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Development of a Decision Support Model for Establishment a Medical Equipment Maintenance Program

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Abstract— The healthcare industry is one among the biggest industries in the world which shows a large amount of expenses for any nation's economy. It includes various areas as medical equipment supplies, pharmaceuticals, healthcare services and biotechnology. Medical equipment worldwide are assets that straightforwardly influence human lives. They provide great and sizeable investments, and in many cases they need high maintenance costs. It is important, therefore, to own a well-planned and managed maintenance program that is ready to preserve pieces of medical equipment in a healthcare organization in a reliable, safe, and accessible state to be used when they are required for diagnostic procedures, therapy, and monitoring of patients. Furthermore, this program shall prolong the useful lifetime of the piece of equipment and limits the expense of equipment ownership. Also an effective maintenance program is very important for hospitals and healthcare organizations to be accredited. Along these lines, this work aims to assist the clinical engineering (CE) department to develop an effective maintenance management program by prioritizing the medical equipment with a consideration made against risk, performance, and cost criteria. The program shall also help the clinical engineering staff to set the appropriate inspection and preventive maintenance frequency. This program is a kind of Multi-Criteria Decision Making (MCDM) model based on the Analytic Hierarchy Process (AHP) approach.

Index Terms—AHP, MCDM, Medical equipment, Maintenance management program, Prioritization, Preventive maintenance frequency.

1 Introduction

The healthcare industry is an aggregation and integration of various sectors inside the economic system, which offers goods and services in order to treat patients. It incorporates the generation and commercialization of goods and services lending themselves to keeping up with and re-establishing health [1]. The healthcare industry is considered one of the biggest and quickest developing industries overall the world [2]. It consumes more than ten percent of the gross domestic product (GDP) of most developed nations. Health care can frame a gigantic piece of a nation's economy [3].

Healthcare technology has turned out to be an essential aspect of healthcare, because it empowers health-care givers to diagnose, treat, monitor, and supply therapy to patients within a suitable environment of care. Quality management of healthcare technology guarantees that these services are furnished safely and within a frame of high quality [4].

Planning a maintenance program is a piece of a broader effort to set up a comprehensive program for healthcare technology management (HTM). This planning procedure involves a review of certain critical elements. The mission for planners is to adjust these elements to form a maintenance program that is suitable and value-effective for their circumstances [5].

Maintenance has a vital function in economic viability regarding medical equipment; it may obviously decrease the overall operating cost. It also boosts its availability, reliability, capability, and quality. In addition, it reduces its potential risk, enhances its efficiency, and safe use [6]. However, maintenance and its strategies are of limited significance. The management staff frequently thinks about maintenance as an expense and as an inevitable source of monetary value. For these organizations, maintenance operations have a corrective function and are just carried out in crisis climate. While on the other hand, some healthcare associations plan a program with the goal to investigate and maintain all equipment similarly. Likewise, this is undesirable as such program is not effective because it consumes much cost, time, and effort.

Additionally, the scheduled work can also remain unfinished as definite matches between the workload for the equipment in the hospital and the team of workers and also the resources available to accomplish the work are rare. Therefore, it is smarter to carefully identify the equipment within the health-care organization that plays the most important role to inspect and maintain upon certain given criteria, and from this point the clinical engineering department could schedule the work as a priority system and decide the suitable frequency of preventive maintenance for the equipment [5].

Moreover, hospitals often suffer in developing countries from insufficient funds and the lack of qualified technical personnel, which results in various problems, among which is the improper and irregular maintenance of medical equipment [7]. Thus, this case requires an effective maintenance management program aiding in prioritizing and scheduling maintenance tasks and helping clinical engineering department to take the appropriate decisions regarding medical equipment maintenance upon multi essential criteria, in order to guarantee safe and efficient equipment by taking into account the available resources and by performing the proper utilization of them.

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In this study, a model utilizing the so-called Analytic Hierarchy Process (AHP) was designed and described, whose hierarchy system relies upon the contribution made by the expertise of previous researches and experts, in order to develop a Multi Criteria Decision Making (MCDM) to support the decision makers in setting the appropriate preventive maintenance frequency for various classes of medical equipment.

