Addis Ababa University

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Center of Biomedical Engineering

Optimized Medical Equipment Replacement Planning

This Thesis Is Submitted To, Addis Ababa University, Addis Ababa Institute Of Technology In Partial Fulfillment Of The Requirements For Degree Of Master Of Science In Biomedical Engineering

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Declaration

I declare that this thesis report, submitted to center of Biomedical Engineering at Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment of requirements for degree of Master of Science in Biomedical Engineering is entirely my own work with the exception of paraphrased or quoted work whose sources are appropriately cited and acknowledged in the references.

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Acronyms and Abbreviation

AIJ	Aggregate Individual Judgment
CMMS	Computerized Maintenance Management System
Cum_Repl	Cumulative Replacement
CR	Consistency Ratio
DHCP	Decentralized Hospital Computer Program
EAC	Equivalent Annual Cost
ERP	Equipment Replacement Planning
ERPS	Equipment Replacement Planning System
ERPW	Equipment Replacement Priority Weight
FDA	Food and Drug Administration
EFDA	Ethiopian Food And Drug Administration
IVD	In Vitro Diagnostic
FMCDM	Fuzzy Multi Criteria Decision Making
FMER	Failure Mode Effect Reasoning
FTA	Fault Tree Analysis
HEMS	Health Equipment Management System
HTA	Health Technology Assessment
HTM	Healthcare Technology Management
MCDM	Multi Criterion Decision Making
MCRDM	Multi Criteria Replacement Decision Making
MERSS	Medical Equipment Replacement Score System
NICU	Neonatal Intensive Care Unit
NPV	Net Profit Value
PRIW	Priority Replacement Index Weight
RIW	Relative Importance Weight
RP	Replacement Point
RRN	Relative Replacement Number
SQL	Structured Query Language
TED	Tenders Electronic Daily
TFN-AHP	Triangular Fuzzy Number-Analytic Hierarchy Process
TFNs	Triangular Fuzzy Numbers
TRF	Total Risk Factor
TSP	Travelling Salesman Problem
TSPDC	Travelling Salesman Problem Distance Calculation
UKNPSA	United Kingdom National Patient Safety Agency
UVM	University of Vermont
VA	Veterans Administration
WGMM	Weighted Geometric Mean Method

Abstract

Owing to the limited hospital replacement budget, making selection concerning medical device substitution is a difficult task. If the selection is not planned, it could have a serious impact within the replacement process, which in turn could cause a possible hazard and accident or fatality to patients. This might result in operational and maintenance costs and premature substitution of medical device while failing to replace other devices that need urgent replacement. In this regard, developing a replacement framework that allows optimal use of the available budget is crucial. Managing non-optimized medical device replacement planning in hospitals is often time-consuming and expensive. Competent replacement planning allows a significant reduction in operational and other maintenance related costs. However, most hospitals often replace their medical devices after they have stopped working for an extended period. On the other hand, when a medical device is replaced too early, that involves additional cost to the procurer. Therefore, a technique has to consider the decision-makers to avoid any risk for patients and additional costs to the hospital. This thesis study proposes a comprehensive framework for an optimized replacement planning for medical devices based on the available budget. The system is supposed to take into account the ever-changing technologies in the field of medical devices thereby avoiding the traditional replacement paradigm. The proposed method uses the TFN-AHP model to set up the assessment criteria and evaluate them by contemplating qualitative/quantitative replacement criteria and a Tabu Search based optimization technique to generate a prioritized list of devices to be replaced. Data was collected at selected hospitals picked as pilots in the current study through structured questioners. The model architecture includes fourteen quantitative and qualitative factors descending as main and sub-criteria, which can affect the replacement decision. The proposed model was applied on thirty-five selected medical devices in several categories where devices with higher ERPW (Equipment Replacement Priority Weight) take higher order for replacement and devices with lower ERPW take lower order for replacement. The proposed model uses both relative and absolute measurements to determine score weight for all criteria. Following analysis of the questioners distributed to respondents, eight main factors and three sub-factors were identified for affecting the replacement process. From the distributed questioners, 85% of the participants agreed that there was a major gap in their hospital when medical device has to be replaced. Furthermore, 73% of the respondents agreed that medical device replacement does not consider the most influential replacement factors. In addition, 89% of the respondents agreed that no device replacement plans is practiced in their hospitals. Moreover, 81% of the respondents agreed that hospitals are not accustomed to efficient replacement techniques. About 85% of the respondents

agreed that the available hospital budget affected the replacement process. In the proposed model, the identified eight main-factors and three sub-factors score weights were determined by using TFN-AHP technique. This technique combined with respondents scored criteria weights given for the 35 medical devices determined the ERPW for each individual device in order to prepare the priority list. The search for optimal/prioritized list of devices to be replaced was carried out using Tabu search algorithm based on TSPDC optimization setup. Results showed that the developed medical device replacement model quantitatively prioritized the medical devices.

KEYWORDS: Equipment Replacement Planning, Equipment Replacement Priority Weight, Multi Criteria Decision, Optimization, TFN-AHP, Tabu Search.

Chapter One

1. Introduction

Medical equipments are used to guide (monitor), substitute, correct anatomy or physiological processes contributing a great deal in healthcare. There are important high-tech healthcare innovations that enable effective treatment using less invasive techniques, and they improve healthcare consignment as well as patient outcomes. The deployed medical equipments proceed to diagnose, treat, or prevent diseases with no natural action in the body, as defined by the US Food and Drug Administration (FDA) [1]. These medical equipments, however, could be harmful if they are not replaced according to their replacement plan. The assessment conducted by the United Kingdom National Patient Safety Agency (UKNPSA) reported major equipment-related circumstances caused by equipment failure (43.8%), inappropriate use (29.3%), lack of training (12.3%), and poor maintenance (1.5%) [2].

In Ethiopia, due to lack of proper replacement planning, the medical equipments function with limited capacity at healthcare institutions to deliver adequate healthcare to patients and the hospital. The Research conducted regarding medical equipment management by the Ethiopian Ministry of Health indicated that more than 40-50% of medical equipments found in Addis Ababa public hospitals are non-functional, and about 50% of the medical equipments are non-functional in regional hospitals. The rising number of these non-functional equipments is due to poor equipment handling and utilization, frequent power surges, the age of the equipment, lack of end-user training, inadequate preventive maintenance, no vendor support, poor maintenance practices, and minimal knowledge regarding sophisticated equipments [3].

Worldwide, the medical equipment markets reached roughly US$200 billion in 2006, and estimated to increase to $400billion to $450billon in 2025. The united states (US) controls nearly 40% of the global market flowed by Europe (25%), Japan (15%), and the rest of the world (20%) [4].In Ethiopia, the annual market for medical devices reached nearly US$22 million [5]. Execution of such large amount of transaction should be preceded by advanced medical equipment replacement planning [6]. In most hospital setting, medical equipments are typically operated by physicians, nurses, or technicians and the equipments may be operated by mechanical, electronic, hydraulic and/or pneumatic mechanisms as well as software applications [7].

The healthcare service sector is growing rapidly day-by-day because of the advanced medical technologies as well as their application areas. This transformation affects patient care service, marketing strategies, and capabilities. To stay up with the changes, one key agenda among the prominent concepts in the healthcare sector is giving a robust health service continuously with functional medical equipment. To manage hospital budgets effectively, hospitals must identify equipment priorities to achieve goals consistent with their financial statement. Therefore, hospitals need to develop the right medical equipments management plan integrating relevant information and planning methodologies for the replacement of equipment in an optimized fashion [8].

Every equipment reaches end of its economic service life after a repeated use and its cost-benefit ratio decreases exponentially, its reliability dwindles, experiences high downtime which results in high operational and maintenance costs. When equipment is not reparable, the subsequent option is to replace it. Furthermore, medical equipments go obsolete to use and at that time replacement must be considered [9].

Most hospitals have limited budget to replace all their medical equipments when in need. A healthcare provider may have various categories of medical equipments in its inventory list. To replace these medical equipments, there are different ways to work out which equipment to replace immediately and a prioritized list of what equipment to replace is important [10]. In fact, most healthcare service organizations ,particularly those in low resource settings, do not possess adequate technical resources to develop/rectify the right replacement plans to replace their medical equipments. Absence of systematic planning to replace medical equipments introduces uncertainty in hospital activities [11].

1.1 Medical Equipment Risk Category

According to the Ethiopian FDA, medical devices are categorized into A, B, C, & D for in-vitro diagnostic (IVD) medical devices; into I, II, III & IV for those non- IVDs as also described in Fig. 1, Tab. 1 and Tab.2.

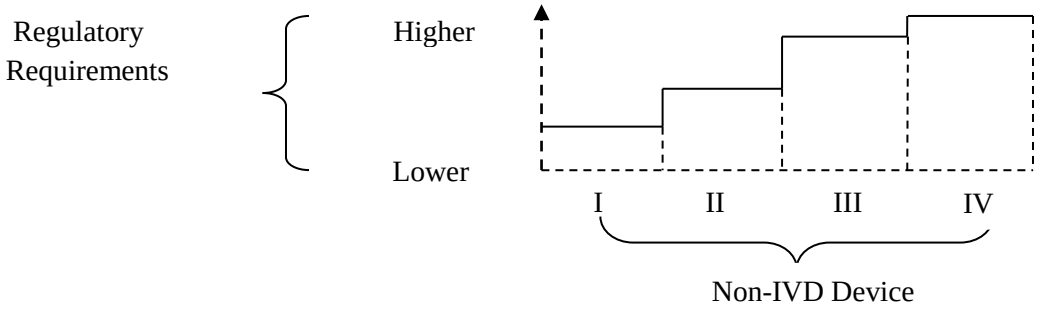


Figure 1: Non-IVD Device Classification.

CLASS	RISK LEVEL	DEVICE EXAMPLES
I	Low Risk	Syringes, examination gloves, nonelectric wheelchairs, microbiological culture media
II	Low-Moderate Risk	Hypodermic needles / suction equipment
III	Moderate-High Risk	Lung ventilator / bone fixation plate
IV	High Risk	Heart valves / implantable defibrillator

Table 1: The general approaches for medical device classification other than IVD medical devices

CLASS	RISK LEVEL	DEVICE EXAMPLES
A	Low Individual Risk and Low Public Health Risk	Clinical Chemistry Analyzer, prepared selective culture media
B	Moderate Individual Risk and/or Low Public Health Risk	Vitamin B12, Pregnancy self-testing, Anti-Nuclear Antibody, Urine test strips
C	High Individual Risk and/or Moderate Public Health Risk	Blood glucose self-testing, HLA typing, PSA screening, Rubella
D	High Individual Risk and High Public Health Risk	HIV Blood donor screening, HIV Blood diagnostic

Table 2: The general principles of IVD Medical Device classification

Medical equipments could also be classified based on their functions:

Life Support Devices: it consists of different intensive care unit apparatus like mechanical ventilators, ECG, anesthesia, infusion pump and the like.

Therapeutic/Rehabilitative Devices: includes surgical therapy, artificial organs, prostheses and orthotics.

Diagnostic Devices: includes devices used in bio-imaging and clinical diagnosis.

Analytical Devices: include laboratory examination equipments and other related devices like centrifuge, laboratory instruments, computers, and related tools.

1.2 Hospital Strategic Replacement Plan

The device substitution strategic plan is a process that hospitals adopt to achieve their replacement targets. Prospect strategic plans affect equipment repair or replacement decisions; therefore, medical equipments replacement decisions consider the available hospital substitution plans. In general, within the hospital, subsequent replacement strategy plans exist:

A. Individual Replacement Strategy: Whenever any item fails, it is necessary to replace it immediately.

B. Group Replacement Strategy: All items/parts need to be replaced after a particular period even if they are in good working condition. This ends up in replacement practice for the hospitals to become effective, improve health outcomes and supply sustainable health services [12].

1.3 Factors Necessary for Replacement of Equipment

All equipments hit its their service life and their net present value goes to negative which results in reduced reliability, increased downtime, safety problems, compromised treatment, increased running costs, changing legislations, or simply obsolescence and at this point replacement must be considered. Often times, hospitals respond to healthcare technology replacement requests by causing immediate, unplanned and unbudgeted replacement of expensive technologies. Examples of reactive replacement requests include the following:

- When a device fails at a critical time and maintenance is not an option;
- When a medical staff claims present technology is obsolete and need to be replaced;
- When repair is undergoing and parts and supports are no longer available;

Equipment replacement techniques take various criteria into consideration while developing equipment replacement plans: technical, financial/cost and safety factors.

1.3.1 Technical Factors

- **Obsolescence:** The existing equipment has good performance; unfortunately, new alternatives are available in the market that provide better results because of technological developments [13]. Obsolescence is usually the rationale why equipment has to be replaced before its estimated economic life expires.
- **Inadequacy***:* When the prevailing equipment becomes inadequate to satisfy demand or it is powerless to extend the assembly rate to specified level, then the question of replacement will arise.
- **Deterioration Due to Aging**: Deterioration is a process that usually arise from natural wear induced by usage and passage of time. As a medical equipment gets older, the maintenance and operational costs increase. Those are financial losses for organizations and therefore they tend to replace assets even they are in good conditions. To verify the state of deterioration of an asset, it is necessary to compare the performance of the same machine in different ages, regarding factors such as failure rate, average downtime, average cost per failure and average maintenance cost for a period [14].
- **Equipment Downtime**: measures the time the device is out of service because of breakdown.
- **User Errors:** These errors happen while identifying the areas where assets have failed.

1.3.2 Financial/Cost Factors

- High repair and maintenance costs can arise for several reasons and that may call for replacement.
- **Economic Life of Equipment:** This refers to the utmost length of usefulness where equipment expense could be a minimum [15].

1.3.3 Safety Factors

These factors are associated with sociological and humanitarian considerations with extensive effects:

- Replace equipment that causes undesirable noise as well as hazard during working conditions.
- During the time of equipment replacement, it causes unexpectedly displacement of workers.

In general, different techniques have been developed in the literature for use in medical equipment replacement. These techniques are either qualitative which employ a combination of factors listed above to estimate the correct replacement decision or quantitative that exploit mathematical models to work out the replacement threshold.

1.4 Medical Equipment Replacement Plan: Overview

Here we want to capture differences between replacement cultures in different set-ups considering Ethiopia, Egypt and the US.

