, safety and environment have the highest proportion which is 15% and net depreciation value and lifespan the lowest with 6% of the proportional distribution. In AHP, the level of consensus is used to check the consistency of the opinion and to avoid self-contradiction (Herrera-Viedma et al., 2007).

Table 6 - Proportional distribution versus average priority vector

No.	Decision-making criteria	Proportional distribution	Decision-making criteria	Average priority vector (%)
1	Health, safety, and environment (HSE)	15.0	Health, safety & environment (HSE)	14.65
2	Regulatory compliance (RC)	15.0	Regulatory compliance (RC)	14.59
3	Beyond economical repair (BER)	11.0	Beyond economical repair (BER)	10.90
4	Failure risk (FR)	10.0	Failure risk (FR)	9.91
5	Hardware & software obsolete (HSO)	10.0	Hardware & software obsolete (HSO)	9.88
6	Support (S)	8.0	Condition (C)	8.76
7	Life cycle cost (LCC)	7.0	Support (S)	7.85
8	Technology	7.0	Life cycle cost (LCC)	6.30
9	Condition (C)	6.0	Technology (T)	6.22
10	Lifespan (L)	6.0	Lifespan (L)	5.62
11	Net depreciation value (NDV)	6.0	Net depreciation value (NDV)	5.11

The results of the priority vector are quite parallel to the results of the proportional distribution as shown in Table 6. A high value of the priority vector designates a high selection weight of the criteria compared to other criteria based on the scores given by the respondents when answering the survey (Hadi-Vencheh & Mohamadghasemi, 2011). Inconsistent results can be minimized if the number of criteria is reduced to 6–8. According to Saaty and Ozdemir (2014) in a real scenario, it is difficult to achieve a level of consistency because people always receive added information that leads to variations in knowledge. Inconsistent results arise because humans have a limited capacity to process many comparisons at a time. Therefore, a value of CR>10% is relevant if the weights obtained are reasonable. Next five experts who had worked as biomedical engineers and were involved in decision making were selected for confirming the findings. The results of a quantitative study on decision-making criteria were presented to these experts. Four out of the five experts agreed on the ranking. Once confirmation is done, decision making framework is developed as shown in Figure 4. Next section, which is section 5, will briefly discuss the findings that we already report in section 4.

5. Discussion

This section will recap the entire process of the research and the contribution of the research to academics and practitioners. The research begins with identifying an initial set of criteria that influence decision makers whether to maintain or replace medical equipment in hospitals through the SLR approach (i.e., phase 1). Next, findings from the SLR were validated through semi-structured interviews with biomedical engineers (i.e., phase 2). From the expert interviews, four out of fifteen criteria recognized through the SLR were removed since that criteria were not preferred by the experts. Discarded criteria are downtime, salvage value, purchase cost and usage. Equipment downtime partly worries them but is not considered as priority criteria for medical equipment replacement. Specialists rarely choose equipment downtime as the most important criteria, as the equipment unavailability does not disturb the operation of the hospital. Other criteria that are omitted is salvage value and purchase cost as both criteria never mentioned by experts as essential elements in relation to replacement costs. Consumption criteria were also removed from the list in the qualitative phase as there were only two experts who chose these criteria. Nine out of fifteen criteria obtained through the SLR were the same as the criteria obtained from the expert interview. In the last phase of the research, which was a quantitative paired comparison survey, the questionnaires have been distributed to 50 medical equipment engineers. In this phase also, AHP approach has been used to analyse the responses. Five biomedical engineers have confirmed the ranking of the criteria based on their weighting. Based on the results, “regulatory compliance” and “health, safety and environment” are the criteria that have the highest percentages voted by the experts. Figure 4 illustrates the overall process that we follow for developing the final decision-making framework for medical equipment replacement.

There are several contributions to this research. First, an improvement method has been identified to understand the criteria that should be considered to evaluate and replace medical equipment focusing on private hospitals. Previous studies on the maintenance of medical equipment have highlighted several criteria that contribute to decision-making such as total cost of ownership, age, and other criteria related to critical evaluation devices (Husereau & Drummond, 2022) vendor support (Byrom, 2018). However, it has been identified that little work has been focused on the empirical priority of decision-making criteria for structured and systematic maintenance of medical equipment, especially in private hospitals. Most studies have focused on the efforts of private hospitals to grow patients’ numbers as this will also increase the profit margins and revenue of the hospital (Behrouzi & Ma'aram, 2019). It also found out that most private hospitals do not have a proper approach for medical equipment maintenance (Meesala & Paul, 2018). This has caused some of the hospitals to use medical equipment for a longer time and extend its useful life (Papa & Mital, 2020). . Maintaining medical equipment is a complicated procedure that involves ‘back and forward interaction’ between the equipment and its social environment (Lee, 2019) including patients, doctors, and staff such as those in the maintenance unit, making it difficult to draw a line between the medical equipment and its social circle. Hence, findings from this study could be used as a benchmark and contribute to the body of knowledge, especially medical equipment maintenance research domain. While the AHP method used in this study could be a reference for future researchers to understand more on prioritization of medical equipment maintenance.