Georges Adunlin et al. [8] found that the utilization of Multi-Criteria Decision Analysis (MCDA) in health care has turned out to be common. In addition, they carried out a bibliometric analysis to present the publication trends of MCDA methods in health care. Interestingly, AHP was confirmed to be the most utilized MCDA approach in health care. Also, Katharina Schmidt et al. [9] explored that there has been a clear upward trend within the number of publications that apply the AHP to healthcare since 2005, and they illustrated that the majority of researches were from Asia (almost 30%), accompanied by the US (25.6 %). Also, the literature is full of various techniques for maintenance strategies and its management as found in Omega et al. study [10], where the authors determined the priority level of medical device maintenance based on seven main criteria. Ben Houria et al [11], however, showed quantitative techniques with the AHP, TOPSIS and MILP approaches. They utilized AHP to get the critical score for medical equipment, while TOPSIS was utilized to identify the order of strategies for maintaining medical equipment, On the other hand, MILP was used in order to make a decision about medical equipment maintenance strategy.

2 Materials and Methods

2.1 Research Framework

As illustrated previous, the study aims to prioritize medical equipment and set for them the appropriate preventive maintenance frequency. Fig. 1 shows the steps that the study follows in order to achieve the aim of the research.

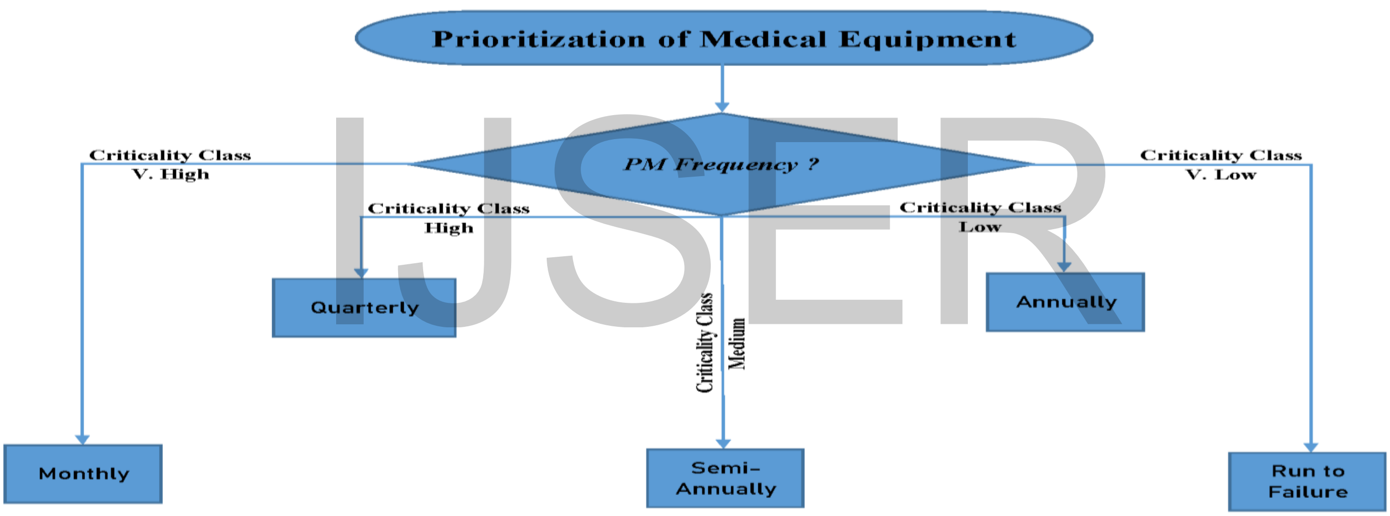

Fig. 1. Research framework

Interviews and meetings were conducted with various groups of individuals involved in the maintenance and service contract process including biomedical engineers, managers in order to obtain the criteria and sub-criteria needed to build the model hierarchy. Based on literature review and information gained from interviews, a questionnaire was developed in order to rate the relative importance of the involved criteria and sub-criteria.

2.2 Building the model

The study proposes a MCDM model to prioritize medical equipment according to their criteria using Analytic Hierarchy Process (AHP). AHP is a fundamental method to deal with decision making. It is intended to assign to each piece of equipment the rationale and the intuition to pick out the best from a variety of alternatives assessed regarding numerous criteria. During this process, the decision maker incorporates simple pair-wise comparison judgments, which are then accustomed to develop overall priorities for ranking the alternatives. The AHP takes into account the inconsistency within the judgments.