1.4.1 Current Replacement Processes in Ethiopia (Addis Ababa)

In governmental hospitals found in Addis Ababa, there is scarcity of factual, scientific and inclusive assessment of medical equipment replacement decisions that do not occur in an exceedingly planned way and do not take under consideration pre-defined replacement criteria. It is estimated that only 28% of the medical equipments found in public hospitals in Addis Ababa are functional [16]. The non-functionality of the medical equipments mainly arise when the equipments get in trouble with different technical problems: equipment suffers a significant breakdown, increased failure rate and age, equipment outlook and utilization levels. Electrical power surges, absence of possible vendor end support, shortage of qualified technicians, user errors and administrative problems and benefits from new technologies are other causes that could trigger equipment replacement.

1.4.2 Current Replacement Plans in the US and Egypt

In well organized setups in Egyptian hospitals, medical equipment replacement strategies are substantially based on the history of its repairs and maintenance raw data (such as replacement dates) which evaluate the

types of equipment in need of substitution per several parameters and replacement criteria [17]. Equipment obsolescence, like functionalities and characteristics, that may result in scarcity of services within the hospital are all considered. During this process, the hospital department commonly makes a request for replacing the equipment to the right department for decision by the administration.

Veterans Administration (VA) hospitals throughout the US expend thousands of dollars and man-hours planning the acquisition of the latest medical equipment to stay their facility up so far with current technology so as to supply the foremost effective patient care possible. However, VA hospitals do not exert the same amount of effort planning for the replacement of medical equipment. Hospitals within the VA examine the Equipment Replacement Planning (ERP) tool by performing analysis of turned equipment and obtaining input data from the clinical engineering department. Equipment records are retrieved from the VA's Decentralized Hospital Computer Program (DHCP) equipment database employing a Structured Query Language (SQL) program. The information obtained using the SQL program is transferred into Microsoft Excel for further processing [18].

1.5 Statement of the Problem

The decision to replace medical equipment is typically a subjective process, particularly in governmental hospitals like those in Addis Ababa. Hospital administrators and hospital staff (physicians, nurses, laboratory technologist, imaging technologists, etc), purchasers, and biomedical engineers all contribute recommendations to urge and/or replace equipment supported by several factors. The present replacement policy in hospitals supports the highest service of equipment until it reaches the highest of its useful life, totally breakdowns and/or when there is vendor end support and the preferential judgment of hospital administrators and health workers as well as patients well being and safety. No specific decision making tools are utilized to identify what equipment to replace urgently and when the replacement should happen. In fact, most hospitals tend to focus on current or short-term needs with little or no consideration for future equipment replacement and perform inadequate assessment for essential equipment information. Moreover, they practice to replace equipment without considering factors that affect the replacement process. Traditionally, decision to replace an equipment is made mostly based on good sense and work experience of clinical engineers, doctors, nurses as well as administrative staff, risks associated to patients such as mortality, and technical failure of the equipment that is triggered by equipment malfunction, and only then, replacement analyses come into effect. This type of practice will have an impact on the right execution of replacement budget plan of the hospitals. Shortage of systematic planning of replacement introduces a large

amount of uncertainty in hospital activities, which might result in huge unexpected expenses. Replacing equipment without considering replacement decision factors increases chances of disruption of services and improper utilization of available budget. This calls for the development of a model that could be used to identify and inform healthcare institutions/hospitals how to prioritize equipment replacement practices in a systematic and methodological way. As a result, the model aspires to provide a general indicator for the need for replacement of any type of equipment.

1.6 Research Questions

The following research questions are relevant:

- How governmental hospitals in Addis Ababa replace medical equipment?
- Do governmental hospitals in Addis Ababa have replacement plans?
- Do governmental hospitals in Addis Ababa replace medical equipment based on well-defined replacement plan?
- What are the challenges as well as opportunities in medical equipment replacement systems in governmental hospitals?
- What is the difference between conventional and optimized medical equipment replacement plan?
- How effective are replacement practices in governmental hospitals in Addis Ababa?
- Do governmental hospitals in Addis Ababa use medical equipment replacement decision-making support system?

1.7 Research Objectives

1.7.1 General Objective

Design, develop and optimize a medical equipment replacement planning tool.

1.7.2 Specific Objectives

- To assess the current medical equipment replacement practices in selected hospitals;
- To identify major challenges in the existing medical equipment replacement system/s;
- To review medical equipment replacement practices in different countries;
- Propose an optimized medical equipment replacement planning system and check its effectiveness using medical equipments data set at selected governmental hospitals (in Addis Ababa and an Egyptian Hospital).

1.8 Relevance of the Research

Equipment replacement planning is part of the technology planning process. Immediate benefits include dramatic reduction in emergency purchases for replacement and improved safety as well as effectiveness of clinical technologies. The intent of the current thesis study is to develop an optimized medical equipment replacement plan to support decision-makers and extend effectiveness of equipment replacement practices in hospitals. It is understandable that effective equipment replacement practices lead to increased value of health service provision. The principal proposition of this thesis research is first to assess present replacement practices in governmental hospitals and address gaps observed. The intended study involves different elements of the replacement processes including equipment service and support, equipment function, cost benefits, clinical efficiency, user errors, and reliability and appeals for their optimal combination during the replacement process.

1.9 Scope & Limitations of the study

This study is conducted to optimize equipment replacement plans. The study focuses on designing and implementing optimization tools to improve present medical equipment replacement processes in hospitals. The study is limited to only governmental hospitals. Most hospitals have limited information about replacement budgets and replacement plans. In some hospitals, administrative and medical staffs are willing to replace existed medical equipment with new technology whether or not present equipment continues to be effective. This could significantly reduce the general productivity of the healthcare system due to in conceived expenditures on replacing devices. In this regard, some bias is expected with the data collected.

1.10 Fundamentals of Analytic Hierarchy Process (AHP)

In the late 1970's, the analytic hierarchy process (AHP) was first proposed by T. L. Saaty, who is an author of many operational analysis publications, as a complex, multi-criteria replacement decision making (MCRDM) method that is strong and helpful tool to resolve qualitative and quantitative criteria and used to solve decision-making problems. This tool consists of a hierarchy structure of complex problems into many divisions of problems/smaller pieces (main-criteria, sub-criteria, and alternatives). The separated subjective preference of an individual or group of experts on pairs of relevant factors assessing and analyzing decisions is executed by pairwise judgments comparisons. The tool assesses weights of importance of every criterion and therefore the relative measures are applied to compare to alternatives with one another [19]. According to Saaty [14, 16], AHP tools are used to organize problems into a hierarchy level and make judgment. Hierarchical level is usually categorized into *Goal (Level-I)*, *Criteria (Level-II)*, and *alternatives (Level-III)*.

Based on constructed hierarchy, decision-makers compare procedures to work out relative importance weight of criteria.

1.10.1 Forming the Hierarchy

The first step is developing a graphical representation based on goals, criteria, and alternatives. In a multicriteria decision-making problem, TFNs have been extensively used because of their simplicity in fuzzy applications where unpredictability exists [20]. Generally, the AHP approach involves three integrated levels:

a. *The Goal*: AHP measures medical equipment replacement priority.
b. *The Criteria*: attributes integral towards attaining replacement goal, e.g. equipment risk level, utilization rate, maintenance cost and the like.
c. *The Alternatives*: medical equipment to replace.

The traditional AHP approach, however, comes with its own drawbacks. Generally, AHP lacks flexibility, is imprecise and involves subjective judgment in its pairwise comparison process. To overcome these problems, hybrid AHP model with formal logic called Fuzzy-AHP model has been proposed in the literature where triangular fuzzy numbers (TFNs) and linguistic variables are used to achieve better accuracy and consistency with decision-makers (DM) judgmental system.

1.10.2 Triangular Fuzzy Number-Analytic Hierarchy Process (TFN-AHP)

In order to overcome the shortcomings of the AHP method and to resolve vagueness of the AHP criteria, a fuzzy extension of AHP called TFN-AHP has been proposed previously. This method is used to resolve hierarchical fuzzy problem [21]. The TFN-AHP method is a hybrid method that combines advantages of fuzzy set theory and the AHP. In TFN-AHP, fuzzy ratio scales are used to indicate relative strength factors and to construct fuzzy judgment matrix. A TFN, $\tilde{a}$, is mathematically expressed as:

$$\tilde{a} = (a^L, a^M, a^U) - - - - Equation: 1$$

where $\tilde{a}$ is a triplet of real numbers, a^L is lower number, a^M is middle number, a^U upper number, $a^L \leq a^M \leq a^U$. If $a^L = a^M = a^U$, then $\tilde{a}$ is a non-fuzzy number [22]. In a multi-criteria decision-making problem, TFNs have extensively been used due to their simplicity where uncertainty exists in qualitative and quantitative methods [23]. The membership function of a TFN is given by:

$$\mu(x|\breve{a}) = \begin{Bmatrix} 0 & x < l \\ \frac{x-l}{m-l} & if\ \ l \le x \le m \\ \frac{u-x}{u-m} & if\ m \le x \le u \\ 0 & if\ x > u \end{Bmatrix} ----Equation: 2$$

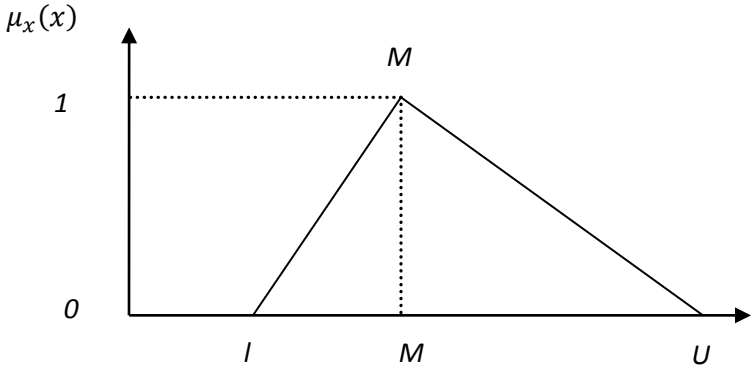


Figure 2: TFN and its member function (source: Prioritization of climate change adaptation approaches in the Gambia - Scientific Figure on ResearchGate).

Linguistic Term	Fuzzy Number	Triangular Fuzzy Scale	Reciprocal Fuzzy Scale
Equally Important	$\tilde{1}$	(1,1,1)	(1,1,1)
Intermediate Value	$\tilde{2}$	(1,2,3)	(1/3,1/2,1)
Moderately Important	$\tilde{3}$	(2,3,4)	(1/4,1/3,1/2)
Intermediate Value	$\tilde{4}$	(3,4,5)	(1/5,1/4,1/3)
Strongly Important	$\tilde{5}$	(4,5,6)	(1/6,1/5,1/4)
Intermediate Value	$\tilde{6}$	(5,6,7)	(1/7,1/6,1/5)
Very Strongly Important	$\tilde{7}$	(6,7,8)	(1/8,1/7,1/6)
Intermediate Value	$\tilde{8}$	(7,8,9)	(1/9,1/8,1/7)
Extremely Important	$\tilde{9}$	(8,9,10)	(1/10,1/9,1/8)

Table 3: Triangular Fuzzy Number [24].

Fuzzy-AHP method relies on classical AHP method; it uses a fuzzy judgmental comparison matrix interpretation supported by decision maker's attitude toward equipment replacement as proposed by H. Deng and presented in Table 3. In general, the application of TFN-AHP involves six essential steps [25]:

1. Determine unformed problem and explain distinctly objectives and outcomes.
2. Disintegrate the complex problem into a hierarchical arrangement with decision elements (criteria and alternatives).
3. Employ pairwise comparisons among decision elements using TFN numbers.
4. Use the eigenvalue method to judge relative weights of decision factors.
5. Check consistency property matrices to make sure judgments of decision-makers are consistent.
6. Aggregate relative weights of decision elements to induce weight for the criteria.

1.10.3 Triangular Fuzzy Number Pairwise Comparison Matrix

Using TFN, the decision-maker evaluates comparison matrix without loss of generality and all its parameters are given as a TFN matrix as:

$$\tilde{A} = \begin{bmatrix} (a_{11}^L, a_{11}^M, a_{11}^U) & \dots & (a_{1n}^L, a_{1n}^M, a_{1n}^U) \\ \vdots & \ddots & \vdots \\ (a_{m1}^L, a_{m1}^M, a_{m1}^U) & \dots & (a_{mn}^L, a_{mn}^M, a_{mn}^U) \end{bmatrix} - - - Equation: 3$$

1.10.4 TFN-AHP Group Decision Making Aggregation Method

TFN-AHP group decision-making process combines individual judgments, construct group choices from individual preferences, and calculates:

$$a_{ij}^* = \sqrt[k]{\left(a_{ij}^{*1} \times a_{ij}^{*2} \times \dots \dots \times a_{ij}^{*n}\right)} - - - Equation: 4$$

Figure 3 presents the general fuzzy analytic hierarchy process starting from formulation of the hierarchical problem, creation of fuzzy pairwise comparison matrix, to calculation of the aggregated group matrix weight.