From a practitioner perspective, this study provides some important highlights as well. Findings from this research can help hospital administration manage cost and consider safety qualities in medical equipment maintenance. The criteria highlighted in this study could also become guidelines for the private hospital to monitor the condition of medical equipment and suggest the proper timely manner to repair or replace the equipment. It is also important for hospitals authority to correctly identify equipment that needs to be replaced versus equipment that does not and avoiding purchase of unnecessary equipment; and this study also provides that guideline. In general, having well-organized decision-making criteria and processes could save cost medical equipment maintenance as well as identifying the safety elements (e.g., staff and patient safety). Medical equipment maintenance is required based on several reasons that make the hospital authority needs to take immediate action including equipment with major damage and the problem has occurred quite some time where the downtime has occurred for some time or unavailability of some spare parts. In general practice, equipment that is not in a good condition and has been used for a certain period needs to be replaced with new equipment ((Maddox et al., 2019). Another contribution this research has given is to incorporate the final criteria identified into Asset Management System (AMS). AMS is a system that has been used in most healthcare facilities to monitor assets more systematically. This system also could be used for asset tracking where it provides details including location, status, due date of the asset and many more features (Zamzam et al., 2022). AMS also helps hospital management to have adequate analysis of the financial and clinical indicators of medical equipment.

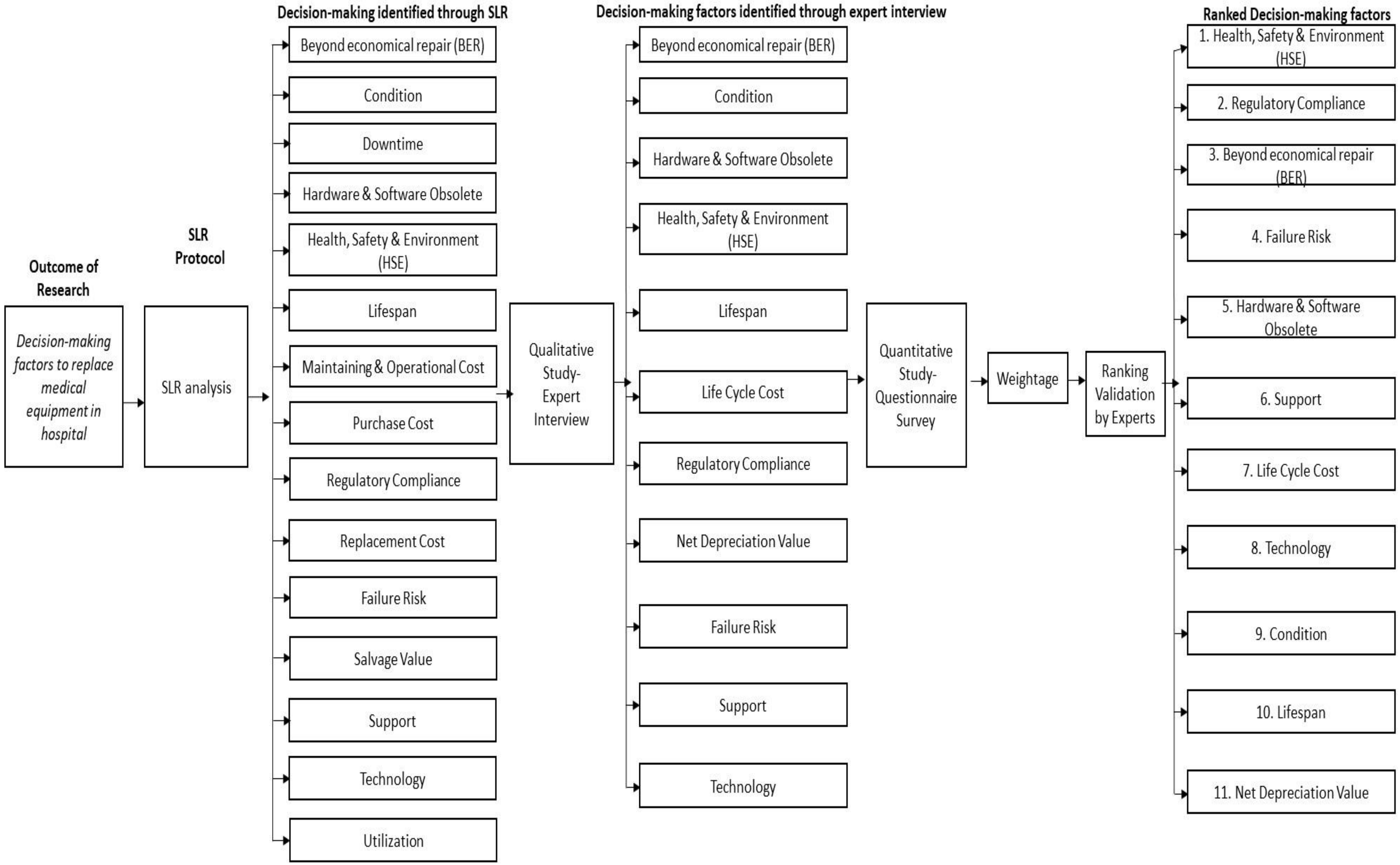


Fig. 4 - Process flow of decision-making criteria identifie

6. Discussion

Regular, thorough, and appropriate hospital equipment maintenance practices can contribute to efficiency in the health sector, thereby improving health outcomes and ensuring equipment is functioning properly by increasing patient reliability of hospital services and reducing equipment failure rates. Thus, the empirical results suggested in this study are valuable and promising; nevertheless, it is also essential to acknowledge the constraint of this study. Although this study is focused on the maintenance and replacement of medical equipment in private hospitals, future researchers can still use the insights from the results of this study because the findings of private hospitals can also be combined with other studies by taking the best approach that is produced or reported. Furthermore, we only interviewed biomedical experts due to time constraints. Future work could incorporate other views including biomedical contractors, vendors, medical equipment suppliers to provide a comprehensive view of decision-making criteria. Future researchers can also use the framework that has been produced to make the decisions that have been suggested in this study for other contexts including public hospitals. The availability of good medical equipment is an important part of the sustainability of healthcare services; therefore, system management needs to be safe, timely, effective, efficient, and patient-centered. Through the right decision-making framework, hospitals can study the needs of, and performance of, medical equipment and apply an analytical approach to asset management throughout their lifecycle.