The simplest structure used to shape a decision issue is a hierarchy consisting of three levels (Fig. 2) [10]. The goal of the decision lies at the top level. It is accompanied by a second level consisting of the criteria by which the alternatives, placed within the third level, are going to be assessed. Hierarchical decomposition of complicated systems appears to be a fundamental device utilized by the human thought to adapt with diversity.

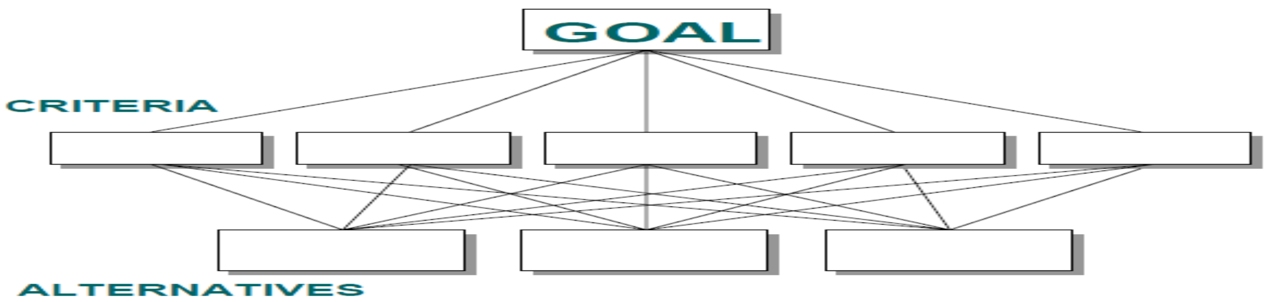

Fig. 2. AHP Hierarchy Structure

AHP utilizes pair-wise comparison to assign weights to the factors of every level, estimating their relative importance then it computes the weights for assessment at the last level. Thomas L. Saaty [12] made a standard rating scale as presented in Table 1.

TABLE 1

THE FUNDAMENTAL SCALE OF ABSOLUTE NUMBERS

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

Pair-wise comparison provides a square matrix A whose factors are presented by $A_{ij} = w_i/w_j$, expressing the dominance of weight i with respect to weight j, expressed within the scale of Saaty. When one expresses judgments based on comparisons in pairs, inconsistent judgments are framed, because the human thought has the lack of objectivity.

In mathematical terms, Consistency Index (CI) could be calculated using equation (1)

$$CI = (\lambda_{max} - n)/(n - 1) \quad (1)$$

concurrently taking into consideration all the relations between the terms of comparison [13]

and the Consistency Ratio (CR) may be valued through equation (2)

$$CR = CI / RI \quad (2)$$

Where Random Index value (RI) is the average value of the index determined randomly from the experiment designed by Thomas L. Saaty (1988) that uses the number of matrices as shown in Table 2. The consistency ratio (CR) is proper if its value is < 0.1 [10].

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TABLE 2
RANDOM INDEX VALUE

Matrix Size (N)	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (R.I.)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

In addition, the present study shows the classification of different pieces of medical equipment according to their total criticality scores and illustrates how individual scores for each piece of equipment are utilized to set the guidelines to determine the appropriate preventive maintenance frequency required per year for different classes of equipment.

Briefly, the proposed criticality assessment model for medical equipment may be listed in the following steps [14]:

- Determine all sufficient, efficient, and independent criteria and sub-criteria for criticality assessment of equipment, then decide the weighting values for all these criteria and sub-criteria using the relative measurement method as presented in Figure 3.