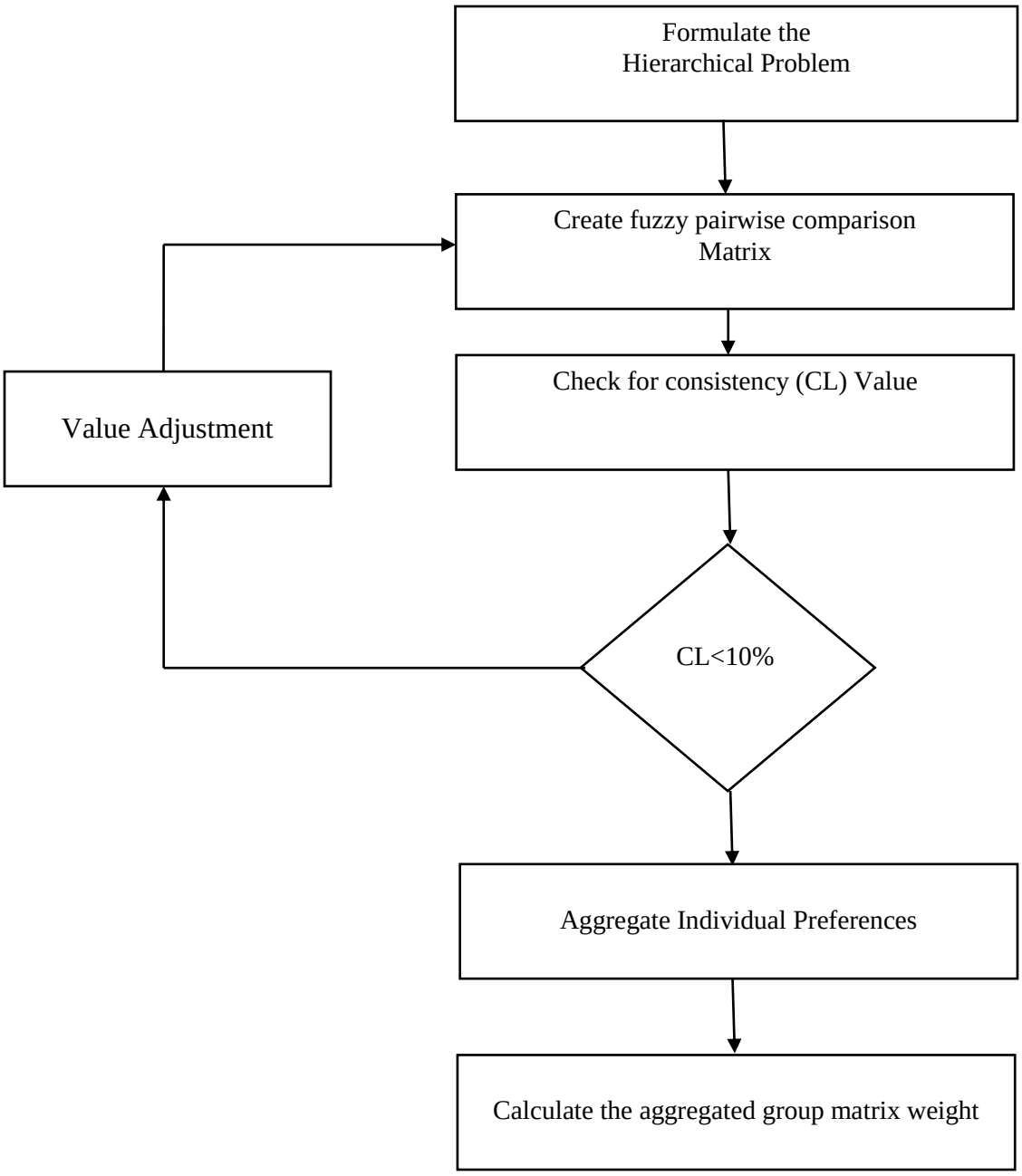


Figure 3: The fuzzy analytic hierarchy process. [26]

Chapter Two
2 Literature Review

To manage hospital equipment effectively, one needs to identify replacement priorities and understand goals (according to hospital budget plan). To maximize service provision, hospitals must design working equipment replacement plans. These plans integrate relevant source and planning methodologies for acquiring most recent equipment such as upgrades, replacement and yearly expenditures related to equipment repairs [27].

It is necessary to know the methodologies and the source guides employed in management of the medical technology deployed in complex healthcare systems. In most practices, they used to link technical capabilities to clinical requirements for current technology. Assessment takes into consideration capabilities of current technology and a socio-technical component that integrates necessities of decision-makers (in the current study these refer to physicians and other health institution managers) [28]. The use of an equipment database management may range from no availability to a very robust, accurate, multilayer database. Data access to outside resources like life expectancy data, FDA safety information, standards and regulations, manufacturers, and clinicians along with CE internal staffing levels and expertise will influence the method utilized. With this background in mind, three increasingly complex methods exist for use in medical equipment planning and reporting [29].

Basic Level: This is often practiced in institutions where a robust equipment management database and necessary resources do not exist. This system uses a straightforward, hand-written or computerized spreadsheet and basic data derived from free sources to organize a first-order equipment management plan. The data include primary information such as locations, device types, manufacturers, models and serial numbers. Once the inventory system is designed, the next piece of information that needs to be known is the equipment age. This is determined through hospital records such as purchase orders and asset lists. Another way is through communication with the manufacturer's customer service [30].

Comprehensive level: this includes use of online databases and analysis. The system uses a Computerized Maintenance Management System (CMMS) (Eg. EQ2's HEMS - Hospital Engineering Management System, Inc. Burlington, VT). The process used to create an equipment replacement plan depends on the existence of a decent historical database of the medical equipment. If one is employing computer program package for

medical equipment management, then the replacement assessment process may require an extra spreadsheet or database in order to manage the replacement information. The CMMS typically consists of control number, department, type, model, serial number, purchase cost and date placed in services, plus the age of the device, reliability value, level of support available, and notes regarding clinical obsolescence, and data associated with the whole number of repairs cost, and if possible, the categories of failures recorded. This can be based totally on age and reliability. Once the essential projection has been determined, each item is evaluated manually to regulate the replacement year to be provided to the department [31].

Advanced Level: this usually involves inventory data; equipment maintenance costs histories, hazards, and use problems, condition assessment, and life-expectancy databases. Such an advanced plan requires analysis for major medical equipment such as imaging systems, laboratory analyzers and other high-tech/high-cost systems. Factors like utilization, clinical input, upgrades, projected maintenance costs and reliability, and technological statues take on greater weight in decision-making and hence should be carefully analyzed [32].

2.1 Preliminary Equipment Replacement Plan

The preliminary equipment replacement plan is a strong program that analyzes seven key factors for reducing the evaluation of every item to one figure of merit, then to rank the candidates for replacement into a concise shortlist. Each item is examined with regard to the seven factors and classified into one in every several broad categories (Eg. low, medium, high). Some classifications are granted replacement point (RP) score zero; others are presented scores between 1 and 10 RPs. The sum of the RP scores for every one of the seven factors listed becomes the item's total score. The greater the score, the higher will be the priority for replacement. This analysis considers not only historical information but also estimated costs and reliability. The newest version of this program - the *Dynamic Asset Replacement Planner* is web-enabled, providing real-time assessment of client-based replacement information [33].

2.2 Removal Options

Although the standard use of replacement planning is to identify devices that need to be replaced one-on-one with a brand device, this is often not the particular option:

- Depending on funding, a piece of medical equipment identified for replacement can be designated as a backup device and kept in service with the understanding that if it fails, it would not be repaired.
- A device could also be employed in neighborhoods of lower acuity, especially if the problems are associated with standardization or technological status.

- A device could also be moved to a storage location if it would be used later. It should be either noted that the device will need to get on the regular inspection program or evaluated closely before it is returned to clinical service.
- A device could also be sold to a secondhand equipment buyer, to a different hospital, or to other purchasers. Typically, devices are sold in an "as-is condition", and the hospital should have a sign-off form to cutback liability.
- Devices should be usable, have all components for clinical application, including user and repair documentation, and, if available, spare-parts.

The device could also be used for parts and perhaps "cannibalized". Regardless, if the device is not being used again, it should be disabled. Many locales have regulations regarding the sort of materials that may be placed in a landfill. In one of the previous studies. it was noted that there is a list of factors that affects the medical equipment replacement process. Some factors are absolute factors calling for urgent replacement, such as serious safety issues or unavailability of parts. Other factors might have formulas associated with the data, which are used to determine whether a threshold has been exceeded (Eg. Age>125%) [34].

Factors including regulatory prohibitions or significant cost benefits might imply immediate replacement. Scoring of these factors requires knowledge of professionals like clinical engineering staff, administrative staffs, clinicians, BMETs, and others. Reduced costs or improved revenues, strong user preferences, and clear clinical advantages are some factors that put a device or system into a high-priority category for replacement. Various algorithms have been developed in the literature for such analysis, some employing a simple classification scoring system and formulas [35].

Another study proposed a replacement support model built by employing a multi-criteria approach. This is often a socio-technical methodology, which builds a quantitative evaluation tool based on decision-makers preferences. The methodology follows development of a cognitive map to identify replacement criteria and descriptors of impact (from structured questionnaires) and determination of weights of the standards in an exceeding decision [36].

In another study, Rajaskaran noted that making a decision regarding a replacement problem needs performing a quantitative assessment of the replacement criteria. The model considers the replacement decision based on the status of the vendor support. The model was validated by selecting eight different types

of Neonatal Intensive Care Units (NICU) based on their three years history and the model works out a priority list of equipment to be replaced. In this method, the type and number of equipment to be replaced are determined according to the available budget. The experiments carried out by the authors for the eight NICUs showed that 15% of the equipment should be replaced while 33% need to be tested, 33% are under surveillance and 19% could be maintained [37]. Another author noted that the ERP survey proved the importance of developing a tool that the VA can use to plan equipment replacement. The assessment also showed how Clinical Engineers rank equipment replacement indicators. Based on rankings and weighting factors, the ERP tool is created in Excel.

2.3 Traditional Asset Replacement

Hartman (2001) defined a traditional asset replacement analysis as something related to the provision of asset purchase for an outlined time based on selected factors like initial capital expenditure, Operating and Maintenance (O&M) costs, and salvage values. Furthermore, Hartman and Tan (2014) stated that a conventional asset replacement solution aims to generate a replacement policy that minimizes total cost while the interest rate and therefore the cost structure remains constant across an infinite horizon [38]. The traditional methodology also assumes similar O&M cost structures for replacement assets, accurate salvage value, and certainty in tax regulations. Moreover, the traditional model usually assumes asset performance deterioration with age or operating life. In addition to the aforementioned aspects, Rogers and Hartman (2005) stated that asset replacement should also consider technological advances in the market. However, the traditional model does not take into consideration aspects like changes in tax policies, variable utilization, unpredictability, and risks that may affect financial performance of an organization significantly. Figure 4 shows the variation of O&M, salvage value and equivalent annual cost (EAC = the annual cost of owning, operating, and maintaining an asset over its entire life).

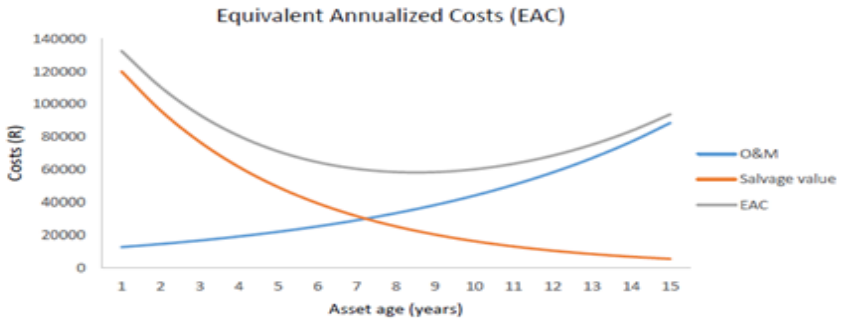


Figure 4: Determining the economic life of an asset.

2.4 Replacement Solution Approaches

Hartman and Murphy (2006) state that there are two popular approaches to define solutions for asset replacement problems. The primary approach is to specify a sequence of *keep* or *replace* decisions every time, also called a decision epoch, into consideration over a time horizon *X*. This approach is also called the "time zero" approach. A typical solution output using this approach is (K, K, R, K, K) which suggests that the asset should be kept for two decision epochs, replaced at the third decision epoch, and retained for the remainder of the time horizon. The second approach is to define a sequence of asset service lives, ages, or physical operating conditions. The sum of those asset service lives, ages, or physical operating conditions should sum to *X* times. The latter solution approach guarantees an optimal replacement solution for the present asset [39].

2.5 Uncertainty and Risk

Hartman and Tan (2014) noted that one amongst the foremost prominent obstacles in equipment replacement problems is the incorporation of unpredictability and risk. Knight (2012) described risk and unpredictability as two ends of an identical spectrum risk describing cases of known possibility and unpredictability cases of unknown probability. Risk is therefore measurable unpredictability. Stott (2012) stated that there are three basic styles of risk and uncertainty: discrete, continuous, and complex. Chang (2005) noted that it often aims to search out a replacement policy to reduce life cycle costs or to maximize expected NPV (Net Profit Value) when including uncertainty in asset replacement studies. Other causes of uncertainty in asset replacement include technological changes and horizon uncertainty that refers to the time that an asset is operational. Technological changes affect the cost and efficiency considerations within the replacement decision. According to Rogers and Hartman (2005), the majority of traditional asset replacement models assume that technology stays constant for the duration of the study period.

Replacement under these conditions can be avoided through a scientific approach to replace equipment in a prioritized fashion. Hospitals often have limited funding for capital purchases, with many under strict budgeting guidelines. The hospital's clinical engineering department is highly affected if it does not have a replacement plan when major repairs occur in older equipment. The best healthcare technology replacement planning system is facility-wide, covering all clinical equipment; utilizes accurate and objective data for analysis; is flexible enough to include non-equipment factors; and is futuristic by including strategic planning referring to clinical and marketplace trends and hospital strategic initiatives relating to technology [40].

Some approaches rely on qualitative data analyses based on a list of medical equipment with basic data in order to quantify the total cost of replacement and then establish a "cut off" line based on the budget available [41]. Another approach prioritizes replacements based on a combination of the above criteria using a software program that generates a relative replacement number (RRN) for each equipment [42]. The Equipment Replacement Score System (ERSS) is a similar automated technique focused on technological, safety, and mission-critical guidelines, with higher scores indicating higher replacement priorities [43].

Mathematical models using a quantitative technique provide better reasoning, hence a more accurate decision for replacement. One technique made use of model optimal policies machine replacement under technological changes [44]. It develops a brand new analytical technique based on deriving a nonlinear equation for optimal variable machine service life. However, the technique is complicated to be used for medical equipment and lacks other important factors such as safety and vendor support. Another model [45] uses an artificial neural network to classify the medical equipment life into three zones, depending on its service costs and age factors using a software program: Zone I (Remove Equipment), Zone II (Surveillance) and Zone III (Maintain Equipment).

There are two generic analytical approaches: induction and deduction. Inductive approaches constitute interpretation from specific cases to broad conclusion (bottom-up analysis). A good example is failure mode as well as effect reasoning (FMER). Deductive approaches constitute interpretation from overall to precise (top-down analysis). As a result, the technique identifies and prevents process problems before they occur. A good example is a deductive method developed in the literature based on an automated software program to identify equipment need of replacement where the system was designed based on safety, technical and financial criteria and rules were developed to assist which equipment to replace [46]. Another example is fault tree analysis (FTA) [47]. FTA is a statistical analysis approach that provides decision markers quantitative tools for replacement process. Using FTA, replacement action is taken as a final event because of some factors like service costs, useful life, and unavailability. Through theory of probability, replacement occurs if the replacement score is greater than 1 and else, the equipment does not have to get replaced [48]. The FTA model is based on a group of indicators that include hazards and alerts, vendor support, cost, and useful life ratio that influence replacement decisions [49]. In another study, a Fuzzy inference method was

proposed to work out equipment replacement plans. The model considers both quantitative and quantitative factors that truly influence replacement decisions [50].

Another authors proposed the analytical hierarchy processes (AHP) model that prioritizes equipment for replacement [51]. The method is known for its simplicity and ability to accommodate quantitative and qualitative data [52]. There are several studies that have proven AHP's effectiveness in health technology management. For example, the AHP technique was applied in order to support choosing neonatal ventilators during purchase procedure for a new women's health hospital; where model may be updated or adapted to different medical technologies whenever needed [53].