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Appendix

Appendix A: Pairwise Comparison Survey

The table below is a pairwise comparison scale used to express the importance of one criteria compared to other criteria. Therefore, we would like to get your opinion to identify the most important criteria for deciding to maintain and replace medical equipment in the hospital.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	Used to compromise between two judgment

The definition criteria for medical equipment maintenance and replacement are as follows:

1. **Beyond economical repair**: an asset is considered beyond economical repair when it is more cost-effective to replace the asset than it is to repair it.
2. **Condition:** the condition of the equipment is either in good or bad shape, physically and functionality.
3. **Hardware & Software Obsolete**: End of support and no longer produced by the manufacturer.
4. **Health, Safety & Environment:** The impact of equipment on a user's health and safety and the environment.
5. **Support:** Support given by supplier or manufacturer in spare parts, advice, software, skill etc
6. **Regulatory Compliance:** Compliance to the local or international standards and regulations
7. **Technology:** Compatibility of equipment, able to integrate and update
8. **Net Depreciation Value**: Depreciation value of equipment in every year
9. **Life Cycle Cost (LCC):** Whole-life cost
10. **Lifespan:** Life expectancy or useful life of equipment.
11. **Failure Risk:** Failure rate, frequency, and level of failure

Example:

FACTORS	WEIGHT																	FACTORS
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Condition

If you think criteria **Beyond Economical Repair** is extraordinarily strong important compared to criteria **Condition**, you can select scale 7 as your answer. Please complete the scale below with the appropriate selection of the criteria.

FACTORS	WEIGHT																	FACTORS
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Condition
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hardware & Software Obsolete
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Health, Safety & Environment
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Lifespan
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Regulatory Compliance
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Failure risk
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Support
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Technology
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Depreciation Value
Beyond Economical Repair	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Life Cycle Cost