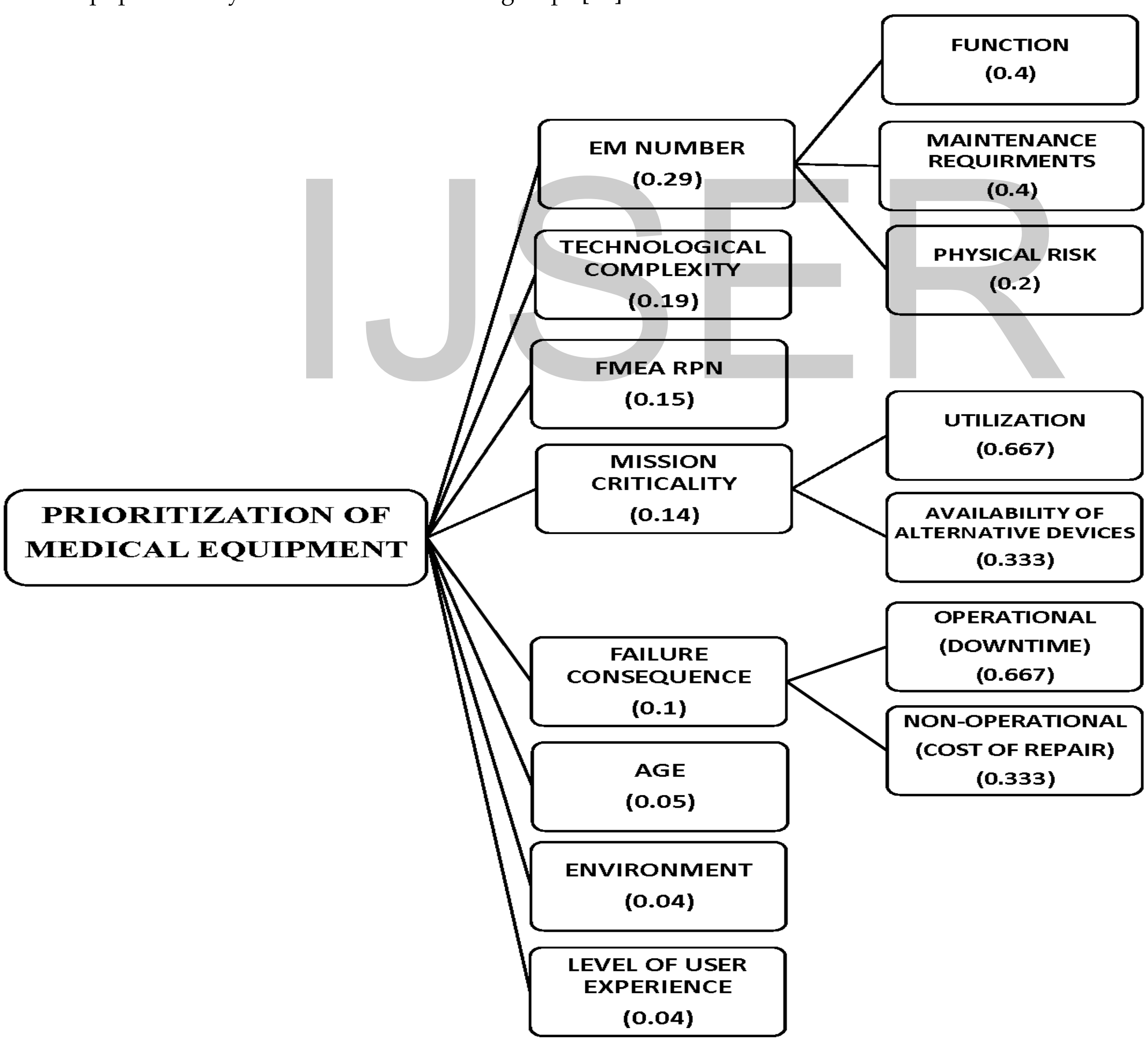

Fig. 3. Weights of Criteria and sub-criteria of the proposed prioritization model

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- Set up grades and determine intensities for every criterion utilizing the relative measurement method. To be able to assess the equipment with respect to a criterion, the criterion's grades and their related intensities should be defined in advance. The grades are possible categories or classes of a criterion. For example, 'old', 'almost old', 'average', 'almost new' and 'new' will be viewed as five classes of equipment's age.
- Evaluate alternatives (equipment) with relevance to every criterion and assign the most descriptive grades utilizing the absolute measurement method; the assigned grade's intensity for an alternative is known as its score with concern to a criterion.
- Compute the criticality, CS_i score for every equipment i as given by

$$CS_i = \sum W_j S_{ij} \quad (3)$$

i = 1,…, m where m is the maximum equipment number
j =1,…, n where n is the maximum criteria
W_j is the weight of the j^{th} criterion
S_{ip} is the score of the i^{th} equipment with respect to the j^{th} criterion

3 CASE STUDY

The present study applied the proposed model to a case study on seventy-two medical equipment belonging to different medical departments. These are mentioned in Table 3.