The AHP model has been used to prioritize medical devices in keeping device conditioning in equipment management systems in healthcare facilities. The model gives an actual analysis of entire risk devices by consideration of its several failure modes and evaluates their frequency, delectability, and consequences. The strategy is easy to implement and may decrease device failure rates. The AHP approach has also been used to buy a replacement CT scanner in step with user demands in healthcare facilities. Studies have shown a wider effect of the AHP approach on manufacturing of medical devices because it describes an explicit and effective method for selection of user demands [54]. This paper proposed an equipment replacement framework to identify and prioritize equipment using numerical output. The framework inscribes six replacement factors to address four replacement issues: *Equipment Service and Support*, *Equipment Function, Cost Benefits,* and *Clinical Efficacy.* To minimize model's sensitivity for subjective information, data were recorded using a "*yes-no"* (0, 1) scoring technique. Another author proposed an alternative conventional deterministic model applied on 146 medical devices in five different device categories.

Usually, there is a limited budget to replace all old medical equipment in various departments in hospitals. There are a number of ways to determine what needs to replace immediately, but it is very important to choose the most logical, the most defensible, and the one most understood by the majority of the key players. A researcher noted that the method to replace old equipment is usually depending on the failures caused by age, poor design, and user errors. The failure rate is usually a consideration in this equipment replacement methodology. The more often the item fails, the higher the likelihood it will be replaced. This is quantified by simply including the number of work orders [55]. The author also noted that before establishing the replacement process, all of the hospital equipment should be organized in a spreadsheet in a manner that the

item with the best need for replacement is listed at the highest and the item with the lowest need for replacement is placed at the bottom of the spreadsheet. The author additionally noted that to quantify what equipment to replace, a "cutting line" should be determined also termed as "the cumulative replacement cost column (Cum_Repl)" (see also Table 4). Another methodology focuses a complex approach and focuses on equipment most in need of replacement. It makes use of data available from the upkeep maintenance database and attempts to quantify those subjective items [56].

Equipment Name	Manufacturer	Model #	Serial #	Manuf Date	Life Exp (Yrs)	Repair Work-Orders	Cum Repair Cost	Orig Cost	Adv In Tech	Fit into 5-Yr Plan	Order of Merit Number	Repl Cost	Cum Repl
Audiometer	Brand D	ABCD 4	4	1997	10	15	$5,500	$4,646	5	5	16,7176	$4,646	$4,646
Audiometer	Brand F	ABCD 6	6	1987	10	5	$753	$4,646	5	5	10,6741	$4,646	$9,292
Centrifuge	Brand B	ABCD 2	2	1995	8	9	$158	$1,117	2	5	10,532	$1,117	$10,409
Vital Signs Monitor	Brand J	ABCD 10	10	1996	8	4	$240	$1,693	4	5	8,90852	$1,693	$12,102
Centrifuge	Brand A	ABCD 1	1	1997	8	3	$741	$1,117	2	5	8,32677	$1,117	$13,219
Centrifuge	Brand C	ABCD 3	3	1994	8	2	$312	$4,571	2	5	8,32677	$4,571	$17,790
Audiometer	Brand E	ABCD 5	5	1998	10	0	$-	$4,646	5	5	6,75	$4,646	$22,436
Scale	Brand K	ABCD 11	11	1996	14	0	$-	$725	5	5	6,75	$725	$23,161
EKG	Brand I	ABCD 9	9	1993	8	0	$-	$4,220	3	1	5,60948	$4,220	$27,381
EKG	Brand L	ABCD 12	12	1993	8	0	$-	$4,220	3	1	4,63602	$4,220	$31,601
EKG	Brand H	ABCD 8	8	1994	8	2	$350	$4,220	3	1	4,54088	$4,220	$35,821
EKG	Brand G	ABCD 7	7	1993	8	2	$75	$4,220	3	1	4,53555	$4,220	$40,041

Table 4: Complex method matrix, sorted by order of Merit Number and with the cut line drawn [57]

A simple model to identify and rank medical equipment for replacement was developed in another study [58]. In another study, a medical equipment replacement score (MERS) system was proposed as an automated system designed based on technical, safety, and mission-critical rules, where weight and score are assigned for every criterion. The final score was calculated in such a way that the device that has higher scores has high priorities for replacement [59].

Because of a variety of financial constraints, hospitals have become increasingly sensitive to the costs associated with their abundance of technology. As it is not uncommon for medium-sized hospitals (200-400 beds) to possess over 2,000 medical devices, this costs-especially replacement costs-can become substantial. In another study, a model was proposed to recommend and prioritize equipment replacement based on a numerical output. The model contains a ten-replacement factor, addressing four primary replacement issues: *equipment service and support*, *equipment function*, *cost benefits*, and *clinical efficiency*. Another author took into consideration three primary factors to assess equipment replacement decisions. The author considered the number of failures since the item was put into service, the cumulative cost of repairs, and item's age during equipment evaluation. This information provides a database with equipment's repair information, and therefore it is of vital importance that institutions keep this sort of database for equipment management [60].

A set of subjective factors that will be influential in the replacement decision were also included in the analyses. Such factors are obsessed with the interest of every organization, but the author suggested the advancement in technology to quantify the technological improvement brought by the replacement. Second suggested factor refers how well replacement of specific item fits the organization's five-year plan. Note that such model only evaluates the performance of the present equipment and does not make a comparison with the estimated costs of a challenger alternative [61].

As studied previously, decision making by only subjective matters is not accurate, and such factors are deemed unsatisfactory. These give rise to typical mistakes by decision-makers when performing quantitative assessment and do not take into consideration all replacement criteria. This calls for the development of alternative methodologies to deal with the problem. The major two approaches to the replacement of medical equipment, i.e. qualitative and quantitative, are summarized below.

A. **Qualitative Replacement Approach**

Qualitative approaches are based on the evaluation of a collection of criteria that result in the replacement of medical equipment. These criteria are a combination of various attributes that have control over replacement decisions, like age, lifecycle costs, risk assessment, durability, user satisfaction and the like. The replacement decision is approved in keeping with the contribution of those factors [62]. One study considered the prioritization of medical equipment by the following procedure: compile a listing of medical equipment with basic information, then sort the devices based on their retirement date, add another column calculating the

cumulative cost of replacement and then determine where the medical equipment "cut off" line should be based on the available budget for replacement and then prioritize replacement [63].

B. Quantitative Replacement Approach

Quantitative approaches for replacement of medical equipment are based on designing and/or developing a mathematical approach or generating a range of scores that contribute in a realistic and comprehensive way for replacement decisions. Mathematical approaches for replacement purposes usually consider employing set of criteria. Often, the output of these models generates thresholds that help and guide decision-makers to approve appropriate decision [64].

Equipment replacement processes are well studied in the literature dating back to the first 20th century with Taylor (1923) and Hotelling (1925) incorporating depreciation effects into asset replacement problems. Since then, evolution of asset replacement theory is well documented. Equipment replacement models and methodologies are developed for variety of industries and types of assets. Examples from automotive industry include developing replacement models for buses by Simms et al. (1984) and Keles and Hartman (2004). Dondelinger (2004) also investigated medical equipment replacement by developing a generic asset replacement and planning methodology. Others include equipment replacement planning system in hospitals by Rajasekaran (2005), and a medical asset replacement scoring system for use in prioritizing replacement actions by Taylor and Jackson (2005). Asset replacement is additionally a crucial decision-making process in healthcare services. Few commonly assumed asset replacement variables with their scope are listed in Table. 5. The table illustrates scope of asset replacement specializing in generic aspects to contemplate within asset replacement process.

Asset Replacement Variable	Scope of Variables
Number of assets	Single asset, fleet of assets, individual components
Time horizon	Finite, infinite
Variables to consider	Quantitative and/or qualitative
Replacement asset	Identical asset, technologically advanced asset
Costs	Stationary, on-stationary
Replacement action	Keep, repair, replace, capacity expansion

Table 5: Asset replacement variables [65]

Replacement theories and optimal life utilization are both important factors within the decision-making process for asset replacement and are studied by many financial or business experts (Cooper and Haltiwanger, 1990 and Jin and Kite-Powell, 2000). Optimal life utilization refers to the operation of an asset to its economic life. An asset's economic life is that optimal amount of time to retain and keep an asset operational, or the time and physical condition that satisfies an objective function for a specific period. Hartman and Murphy (2006), Thuesen and Fabrycky (2001) agreed that economic life of an asset is that age where Equivalent Annual Cost (EAC) is minimized. Moreover, in process of determining optimal life utilization of an asset, it is important to obviously state scope of variables included in calculations. Time horizon considered in this research is finite. In addition, both qualitative and quantitative variables that affect the replacement process are considered. Moreover, this study excludes expansion of an asset system thus specialized in keeping and repairing or replacing an asset.

2.6 Information Source for Equipment Price

Medical equipment price estimation is usually based on international price lists; for the aim of the current study, a possible approach is suggested to assemble information about medical equipment estimated prices from the web sources. Regardless of the information quality and reliability, the study focuses to identify all available data that includes price for the medical equipment type. As a result, for the purpose of this study, data was retrieved from different information sources, like public-procurement databases, sales contracts (purchase order), price quotes from sellers, price lists from manufacturers and distributors, scientific publications, health technology assessment (HTA) studies, reports from professional medical societies and other experts, and general news and internet discussions [66]. Additionally, public-procurement databases contain information about ongoing and completed tenders. In the EU, as an example, public organizations are governed by local public-procurement acts. Specific types of tender-related information on such procurements have to be published in an EU-wide database known as the "Tenders Electronic Daily" (TED) database. Among other data, the TED database contains information associated with results of public tenders: descriptions of purchased products, buyers, and suppliers, final achieved prices and related taxes. Various types of prices are available within the information sources mentioned above, including price list, sale prices, and others.

In general, equipment replacement planning has to date received only minimal attention while only few hospitals have formal mechanisms and define device replacement programs manually. Absence of usable

models results in premature procurement, which is costly, inappropriate or just unnecessary. There is still a research gap for making decisions to replace medical equipment optimal.

Chapter Three
3 Methodology

In this chapter, we explore equipment replacement model proposed in this thesis for use in prioritization and optimization. The different sections describes in detail the method and materials used including sample data collection and analysis as well as software-developing tool. Both qualitative and quantitative approaches were employed to understand the equipment replacement system. The TFN-AHP approach has been used for equipment prioritization and the Tabu search algorithm for solving the developed optimization problem. A rough schematic of the developed framework is depicted in Fig. 5.

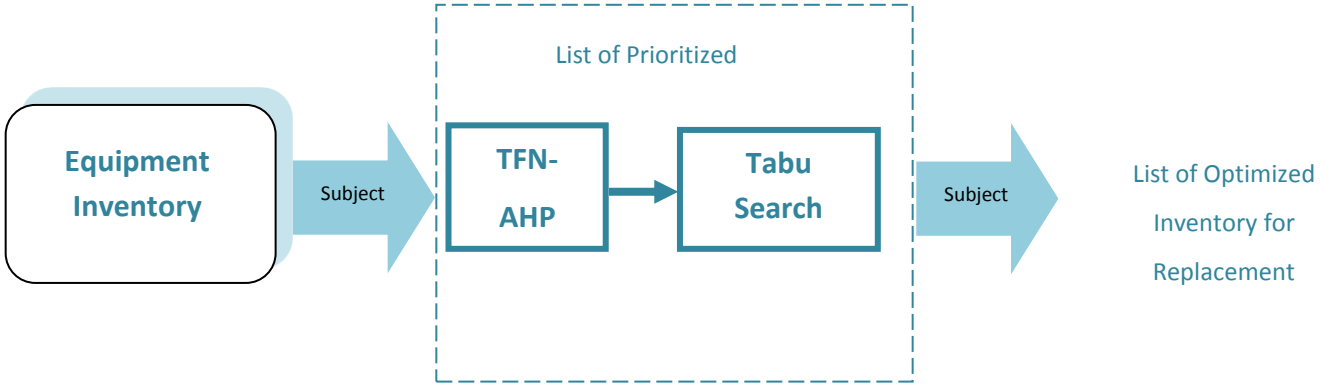


Figure 5: TFN-AHP and Tabu search models for prioritization and optimization of replacement of medical equipment.

Because of their limited equipment replacement plan (ERP), governmental hospitals often replace their medical equipments without considering important factors that affect the replacement process. There is a practice to replace their equipment based on various non-structured reasons. As a result, healthcare institutions do not ensure effective re-use or safe disposal of their equipment. The governmental health institutions do not give attention to prioritization to replace the equipments [67]. While, the equipment replacement process should be an integral part of the entire healthcare technology management. For the purpose of the current study, judgmental study selects the equipment replacement criteria weight employing a process of weighting alternatives (medical equipments evaluating criteria that affect the replacement process).

3.1 Description of the Study Area

This study was executed at selected governmental hospitals in Addis Ababa, a city with estimated 3,194,999 populations [68]. The city is found at 8.9806^{o}N, 38.757^{o}E and at an elevation of 2355 meters above the sea level with a total area covering 527 km².

3.2 Sample Size Calculation

For the purpose of this study, a sampling proportion formula (https://unstick.me/determine-the-sample-size-study/) was used to determine the precise sampling size given in Eqn. (5):

$$n_o = P \times (1-P) \times \left(\frac{Z}{e}\right)^2 \quad --- \textit{(Equation: 5)}$$

where n_o is the sample size, Z^2 is the normal value distribution (1.96 based on the level of 95 % confidence), e is the desired level of precision (0.05), P is estimated proportion of an attribute of 0.5 variant of success. Based on Eqn. (5), the sample size was calculated to be n_o=384. In Eqn. (5), it was assumed a maximum variant proportion of $P=0.5$. For this study, an estimated 1000 sampling population were considered.

The sample size in Eqn. (5) is adjusted to provide an appropriate proportionality for estimated population based on the following equation:

$$n = \left[\frac{n_o}{1+\left(\frac{n_o-1}{N}\right)}\right] \quad --- \textit{(Equation: 6)}$$

where n is the adjusted sample size and N is the population size. Accordingly, a total sample size of 278 participants was assumed for this study. Eventually, to determine the sample size for the number of hospitals for this research, an estimated 10 sampling population were considered. Thus by using Equ. 6, a total sample size of 9 hospitals was assumed for this study.

3.3 Research Method

The medical equipment replacement model is based on a prioritizing optimization scheme that consists of three main phases. First, the replacement parameters are defined. Next is the model phase that makes use of TFN-AHP and Tabu search. Finally, it aims to validate the built model. To achieve the stated objectives, the study made use of multi-criteria TFN-AHP decision-making tools for prioritization of medical equipments by evaluating their relative weights and Tabu search for optimizing the prioritized list based on the available hospital budget. The data used for the study were collected through direct observation, interviews, questioners and review of documents from the hospitals.