Appendix B : The Design of Pairwise Comparison Survey

Criteria	Beyond Economical Repair	Condition	Hardware & Software Obsolete	Health, Safety & Environment	Lifespan	Regulatory Compliance	Failure Risk	Support	Technology	Net Depreciation Value	Life Cycle Cost
Beyond Economical Repair	1	BER/ C	BER/ HSO	BER/ HSE	BER/ L	BER/ RC	BER/ FR	BER/ S	BER/ T	BER/ NDV	BER/ LCC
Condition	C/ BER	1	C/ HSO	C/ HSE	C/ L	C/ RC	C/ FR	C/ S	C/ T	C/ NDV	C/ LCC
Hardware & Software Obsolete	HSO/ BER	HSO/ C	1	HSO/ HSE	HSO/ L	HSO/ RC	HSO/ FR	HSO/ S	HSO/ T	HSO/ NDV	HSO/ LCC
Health, Safety & Environment	HSE/ BER	HSE/ C	HSE/ HSO	1	HSE/ L	HSE/ RC	HSE/ FR	HSE/ S	HSE/ T	HSE/ NDV	HSE/ LCC
Lifespan	L/ BER	L/ C	L/ HSO	L/ HSE	1	L/ RC	L/ FR	L/ S	L/ T	L/ NDV	L/ LCC
Regulatory Compliance	RC/ BER	RC/ C	RC/ HSO	RC/ HSE	RC/ L	1	RC/ FR	RC/ S	RC/ T	RC/ NDV	RC/ LCC
Failure Risk	FR/ BER	FR/ C	FR/ HSO	FR/ HSE	FR/ L	FR/ RC	1	FR/ S	FR/ T	FR/ NDV	FR/ LCC
Support	S/ BER	S/ C	S/ HSO	S/ HSE	S/ L	S/ RC	S/ FR	1	S/ T	S/ NDV	S/ LCC
Technology	T/ BER	T/ C	T/ HSO	T/ HSE	T/ L	T/ RC	T/ FR	T/ S	1	T/ NDV	T/ LCC
Net Depreciation Value	NDV/ BER	NDV/ C	NDV/ HSO	NDV/ HSE	NDV/ L	NDV/ RC	NDV/ FR	NDV/ S	NDV/ T	1	NDV/ LCC
Life Cycle Cost	LCC/ BER	LCC/ C	LCC/ HSO	LCC/ HSE	LCC/ L	LCC/ RC	LCC/ FR	LCC/ S	LCC/ T	LCC/ NDV	1

Appendix C: Sample of AHP Result Analysis

Priority vector (%)/ Expert	Beyond Economical Repair	Condition	Hardware & Software Obsolete	Health, Safety & Environment	Lifespan	Regulatory Compliance	Failure Risk	Support	Technology	Net Depreciation Value	Life Cycle Cost
EX#1	1.1	9.6	8.3	28.0	2.2	4.1	16.8	16.6	5.5	3.1	4.7
EX#2	24.2	19.8	13.5	11.0	8.5	6.9	5.3	4.1	3.3	2.2	1.3
EX#3	8.5	8.6	2.9	12.9	6.5	12.1	15.3	3.7	14.2	7.0	8.4
EX#4	9.1	6.8	0.5	3.8	8.7	11.6	11.6	8.4	12.4	12.0	15.1
EX#5	9.6	4.9	1.0	16.9	3.0	30.6	12.3	6.9	2.9	5.1	5.6
EX#6	9.5	9.0	1.5	10.2	2.9	10.6	13.3	3.4	33.5	2.8	3.1
EX#7	1.1	2.2	3.1	26.3	4.1	16.8	5.2	14.3	11.1	8.8	7.0
EX#8	4.3	20.8	8.6	6.0	2.9	13.1	15.2	10.4	7.9	4.3	6.4
EX#9	3.8	5.8	12.9	19.2	2.2	11.0	9.1	8.3	15.6	5.4	6.6
EX#10	7.8	16.2	15.0	23.8	3.3	15.7	1.6	7.0	3.6	2.0	4.1
EX#11	1.8	2.6	3.5	3.9	5.6	6.7	8.6	10.3	13.4	24.8	18.8
Priority vector (%)/ Expert	Beyond Economical Repair	Condition	Hardware & Software Obsolete	Health, Safety & Environment	Lifespan	Regulatory Compliance	Failure Risk	Support	Technology	Net Depreciation Value	Life Cycle Cost
EX#12	12.1	9.7	5.9	10.0	9.0	9.4	9.7	5.3	8.9	8.5	11.4
EX#13	3.7	7.0	5.1	4.9	10.4	10.2	9.1	11.7	14.6	12.9	10.4
EX#14	7.5	4.8	13.3	19.2	1.1	30.0	11.9	3.9	2.1	3.1	3.1
EX#15	9.3	6.9	4.3	14.5	7.0	18.7	9.0	11.3	8.4	4.7	5.8
EX#16	14.1	7.2	16.0	6.2	15.6	8.9	9.6	8.0	5.4	3.9	5.1