TABLE 3

MEDICAL EQUIPMENT INCLUDED IN THE STUDY

Equipment	Number
Analyze blood gas (ABG)	3
Anesthesia machine	3
Aortic balloon	3
Cardiac Catheterization	2
Cavitronic ultrasonic surgical aspirator (CUSA)	1
Computer-Aided Detection Systems, Image, Breast, Mammography	2
Defibrillator	4
Dialysis machine	4
Dual-energy X-ray absorptiometry (Dexa Scan)	1
Electro cardio graph (ECG)	4
Heart lung machine	2
Infusion pump	5
Operating table	1
Panorama	1
Patient bed	3
Patient monitor	4
Pulse oximeter	2
Scanning System, Computed Tomography (CT)	2
Scanning Systems, Magnetic Resonance Imaging (MRI)	1
Sphygmomanometer	4
Surgical Light	1
Syringe pump	5
Ultrasound (Diagnostic Unit)	3
Ventilator	6
X-ray system, General Purpose	2
X-ray system, mobile	3
Total	**72**

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Classification and Maintenance Intervals

As mentioned before, the proposed model prioritizes pieces of equipment according to their criteria to establish a relative priority for PM. The total scores of equipment can be used as absolute measurements for classification. The total score is a metric which can be compared with pre-set thresholds in order to determine to which category the equipment belongs. In this model, the total score of equipment may vary between 0.14755 and 1.0. The total score can then be mapped to 0, 100% using the following equation [14]:

$$Transformed\ score\ value, TSV = \frac{score\ value - min}{max - min} \times 100\% \quad (4)$$

Where min & max are the minimum and maximum scores, respectively.

In order to easily prioritize and classify the various pieces of equipment, the TSV should be normalized. Those devices with the highest scores will obviously benefit more than those with lower scores. This study in fact considers five levels of PM Priority and sets boundaries between the five levels as given in Table 4. Equipment with a TSV greater than 70% are considered to be of PM Priority with highest PM frequency (monthly), while for pieces of equipment with a TSV between 45% and 70% a preventive maintenance interval of three months is recommended. As for a piece of equipment with a TSV between 25% and 45%, it is scheduled for a semi-annual preventive maintenance, while the equipment with a TSV between 10% and 25% has to undergo annual preventive maintenance. On the other hand, equipment with TSV less than 10% are either virtually insensitive to PM or realizing no necessary benefits from PM, and so they are given a PM Priority ranking of zero (fix-it-when-broken).

TABLE 4

PROPOSED CLASSES AND THE THRESHOLDS

Criticality Class	Normalized TSV	Preventive Maintenance Frequency
Very High	70%<TSV≤100%	Monthly
High	45%<TSV≤70%	Quarterly
Medium	25%<TSV≤45%	Semi-annual
Low	10%<TSV≤25%	Annual
Very Low	0 %≤TSV≤10%	Do no PM (Run to failure)

As a result, the total score values, the transformed score values, the criticality class, and the selected suitable maintenance intervals for medical equipment included in the model are presented in Table 5.

TABLE 5

THE NORMALIZED TSV AND THE MAINTENANCE INTERVALS

EQUIPMENT	TOTAL SCORE	NORM. TSV	Criticality Class	Maintenance Frequency	EQUIPMENT	TOTAL SCORE	NORM. TSV	Criticality Class	Maintenance Frequency
A1	0.414	31.222	Medium	Semi-annual	**O1**	0.320	20.214	Low	Annual
A2	0.356	24.394	Low	Annual	**O2**	0.325	20.859	Low	Annual
A3	0.367	25.779	Medium	Semi-annual	**O3**	0.354	24.183	Low	Annual
B1	0.558	48.204	High	Quarterly	**P1**	0.415	31.429	Medium	Semi-annual
B2	0.497	41.037	Medium	Semi-annual	**P2**	0.418	31.781	Medium	Semi-annual
B3	0.543	46.409	High	Quarterly	**P3**	0.424	32.426	Medium	Semi-annual