Both quantitative and qualitative approaches were employed. Primary knowledge source were gathered from chosen hospitals. Qualitative evidences were generated through secondary sources that include physicians and biomedical experts. Questionnaires survey, interviews and site considerations were systematic input collection tools. Colleagues reviewed initial versions of the validity and reliability of the questionnaires while care was given to avoid sequential bias in responses, and questionnaire was pre-tested and evaluated qualitatively throughout. Quantitative data was interpreted via SPSS version 23 and analyzed using descriptive statistics.

3.3.1 Direct Observation

Direct observation was used for collecting required relevant resources from the hospital. Direct observation was used as a method to assess existing replacement techniques based on important documents like internal and external technical reports (maintenance, spare-part, purchase, etc). The data is used to perform quantitative analysis and draw a statistical conclusion from the observations.

3.3.2 Structured Interviews

Interviews were directed by posing questions with respect to an equipment replacement model with various stakeholders in the hospital including doctors, nurses and biomedical engineers. Qualitative evidence obtained from site interviews and direct observations allow understanding of the physical conditions of the equipments. The qualitative data were compiled to support the quantitative evidences revealed in the subsequent sections and show the outcomes are valid, reliable, and significant.

3.3.3 Questionnaires

In order to assess the equipment replacement system in the hospitals, 278 questionnaires were distributed. Out of the 278 questionnaires, there were 241 respondents. The questioner data were interpreted using SPSS version 23. Questionnaires were designed and circulated in an approach to catch equipment replacement perspective in the hospital management, doctors, clinical staff, and biomedical engineers to know the predominant medical equipment replacement practices in governmental healthcare service providers.

3.4 Data Collection

The objective of the medical equipment replacement decision-making process is to reach a decision by identifying the replacement criteria and by scoring priority weight to the medical equipments that have to be replaced. The data collection in this study involved gathering information about the current replacement practices by preparing a preliminary questionnaire, which is designed and distributed among the respondents

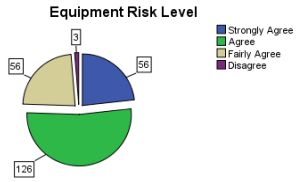
(medical director, physicians, nurses, laboratory technologists, radiographers, administrative staffs and biomedical engineers) to determine the foremost criteria that influence equipment replacement in governmental hospitals. Using SPSS statistical software, the collected data was analyzed and presented in a table. The rating framework was based on the five points likert scale (*strongly agree, agree, fairly agree, disagree, strongly disagree*).

3.4.1 First Questioner

The first questioner was used to determine a replacement criterion (eight main-criteria and six sub-criteria: Equipment Risk Level, Technology Obsolescence, Technology Adaption, Physical Deterioration, Utilization Rate, Reliability, Failure Rate, Down Time, Equipment Life Ratio, Maintenance Cost, User Error, End Support, Vendor Support and Alternative Support). Tables A through N present descriptive statistical analysis carried out per each replacement criterion. The questioner has been attached on Appendix 1.

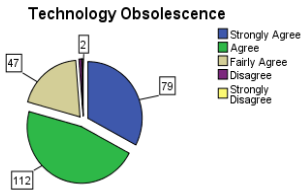
A: Equipment Risk Level

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	56	23.2	23.2	23.2
	Agree	126	52.3	52.3	75.5
	Fairly Agree	56	23.2	23.2	98.8
	Disagree	3	1.2	1.2	100.0
	Total	241	100.0	100.0	



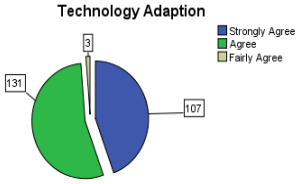
B: Technology Obsolescence

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	79	32.8	32.8	32.8
	Agree	112	46.5	46.5	79.3
	Fairly Agree	47	19.5	19.5	98.8
	Disagree	2	0.8	0.8	99.6
	Strongly Disagree	1	0.4	0.4	100.0
	Total	241	100.0	100.0	



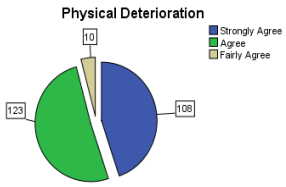
C: Technology Adaption

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	107	44.4	44.4	44.4
	Agree	131	54.4	54.4	98.8
	Fairly Agree	3	1.2	1.2	100.0
	Total	241	100.0	100.0	



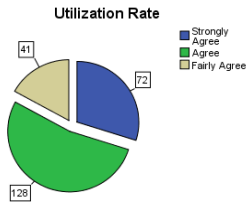
D: Physical Deterioration

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	108	44.8	44.8	44.8
	Agree	123	51.0	51.0	95.9
	Fairly Agree	10	4.1	4.1	100.0
	Total	241	100.0	100.0	



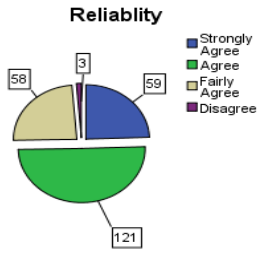
E: Utilization Rate

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	72	29.9	29.9	29.9
	Agree	128	53.1	53.1	83.0
	Fairly Agree	41	17.0	17.0	100.0
	Total	241	100.0	100.0	



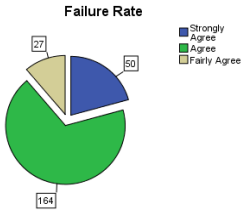
F: Reliability

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	59	24.5	24.5	24.5
	Agree	121	50.2	50.2	74.7
	Fairly Agree	58	24.1	24.1	98.8
	Disagree	3	1.2	1.2	100.0
	Total	241	100.0	100.0	



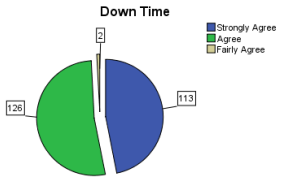
G: Failure Rate

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	50	20.7	20.7	20.7
	Agree	164	68.0	68.0	88.8
	Fairly Agree	27	11.2	11.2	100.0
	Total	241	100.0	100.0	



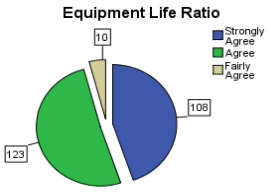
H. Down Time

	Frequency	Percent	Valid Percent	Cumulative Percent
Strongly Agree	113	46.9	46.9	46.9
Agree	126	52.3	52.3	99.2
Fairly Agree	2	0.8	0.8	100.0
Total	241	100.0	100.0	



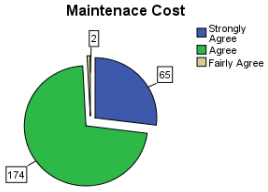
I: Equipment Life Ratio

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	108	44.8	44.8	44.8
	Agree	123	51.0	51.0	95.9
	Fairly Agree	10	4.1	4.1	100.0
	Total	241	100.0	100.0	



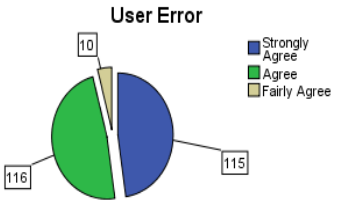
J: Maintenance Cost

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	65	27.0	27.0	27.0
	Agree	174	72.2	72.2	99.2
	Fairly Agree	2	0.8	0.8	100.0
	Total	241	100.0	100.0	



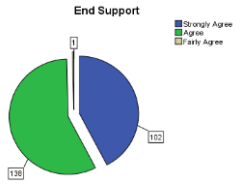
K: User Error

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	115	47.7	47.7	47.7
	Agree	116	48.1	48.1	95.9
	Fairly Agree	10	4.1	4.1	100.0
	Total	241	100.0	100.0	



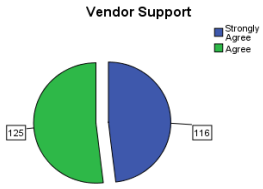
L: End Support

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	102	42.3	42.3	42.3
	Agree	138	57.3	57.3	99.6
	Fairly Agree	1	0.4	0.4	100.0
	Total	241	100.0	100.0	



M: Vendor Support

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	116	48.1	48.1	48.1
	Agree	125	51.9	51.9	100.0
	Total	241	100.0	100.0	



N: Alternative Support

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Agree	122	50.6	50.6	50.6
	Agree	118	49.0	49.0	99.6
	Fairly Agree	1	0.4	0.4	100.0
	Total	241	100.0	100.0	

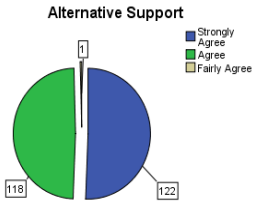


Table 6: A-N indicates the 14 equipment replacement criteria (eight main-criteria and six sub-criteria).

Based on the results obtained from the SPSS software, 126, 112, 131, 123, 128, 121, 164, 126, 123, 174, 116, 138, 125, 118 of the respondents agreed that the equipment replacement process is affected by the criteria mentioned in A to N, respectively. This implies that the specified criteria are applicable for the intended replacement model. Table 7 summarizes the 8 criteria and 6 sub criteria and the frequency and percentage of respondents who agreed with the criteria with the corresponding bar plot shown in Fig. 6.

Lot	Criterion	Frequency	Percent	Remark
C_1	Equipment Risk Level	126	52.3	Agree
C_2	Technology Adaption	131	54.4	Agree
C_{21}	Technology Obsolescence	112	46.5	Agree
C_{22}	Physical Deterioration	123	51.0	Agree
C_3	Utilization Rate	128	53.1	Agree
C_4	Reliability	121	50.2	Agree
C_{41}	Failure Rate	164	68.0	Agree
C_{42}	Down Time	126	52.3	Agree
C_5	Equipment Life Ratio	123	51.0	Agree
C_6	Maintenances Cost	174	72.2	Agree
C_7	User Errors	116	48.1	Agree
C_8	End Support	138	57.3	Agree
C_{81}	Vendor Support	125	51.9	Agree
C_{82}	Alternative Support	118	49.0	Agree

Table 7: Determined criteria for decision-making

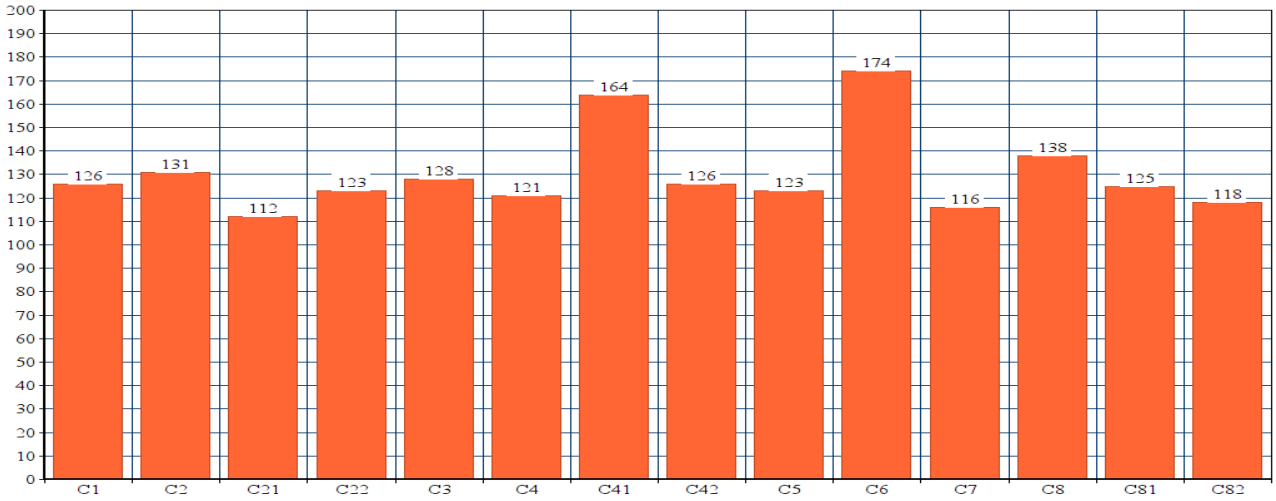


Figure 6: Determined replacement factors.

3.4.2 Second Questioner

The second questioner was developed and disseminated for twenty experts in order to collect their suppositions by employing a *triangular fuzzy number* (TFN) in order to determine the relative importance weight (RIW) for the replacement criteria. During this analysis, doctors and biomedical engineers were specifically selected. Among the twenty, fourteen rounded out questionnaires were returned back (the second questioner is attached in Appendix 2). The group of experts expressed their thoughts by completing the judgment matrix which includes one comparison matrix for main-criteria and one-comparison matrix for

subcriteria, the overall comparison matrices being twenty-eight (see Appendix 2). The criteria weight determination was based on the "Saaty scale 1-9" [69].

3.4.3 Third Questionnaire for Score Determination for Every Medical Equipment

To determine the scoring weight for the selected equipment associated with the eight main criteria and the three sub-criteria, the third questioner was designed. The third questioner aimed to present the scored value for all medical equipment that is related to the replacement criteria (The third questioner attached in the Appendix 3). For the purpose of this study, 50 questioners were distributed and there were 35 respondents. The collected data were analyzed by using excel and SPSS. The data collection and analysis was executed using the methods mentioned in the previous chapter. The next steps were modeling the equipment replacement problem using *TFN-AHP* for equipment prioritization and optimization on a Matlab platform.

3.5 Model Construction

The proposed model considers different replacement factors that affect the replacement process based on e*quipment service and vendor-support*; e*quipment function*, *economic benefits*, and *clinical efficiency*. A rough workflow diagram for the proposed system is depicted below in Fig. 7. The proposed replacement model is built based on a multi-criteria approach using a compensatory geometric aggregation method. This procedure was chosen because of its simplicity as it helps decision-makers to realize a better problem understanding by decomposing the problem into smaller pieces and analyze separately. Generally, three basic phases are required to develop a given equipment replacement model (*Bana e Costa & Beinat, 2005*).

i. Problem definition
ii. Replacement model structure
iii. Result analysis.

I. Defining a Hospital Replacement Problem

The proposed study selectively chosen an approach that identifies equipment replacement problem based on various questioners distributed in selected hospitals to understand their current replacement practices. The equipments are grouped under different categories in order to develop a general medical equipment replacement model. Groups of decision-makers are involved to collect information in order to determine criteria weights.

II. Develop Replacement Structure

Based on the analyzed results from the distributed questioners, a replacement structure was designed as depicted in Fig. 8 that depicts value tree with replacement criteria.

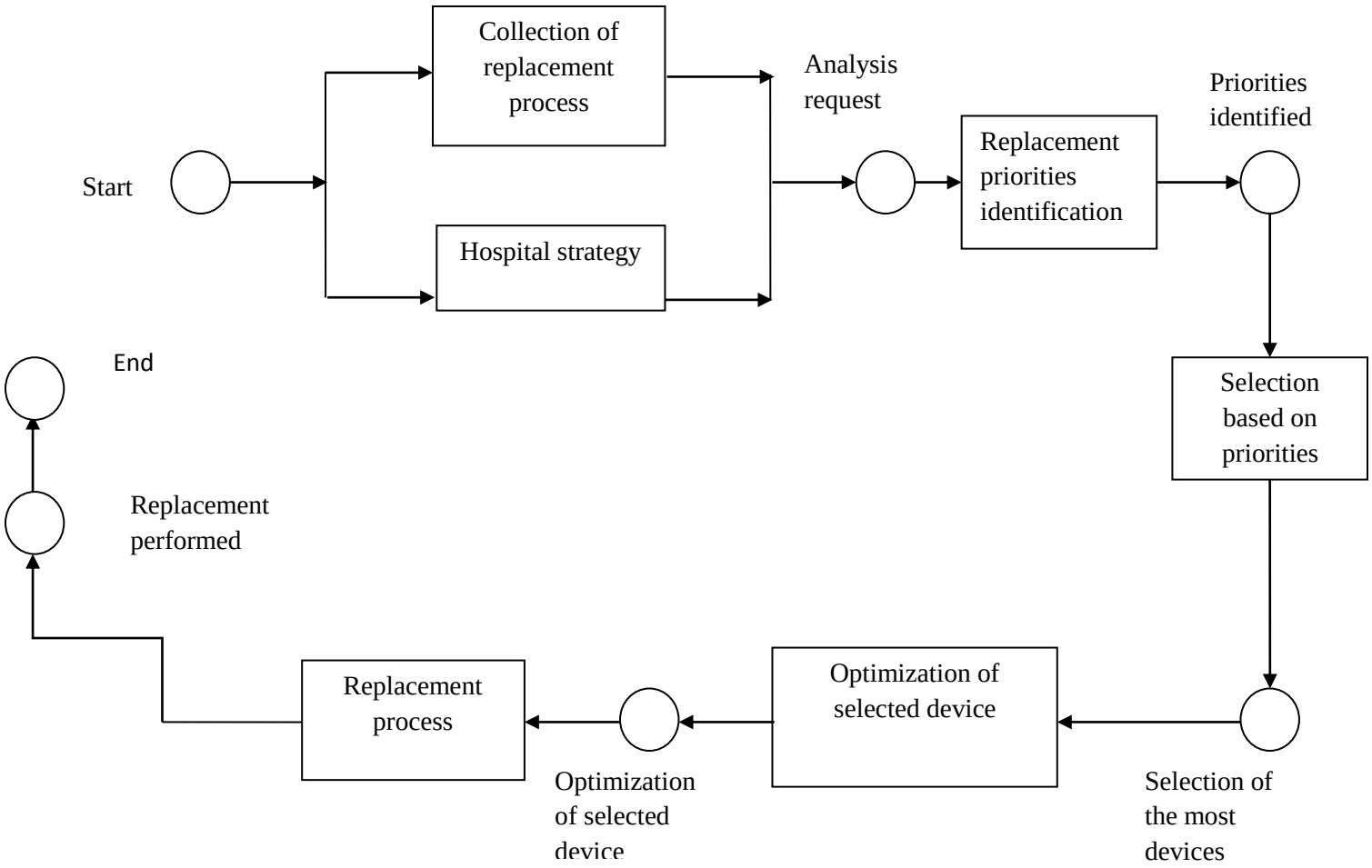


Figure 7: Workflow diagram for replacement process.

III. Analysis of the results (*Banae Costa & Beinat, 2005*).

The TFN-AHP approach was adopted for decision-making. The method combines individual judgment into group judgments and construct a group preference from individual preferences. The model is then able to rank inventory list according to their prioritized scored weight and performs Tabu search for optimization for replacement considering available hospital budget. A flowchart of the replacement strategy has been depicted in Fig. 9 comprising of three major stages.

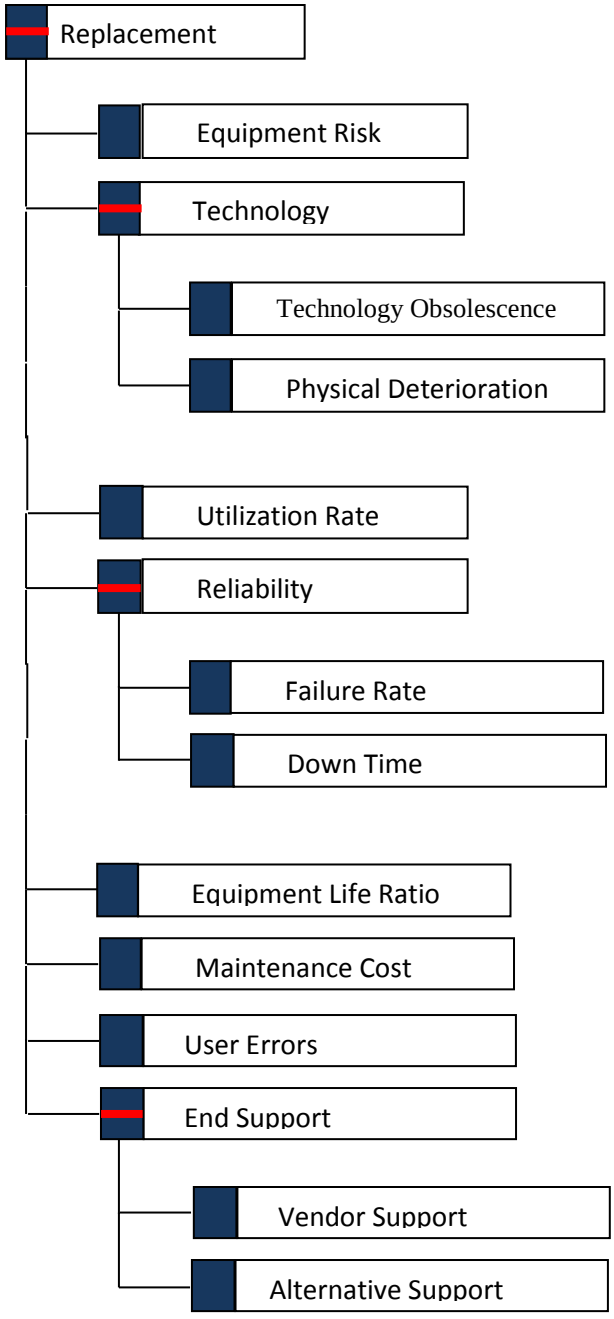


Figure 8: Value tree with replacement criteria.

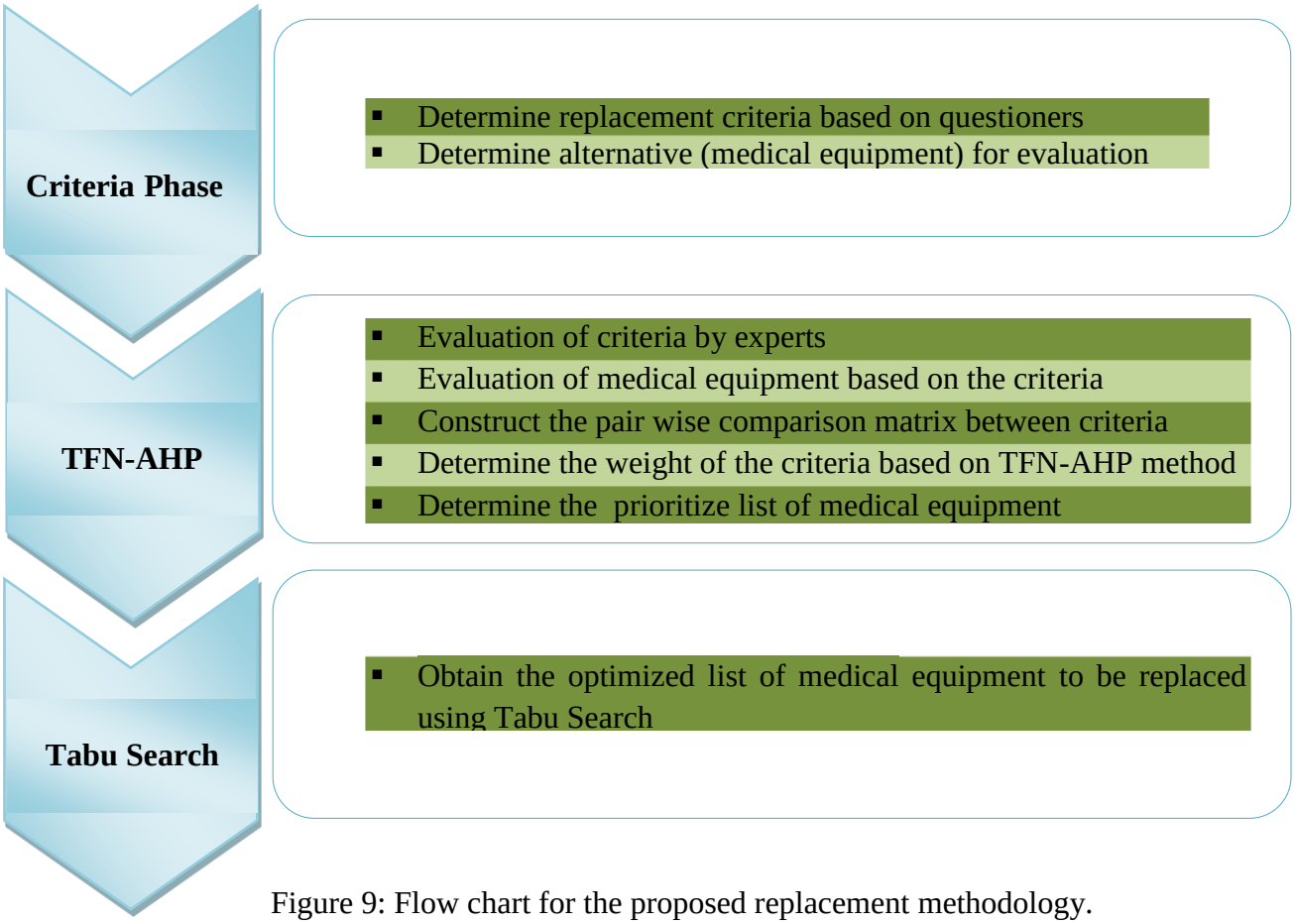


Figure 9: Flow chart for the proposed replacement methodology.

3.6 TFN-AHP Model Structure

Comparison criteria based on the TFN-AHP scale enable decision-makers to incorporate experience and knowledge directly to indicate how many times one criteria dominates another criteria (Millet, 1997). The proposed prioritization equipment for replacement is a multi-criterion decision-making (MCDM) problem and it uses the TFN-AHP replacement methodology. The proposed *TFN-AHP* model consists of three steps:

Step 1: Identify goal/s (medical equipment replacement prioritization in our case).

Step 2: Perform device criteria evaluation (second level of the hierarchy structure).

Step 3: The alternatives (third level of the hierarchy structure).

The proposed hierarchy structure contains eight main-criteria identified at the top level, where some of these are divided into sub-criteria. The hierarchy structure for prioritization of medical equipment replacement shows in Fig. 10.

3.7 Equipment Scoring System (Total Weight)

To determine the equipment total weight, two forms of measurements were used: *relative* and *absolute measurement.* The relative measurement is applied for pair wise comparison between the different criteria in order to determine their relative weights with respect to the problem goal (prioritization of medical equipment for replacement). On the other hand, absolute measurement determines the equipment weight for each device compared per each criterion. Furthermore, the devices are evaluated using each criterion and the total weight is computed accordingly.

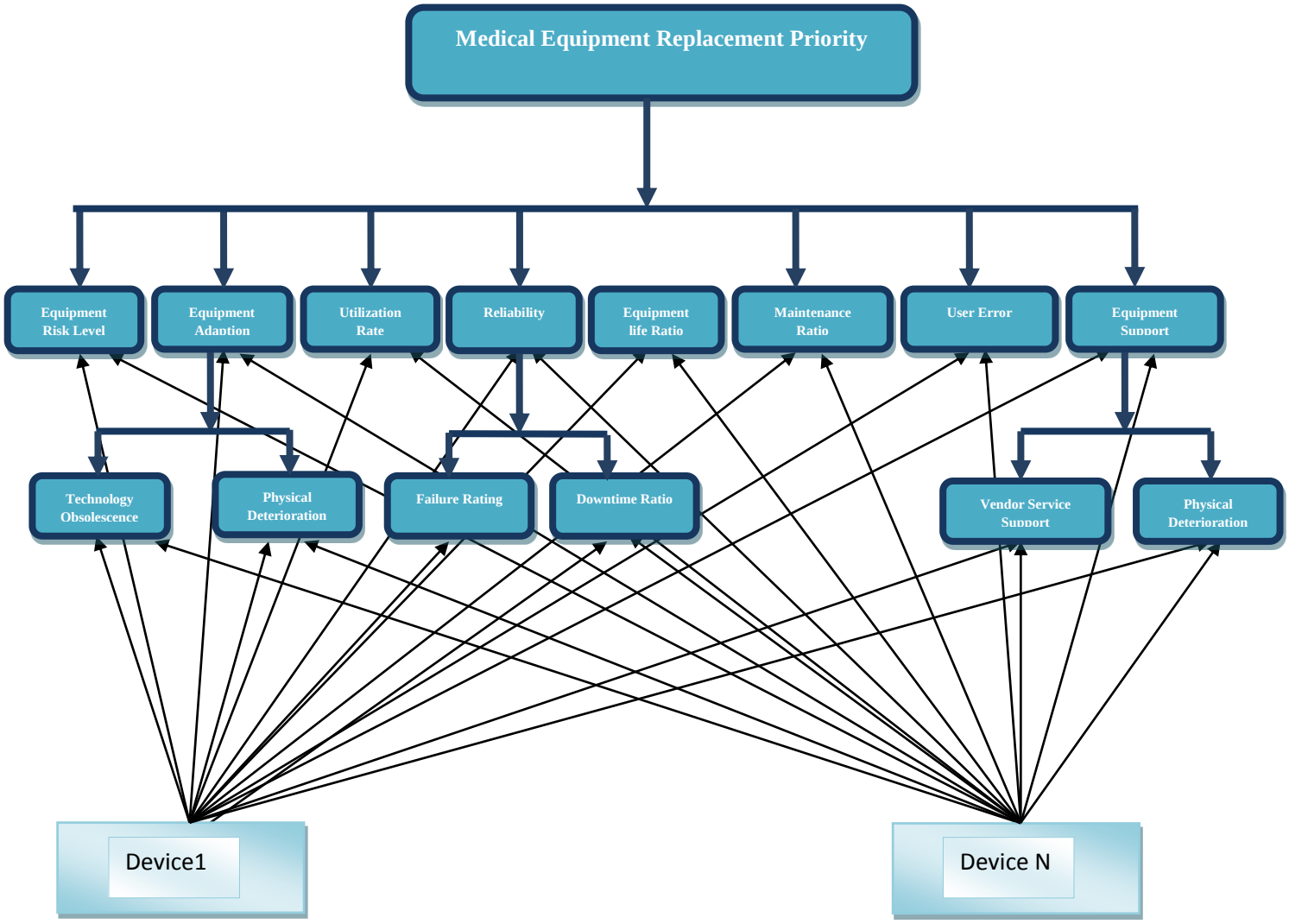


Figure 10: Hierarchy structure for prioritization of device replacement.