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C1	0.583	51.070	High	Quarterly	**P4**	0.452	35.750	Medium	Semi-annual
C2	0.583	51.070	High	Quarterly	**Q1**	0.229	9.525	V. Low	Run to Failure
C3	0.516	43.226	Medium	Semi-annual	**Q2**	0.232	9.877	V. Low	Run to Failure
D1	0.767	72.679	V. High	Monthly	**R1**	0.687	63.286	High	Quarterly
D2	0.682	62.743	High	Quarterly	**R2**	0.550	47.250	High	Quarterly
E1	0.642	58.027	High	Quarterly	**S1**	0.682	62.688	High	Quarterly
F1	0.476	38.550	Medium	Semi-annual	**T1**	0.310	19.074	Low	Annual
F2	0.469	37.685	Medium	Semi-annual	**T2**	0.232	9.877	V. Low	Run to Failure
G1	0.340	22.576	Low	Annual	**T3**	0.253	12.384	Low	Annual
G2	0.361	25.083	Medium	Semi-annual	**T4**	0.232	9.877	V. Low	Run to Failure
G3	0.363	25.216	Medium	Semi-annual	**U1**	0.320	20.214	Low	Annual
G4	0.390	28.481	Medium	Semi-annual	**V1**	0.392	28.653	Medium	Semi-annual
H1	0.595	52.494	High	Quarterly	**V2**	0.395	29.005	Medium	Semi-annual
H2	0.584	51.164	High	Quarterly	**V3**	0.400	29.650	Medium	Semi-annual
H3	0.581	50.887	High	Quarterly	**V4**	0.339	22.447	Low	Annual
H4	0.531	44.959	Medium	Semi-annual	**V5**	0.411	30.878	Medium	Semi-annual
I1	0.403	29.943	Medium	Semi-annual	**W1**	0.292	16.914	Low	Annual
J1	0.314	19.518	Low	Annual	**W2**	0.287	16.406	Low	Annual
J2	0.286	16.226	Low	Annual	**W3**	0.334	21.821	Low	Annual
J3	0.276	15.010	Low	Annual	**X1**	0.339	22.486	Low	Annual
J4	0.364	25.435	Medium	Semi-annual	**X2**	0.352	23.996	Low	Annual
K1	0.558	48.204	High	Quarterly	**X3**	0.464	37.068	Medium	Semi-annual
K2	0.568	49.358	High	Quarterly	**Y1**	0.610	54.296	High	Quarterly
L1	0.392	28.653	Medium	Semi-annual	**Y2**	0.616	54.942	High	Quarterly
L2	0.392	28.653	Medium	Semi-annual	**Y3**	0.633	56.936	High	Quarterly
L3	0.395	29.005	Medium	Semi-annual	**Y4**	0.644	58.265	High	Quarterly
L4	0.322	20.453	Low	Annual	**Y5**	0.675	61.859	High	Quarterly
L5	0.355	24.308	Low	Annual	**Y6**	0.737	69.195	High	Quarterly
M1	0.320	20.214	Low	Annual	**Z1**	0.547	46.883	High	Quarterly
N1	0.403	29.943	Medium	Semi-annual	**Z2**	0.455	36.106	Medium	Semi-annual

4 RESULTS

Concerning the previous proposed model and according to the results, Figure 4 shows that the greatest percentage was attributed to semi-annual preventive maintenance (36% of the involved equipment in the study) while the results revealed a moderate percentage for the three times annually PM and annual PM as they covered 29% and 28% respectively. On the other hand, there is just a small percentage of the medical equipment (only 1%) which needs monthly preventive maintenance, and (6% of the equipment) which does not need PM at all and only runs to failure as shown in the results.