The following steps show summary for the replacement process:

- Determine the effective and independent main-criteria and sub-criteria;
- Using relative and absolute measurement, calculate weights for all main-criteria and sub-criteria;

- ❖ Evaluate each device with the respective scored criteria and determine the replacement ranking order for every device; and
- ❖ Use Tabu Search for optimization and generate final list of prioritized medical equipment.

The total score for each device was calculated as:

$$TS_i = \sum_{j=1}^{m} W_{ij} S_j = 1 - - - Equation: 7$$

where TS_i is the total score for the i^{th} device, i=1… n, n: is the total number of devices, $j = 1, \ldots . m$, m is the number of criteria, W_i is the weight of the i^{th} device with respect to the j^{th} criterion, and the S_{ij} is the score value of the-j criterion, and $\sum_j^n W_i = 1$.

3.8 Medical Equipment Evaluation Based on Risk Category

For the purpose of this study, thirty-five equipments were selected. The selected equipments were in any one of the following three categories:

- ✓ **High-Risk Devices**: refers those equipments used in life support, key resuscitation, critical monitoring, energy emitting, and other devices whose failure or misuse could seriously injure patients or staff (Eg: Anesthesia units and vaporizers, Defibrillators, X-ray, and infusion pumps).
- ✓ **Medium-Risk Devices:** include diagnostic instruments whose misuse, failure, or absence (Example: out of service with no replacement available) have significant impact on patient care, but not likely to cause direct serious injuries (Eg: Ultrasonic nebulizers, Diathermy).
- ✓ **Low-Risk Device:** are devices whose failure or misuse is unlikely to result in serious consequences (Eg: sphygmomanometer, stethoscope**)**.

Listed below are the 35 medical equipments selected in the current study with their risk scores. The list is composed of those equipments commonly found in hospitals.

No	Medical Equipment	Risk Score
1	Oxygen Concentrator	3
2	Defibrillators	3
3	Mechanical Ventilator	3
4	Anesthesia Machine	3
5	Infant Incubator	3
6	X-ray	3
7	Infusion Pump	2
8	Ultrasound	3
9	Baby Warmer	3
10	Ultrasonic Nebulizers	2
11	ECG Machine	3
12	Autoclave	2
13	Laboratory Medical Centrifuge	2
14	Pulse Oximeter	1
15	Clinical Chemistry Analyzer	2
16	Diathermy	2
17	Hematology Analyzer	2
18	Bedside Monitor	2
19	Vertical/Horizontal High	2
20	High Pressure Suction	2
21	Magnetic Resonance	2
22	Hot Air Oven	2
23	Mini-Shaker for immunology	2
24	Computed Tomography(CT)	2
25	Sphygmomanometer	1
26	Surgical Light	2
27	Flat Bed	2
28	Slit Lamp	2
29	Stethoscope	1
30	Operating Table	2
31	Freezer	1
32	Audiometer	2
33	Stretcher Wheeled	1
34	Ophthalmoscope	2
35	Laboratory Microscope	2

Table 8: Medical equipment based on their risk factor

EXPERT-1	C1			C2			C3			C4			C5			C6			C7			C8		
C1	1	1	1	1	2	3	3	4	5	4	5	6	1	2	3	2	3	4	1	2	3	1	2	3
C2	0.333333333	0.5	1	1	1	1	1	2	3	4	5	6	3	4	5	2	3	4	1	2	3	1	2	3
C3	0.2	0.25	0.3333	0.3333	0.5	1	1	1	1	1	2	3	1	2	3	3	4	5	1	2	3	1	2	3
C4	0.166666667	0.2	0.25	0.1667	0.2	0.25	0.3333	0.5	1	1	1	1	6	7	8	6	7	8	2	3	4	1	2	3
C5	0.333333333	0.5	1	0.2	0.25	0.3333	0.3333	0.5	1	0.125	0.1429	0.1667	1	1	1	5	6	7	3	4	5	1	2	3
C6	0.25	0.3333	0.5	0.25	0.3333	0.5	0.2	0.25	0.3333	0.125	0.1429	0.1667	0.1429	0.1667	0.2	1	1	1	7	8	9	1	2	3
C7	0.333333333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.25	0.3333	0.5	0.2	0.25	0.3333	0.1111	0.125	0.1429	1	1	1	1	2	3
C8	0.333333333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	1	1	1

EXPERT-2	C1			C2			C3			C4			C5			C6			C7			C8		
C1	1	1	1	1	2	3	3	4	5	3	4	5	2	3	4	2	3	4	1	2	3	1	2	3
C2	0.333333333	0.5	1	1	1	1	1	2	3	5	6	7	1	2	3	2	3	4	1	2	3	1	2	3
C3	0.2	0.25	0.3333	0.3333	0.5	1	1	1	1	5	6	7	5	6	7	2	3	4	1	1	1	1	2	3
C4	0.2	0.25	0.3333	0.1429	0.1667	0.2	0.1429	0.1667	0.2	1	1	1	5	6	7	4	5	6	1	2	3	1	2	3
C5	0.25	0.3333	0.5	0.3333	0.5	1	0.1429	0.1667	0.2	0.1429	0.1667	0.2	1	1	1	5	6	7	1	2	3	1	2	3
C6	0.25	0.3333	0.5	0.25	0.3333	0.5	0.25	0.3333	0.5	0.1667	0.2	0.25	0.1429	0.1667	0.2	1	1	1	6	7	8	1	2	3
C7	0.333333333	0.5	1	0.3333	0.5	1	1	1	1	0.3333	0.5	1	0.3333	0.5	1	0.125	0.1429	0.1667	1	1	1	1	2	3
C8	0.333333333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	1	1	1

EXPERT-1	C21			C22			C41			C42			C81			C82		
C21	1	1	1	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
C22	0.333333333	0.5	1	1	1	1	2	3	4	4	5	6	1	2	3	1	2	3
C41	0.333333333	0.5	1	0.25	0.3333	0.5	1	1	1	7	8	9	5	6	7	1	2	3
C42	0.333333333	0.5	1	0.1667	0.2	0.25	0.1111	0.125	0.1429	1	1	1	7	8	9	1	2	3
C81	0.333333333	0.5	1	0.3333	0.5	1	0.1429	0.1667	0.2	0.1111	0.125	0.1429	1	1	1	1	2	3
C82	0.333333333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	1	1	1

EXPERT-2	C21			C22			C41			C42			C81			C82		
C21	1	1	1	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
C22	0.333333333	0.5	1	1	1	1	2	3	4	1	2	3	1	2	3	1	2	3
C41	0.333333333	0.5	1	0.25	0.3333	0.5	1	1	1	7	8	9	5	6	4	1	2	3
C42	0.333333333	0.5	1	0.3333	0.5	1	0.1111	0.125	0.1429	1	1	1	7	8	9	1	2	3
C81	0.333333333	0.5	1	0.3333	0.5	1	0.25	0.1667	0.2	0.1111	0.125	0.1429	1	1	1	2	3	4
C82	0.333333333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.3333	0.5	1	0.25	0.3333	0.5	1	1	1

Figure 11: Individual criteria judgment matrix.

3.9 Computing Criteria Weights Using TFN-AHP Model

TFN-AHP method was used for equipment replacement prioritization where experts assigned a score using fuzzy linguistic scale as shown in Fig. 11 [70].

3.10 Steps Used to Determine Criteria Weight Using TFN-AHP

Given a set of criteria and goals, each criterion analysis was performed using Chang's extent approach. In this approach using TFN-AHP technique, the extent analysis for each criterion weight is determined. The flow diagram is summarized in Fig. 12.

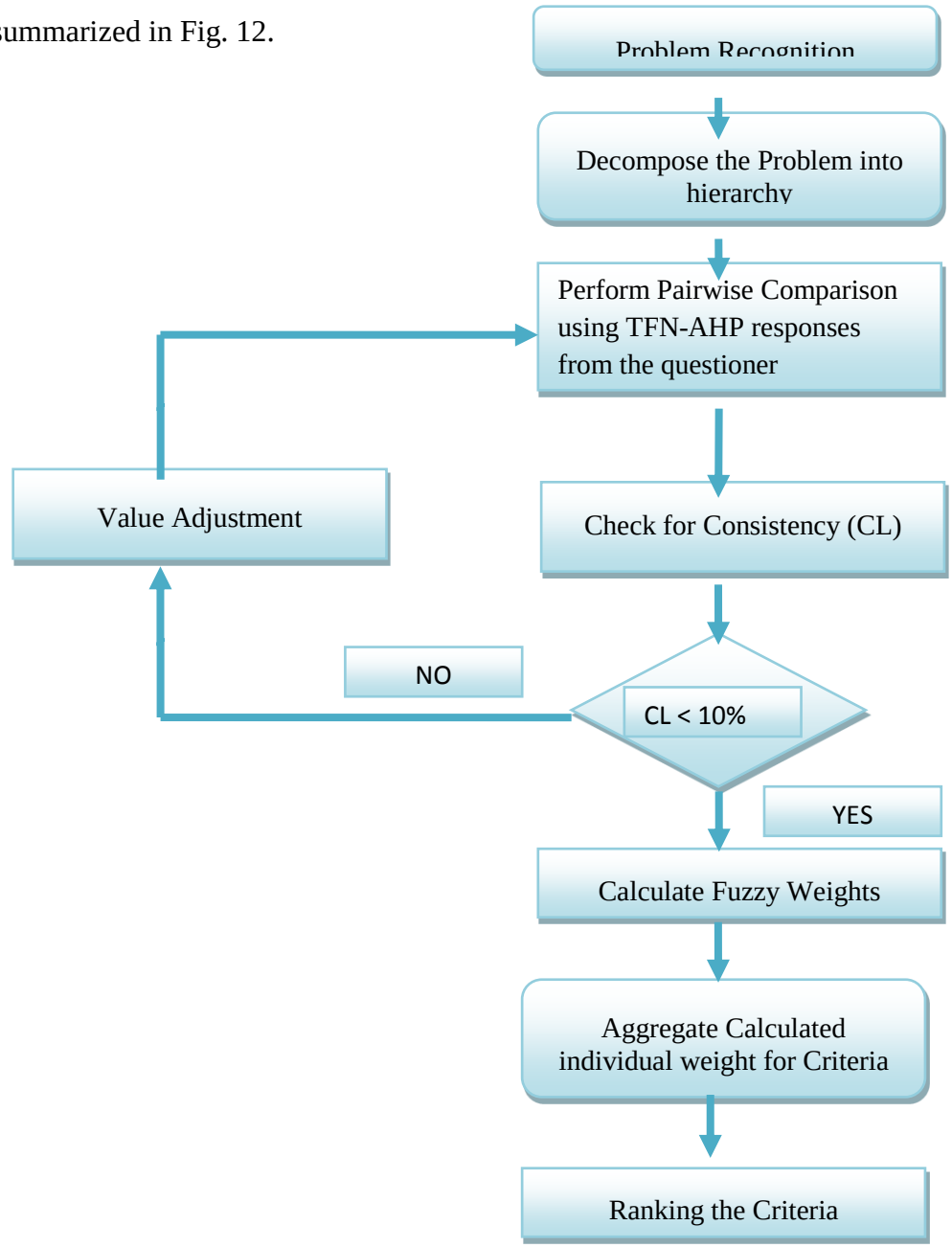


Figure 12: The proposed Multi-Criteria Fuzzy-AHP flow diagram.

Step One (Define the Judgment Matrix): Values in rows and columns of the decision matrix reflect subjective judgments reference to importance of each hierarchical criterion towards other decision elements (Eg. main-criteria and sub-criteria). Table 3 presented the fuzzy numbers and corresponding verbal scales (common fuzzy scale from 1-9) [71]. Results of each comparison are shown in figure 11. Triangular fuzzy number is represented as [*lower- value, mean-value, upper-value*], i.e., [*l, m, u*]. Every decision-maker is asked to express their relative importance of two decision elements at the same level (Eg. two replacement criteria) by using the TFN scale. Through a TFN scale, the second distributed questionnaire is used to collect experts' opinions, tangible and common expressions.

Step Two (Calculate the Normalized Decision Matrix): Once the decision matrix (*A*) is built, the normalized pair wise comparison matrix A_{norm} is derived by using the reciprocal of the TFN, where M_i^{-1} is denoted as $\left(\frac{1}{u_i}, \frac{1}{m_i}, \frac{1}{l_i}\right)$.

Step Three (Aggregate the Expert's Opinions): In this study, the geometric mean approach was applied for aggregating expert's opinions. The following equation was considered to aggregate the expert's opinions for their individual judgment (AIJ) and help to prepare for the final matrices for their pair wise comparisons. Based on the prepared questionnaire, there were fourteen experts who participated in judging main and sub criteria (Expert_1, Expert_2, Expert_3 and Expert_4, etc…). The aggregate of the experts' opinion was computed using the weighted geometric mean method,WGMM .

$$a_{ij}^{*} = \sqrt[k]{\left(a_{ij}^{*1} \times a_{ij}^{*2} \times \ldots\ldots \times a_{ij}^{*n}\right)} - - - - Equation: 8$$

$$A_{ij}^{*} = \left\lfloor a_{ij}^{*} \right\rfloor$$

Step Four (Analyze the Consistencies): To reflect consistency of decision maker's judgments during the evaluation phase, it is important to calculate consistency ratio (CR) which is done by computing the maximum eigenvalue of the experts' evaluation matrix [72]: $\lambda_{max} = n$ where $\lambda_{\max}$ is the maximum eigenvalue and *n* is the dimension of the judgment matrix. Then, using eqn. 9, the consistency index (*CI*) is obtained. The consistency record shows whether a decision-maker gives the right comparison of consistent values in a set of evaluations [73].

$$Cl = \frac{\lambda_{max} - n}{n - 1} - - - - Equation: 9$$

The final inconsistency of pair wise comparison determined using the consistency ratio:

$$CR = \frac{Cl}{RI} - - - - Equation: 10$$

Where RI are random indexes whose values are given in Table and its value presented below:-

n	1	2	3	4	5	6	7	8	9	10	….	38	39	40	41
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	….	1.700	1.702	1.7003	1.7004

Table 9: Random indices for different values of *n*.