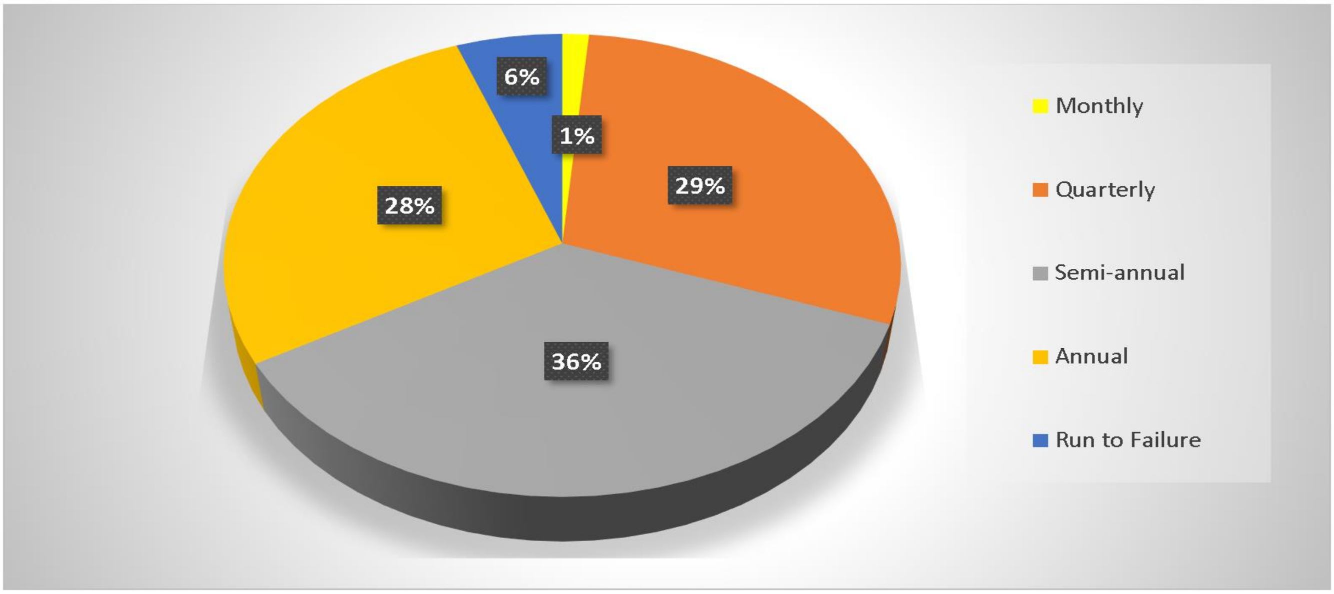

Fig. 4. Maintenance Intervals percentages

5 CONCLUSION

Medical equipment offers numerous precious services to sustain, enhance, and upgrade patient care. Risk management techniques can assist healthcare personnel proactively to manage and control medical equipment. When the equipment is appropriately maintained, it has more chance to work correctly, which might assist to keep away from delays in care, decrease the hazard of patient and staff injuries, and enhance patient outcomes. A maintenance program may be carried out in a variety of methods; so it is essential to think about the variety of methodologies that are accessible.

In this research, a multi-criteria decision-making model has been investigated using AHP approach in order to prioritize different pieces of medical equipment according to their criteria score and set the guidelines that help in determining a suitable maintenance strategy with its appropriate frequency and service provider. AHP is broadly utilized to solve MCDM problems as has been practiced in the majority of applications relevant to decision-making, particularly within the field of engineering. Analytic Hierarchy Process was noted to be relatively simple to utilize for the considered decision issue, because when the decision hierarchy is constructed accurately and with high attention, it is more likely to only concern the essential criteria regarding the discrimination of the alternatives. Additionally, it allows further and deeper analysis to be achieved compared to the manual and ordinary techniques that are commonly applied. Moreover, the background of the included decision makers and their experience is absolutely necessary in order to provide precise and valuable comparisons. The proposed hierarchy structure model includes eight criteria, namely 'Age', 'EM number', 'Environment', 'FMEA RPN', 'Failure consequence', 'Mission criticality', 'Technological complexity', and 'User experience'.

According to the use of age, FMEA RPN, failure consequence, user experience, repair cost, and mission criticality criteria, the model is described as a dynamic model as the grades of these criteria may differ along the equipment life time. For example, the 'age' differs as the equipment becomes older within time. Additionally, the staff may change, get more training, or gain new skills, which leads to changing the grade of "user experience" criteria, etc. Besides, the dynamic criteria depend on the healthcare organization, such as the 'Environment'. Consequently, the results obtained from the proposed model cannot be taken as a standard or reference, as the results depend on every equipment situation and the time that the data of such equipment are extracted.

Moreover, the proposed model makes use of each relative and absolute measurement in the application of AHP in order to estimate the weighting values for the criteria and their grades' intensities, and to evaluate the alternatives, i.e. the equipment.

The proposed model utilizes both relative and absolute measurements in the application of AHP, where the first are utilized in pairwise comparison of the assessment criteria and determining their relative weights with respect to the goal where, the weight of each criterion is identified by comparing its relative contribution to the goal with other assessment criteria. Thus, if a new criterion is added or an existing one is deleted from the hierarchy, all criteria have to be reassessed in order to find their new weights. On the other hand, absolute measurement methods are used for the ranking of medical equipment due to their large number and dynamic nature.

Also, estimating the consistency ratio in a pairwise comparison of the criteria enables the model to provide extra precise and consistent criteria weights compared to the direct assignment of the weights.

6 Recommendations and Future Work

Due to the model dynamicity, it should be repeated periodically to re-evaluate the critical score of each equipment. Moreover, a data base for the study of the proposed model has to be developed in order to simplify the classification process and make it shorter. Such a database has to contain a list of medical equipment and its assigned values for the static criteria utilized in the model.

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