Results of consistency pair wise comparisons for all group preferences are shown for all criteria and sub criteria in Table 10 and Table 11 respectively.

Expert	λ_{max}	Cl	RI	CR(%)
E_{M-1}	8.5501	0.0786	1.40	5.6137
E_{M-2}	8.8375	0.1196	1.40	8.5457
E_{M-3}	8.3662	0.0523	1.40	3.7370
E_{M-4}	8.4429	0.0633	1.40	4.5193
E_{M-5}	8.4895	0.0699	1.40	4.9953
E_{M-6}	8.8490	0.1213	1.40	8.6629
E_{M-7}	8.3852	0.0550	1.40	3.9305
E_{M-8}	8.1528	0.0218	1.40	1.5596
E_{M-9}	8.4470	0.0639	1.40	4.5616
E_{M-10}	8.4615	0.0659	1.40	4.7095
E_{M-11}	8.3227	0.0461	1.40	3.2925
E_{M-12}	8.1250	0.0179	1.40	1.2759
E_{M-13}	8.3162	0.0452	1.40	3.2267
E_{M-14}	8.0530	0.0076	1.40	0.5406

Table 10: Consistence Ratio for Main-Criteria.

Expert	λ_{max}	Cl	RI	$CR(\%)$
E_{A-1}	6.0412	0.0082	1.25	0.6586
E_{A-2}	6.4027	0.0805	1.25	6.4433
E_{A-3}	6.5181	0.1036	1.25	8.2889
E_{A-4}	6.0144	0.0029	1.25	0.2302
E_{A-5}	6.5200	0.104	1.25	8.32
E_{A-6}	6.1194	0.0239	1.25	1.9107
E_{A-7}	6.2732	0.0546	1.25	4.3712
E_{A-8}	6.3241	0.0648	1.25	5.1854
E_{A-9}	6.4979	0.0996	1.25	7.9656
E_{A-10}	6.082	0.0164	1.25	1.3115
E_{A-11}	6.5925	0.1185	1.25	9.4794
E_{A-12}	6.4481	0.0896	1.25	7.1699
E_{A-13}	6.4477	0.0895	1.25	7.1637
E_{A-14}	6.1278	0.0256	1.25	2.0441

Table 11: Consistence Ratio for Sub-Criteria.

Step Five (Weight Calculation for Replacement Factors): Various methods are used to calculate replacement criteria weights [74]. Chang's extent analysis on TFN-AHP depends on the degree of possibility of the superiority of each criterion. Usually, the TFN-AHP technique is the most popular to calculate fuzzy synthetic extent values S_i with respect to the i^{th} criterion as :

$M_{gi}^1, M_{gi}^2, M_{gi}^3, \ldots., M_{gi}^m$, where $g_i(i = 1,2,3, \ldots, n)$ is the goal set and all the M_{gi}^j(*j=1, 2, 3,..., m*) are TFNs,

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left(\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right)^{-1} - - - Equation: 11$$

To obtain $\sum_{j=1}^{m} M_{gi}^j$, perform the fuzzy addition operation of *m* extent analysis values such that:

$$\sum_{j=1}^{m} M_{gi}^j = \left(\sum_{j=1}^{m} l_j , \sum_{j=1}^{m} m_j , \sum_{j=1}^{m} u_j \right) - - - Equation: 12$$

In addition, to obtain$\left(\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j\right)^{-1}$, we perform fuzzy addition operation of $\sum_{j=1}^{m} M_{gi}^j$ $(j = 1,2, \ldots, n)$ values such that:

$$\left(\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^j \right)^{-1} = \left[\frac{1}{\sum_{j=1}^{m} u_j}, \frac{1}{\sum_{j=1}^{m} m_j}, \frac{1}{\sum_{j=1}^{m} l_j} \right] - - - Equation: 13$$

The results of computing pair wise comparisons matrix using extent analysis of all the elements of the main criteria matrix are as follows:

$C_{1M=}$ (11.273, 18.293, 25.141) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0812, 0.1740, 0.3366) ----------1

$C_{2M=}$ (11.934, 18.433, 25.097) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0859, 0.1753, 0.3360) ----------2

$C_{3M=}$ (12.857, 17.782, 22.724) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0926, 0.1692, 0.3042) ----------3

$C_{4M=}$ (13.31, 17.356, 21.402) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0958, 0.1651, 0.2865) ----------4

$C_{5M=}$ (9.7631, 13.103, 16.649) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0703, 0.1246, 0.2229) ----------5

$C_{6M=}$ (8.0992, 10.017, 12.132) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0584, 0.0953, 0.1624) ----------6

$C_{7M=}$ (3.6992, 5.2402, 7.7587) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0266, 0.0498 , 0.1038) ----------7

$C_{8M=}$ (3.7581, 4.8596, 7.8799) $\otimes \left(\frac{1}{138.8}, \frac{1}{105.1}, \frac{1}{74.69}\right)$ = (0.0270, 0.0462, 0.1055) ----------8

The results of computing pair wise comparisons matrix using extent analysis of all the elements of the sub criteria matrix are as follows:

$C_{21A=}$ (9.4055, 14.6447, 19.7625) $\otimes \left(\frac{1}{79.0285}, \frac{1}{60.2779}, \frac{1}{43.2132}\right)$= (0.1190, 0.2429, 0.4573) ----------9

$C_{22A=}$ (10.2459, 14.383, 18.5111) $\otimes \left(\frac{1}{79.0285}, \frac{1}{60.2779}, \frac{1}{43.2132}\right)$= (0.1296, 0.2386, 0.4283) ----------10

$C_{41A=}$ (10.3307, 13.6517, 17.0362) $\otimes \left(\frac{1}{79.0285}, \frac{1}{60.2779}, \frac{1}{43.2132}\right)$= (0.1307, 0.2264, 0.3942) ----------11

$C_{42A=}$ (7.58141, 9.7882, 12.2738) $\otimes \left(\frac{1}{79.0285}, \frac{1}{60.2779}, \frac{1}{43.2132}\right)$= (0.0959, 0.1623, 0.2840) ----------12

$C_{81A=}$ (3.02353, 4.39505, 5.73246) $\otimes \left(\frac{1}{79.0285}, \frac{1}{60.2779}, \frac{1}{43.2132}\right)$= (0.0382, 0.0729, 0.1326) ----------13

$C_{82A=}$ (2.62613, 3.41477, 5.7125) $\otimes \left(\frac{1}{79.0285}, \frac{1}{60.2779}, \frac{1}{43.2132}\right)$= (0.0332, 0.0566, 0.1321) ----------14

Step Six: Next, for each criterion weight, pair wise comparison with other criterion weights is performed using *eqn.* 14, and degree of possibility of being greater than these criterion weights is obtained. Minimum of these possibilities is used as the overall score for each factor.

$M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$

$V(M_2 \geq M_1) = \sup\lfloor \min(\mu M_1(x), \mu M_2(y)) \rfloor$

Equivalently expressed as:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu M2(d) = \begin{cases} 1, & if\ m_2 \geq m_1 \\ 0, & if\ l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \quad --- Equation: 14$$

Tables 12 and 13 compare results for the computed M_1 and M_2 ($V(M_1 \geq M_2)$ values for all main and sub-main criteria.

$V(C_{1M} \geq C_{2M})$	$V(C_{1M} \geq C_{3M})$	$V(C_{1M} \geq C_{4M})$	$V(C_{1M} \geq C_{5M})$	$V(C_{1M} \geq C_{6M})$	$V(C_{1M} \geq C_{7M})$	$V(C_{1M} \geq C_{8M})$
0.9948	1	1	1	1	1	1

A

$V(C_{2M} \geq C_{1M})$	$V(C_{2M} \geq C_{3M})$	$V(C_{2M} \geq C_{4M})$	$V(C_{2M} \geq C_{5M})$	$V(C_{2M} \geq C_{6M})$	$V(C_{2M} \geq C_{7M})$	$V(C_{2M} \geq C_{8M})$
1	1	1	1	1	1	1

B

$V(C_{3M} \geq C_{1M})$	$V(C_{3M} \geq C_{2M})$	$V(C_{3M} \geq C_{4M})$	$V(C_{3M} \geq C_{5M})$	$V(C_{3M} \geq C_{6M})$	$V(C_{3M} \geq C_{7M})$	$V(C_{3M} \geq C_{8M})$
0.9785	0.9724	1	1	1	1	1

C

$V(C_{4M} \geq C_{1M})$	$V(C_{4M} \geq C_{2M})$	$V(C_{4M} \geq C_{3M})$	$V(C_{4M} \geq C_{5M})$	$V(C_{4M} \geq C_{6M})$	$V(C_{4M} \geq C_{7M})$	$V(C_{4M} \geq C_{8M})$
0.9585	0.9516	0.9798	1	1	1	1

D

$V(C_{5M} \geq C_{1M})$	$V(C_{5M} \geq C_{2M})$	$V(C_{5M} \geq C_{3M})$	$V(C_{5M} \geq C_{4M})$	$V(C_{5M} \geq C_{6M})$	$V(C_{5M} \geq C_{7M})$	$V(C_{5M} \geq C_{8M})$
0.7415	0.7297	0.7454	0.7582	1	1	1

E

$V(C_{6M} \geq C_{1M})$	$V(C_{6M} \geq C_{2M})$	$V(C_{6M} \geq C_{3M})$	$V(C_{6M} \geq C_{4M})$	$V(C_{6M} \geq C_{5M})$	$V(C_{6M} \geq C_{7M})$	$V(C_{6M} \geq C_{8M})$
0.5075	0.4882	0.4857	0.4875	0.7580	1	1

F

$V(C_{7M} \geq C_{1M})$	$V(C_{7M} \geq C_{2M})$	$V(C_{7M} \geq C_{3M})$	$V(C_{7M} \geq C_{4M})$	$V(C_{7M} \geq C_{5M})$	$V(C_{7M} \geq C_{6M})$	$V(C_{7M} \geq C_{8M})$
0.1545	0.1248	0.0865	0.0649	0.3100	0.5006	1

G

$V(C_{8M} \geq C_{1M})$	$V(C_{8M} \geq C_{2M})$	$V(C_{8M} \geq C_{3M})$	$V(C_{8M} \geq C_{4M})$	$V(C_{8M} \geq C_{5M})$	$V(C_{8M} \geq C_{6M})$	$V(C_{8M} \geq C_{7M})$
0.1597	0.1311	0.0949	0.0747	0.3096	0.4896	0.9552

H

Table 12: (A - H) degree of possibilities computed for all main-criteria.

$V(C_{21A} \geq C_{22A})$	$V(C_{21A} \geq C_{41A})$	$V(C_{21A} \geq C_{42A})$	$V(C_{21A} \geq C_{81A})$	$V(C_{21A} \geq C_{82A})$
1	1	1	1	1

I

$V(C_{22A} \geq C_{21A})$	$V(C_{22A} \geq C_{41A})$	$V(C_{22A} \geq C_{42A})$	$V(C_{22A} \geq C_{81A})$	$V(C_{22A} \geq C_{82A})$
0.98	1	1	1	1

J

$V(C_{41A} \geq C_{21A})$	$V(C_{41A} \geq C_{22A})$	$V(C_{41A} \geq C_{42A})$	$V(C_{41A} \geq C_{81A})$	$V(C_{41A} \geq C_{82A})$
0.94	0.96	1	1	1

K

$V(C_{42A} \geq C_{21A})$	$V(C_{42A} \geq C_{22A})$	$V(C_{42A} \geq C_{41A})$	$V(C_{42A} \geq C_{81A})$	$V(C_{42A} \geq C_{82A})$
0.67	0.66	0.70	1	1

L

$V(C_{81A} \geq C_{21A})$	$V(C_{81A} \geq C_{22A})$	$V(C_{81A} \geq C_{41A})$	$V(C_{81A} \geq C_{42A})$	$V(C_{81A} \geq C_{82A})$
0.074	0.0178	0.01248	0.29102	1

M

$V(C_{82A} \geq C_{21A})$	$V(C_{82A} \geq C_{22A})$	$V(C_{82A} \geq C_{41A})$	$V(C_{82A} \geq C_{42A})$	$V(C_{82A} \geq C_{81A})$
0.066	0.01377	0.00858	0.2554	0.85244

N

Table 13: (I - N) Degree of possibilities computed for all sub-main criteria.

Step Seven. Using these values the minimum degree of possibilities can be calculated as follows:

$d'(C_{1M}) = V(C_{1M} \geq C_{2M}, C_{3M}, C_{4M}, C_{5M}, C_{6M}, C_{7M}, C_{8M})$ = min (0.9948,1,1,1,1,1,1,1) =**0.9948**
$d'(C_{2M}) = V(C_{2M} \geq C_{1M}, C_{3M}, C_{4M}, C_{5M}, C_{6M}, C_{7M}, C_{8M})$= min (1, 1, 1, 1, 1, 1, 1, 1) =**1**
$d'(C_{3M}) = V(C_{3M} \geq C_{1M}, C_{2M}, C_{4M}, C_{5M}, C_{6M}, C_{7M}, C_{8M})$= min (0.9785,0.9724,1,1,1,1,1) =**0.9724**
$d'(C_{4M}) = V(C_{4M} \geq C_{1M}, C_{2M}, C_{3M}, C_{5M}, C_{6M}, C_{7M}, C_{8M})$= min (0.9585,0.9516,0.9798,1,1,1,1) =**0.9516**
$d'(C_{5M}) = V(C_{5M} \geq C_{1M}, C_{2M}, C_{3M}, C_{4M}, C_{6M}, C_{7M}, C_{8M})$= min (0.7415,0.7297,0.7454,0.7582,1,1,1)=**0.7297**
$d'(C_{6M}) = V(C_{6} \geq C_{1M}, C_{2M}, C_{3M}, C_{4M}, C_{5M}, C_{7M}, C_{8M})$=min (0.5075,0.4882,0.4857,0.4875,0.7580,1,1,)=**0.4857**
$d'(C_{7M}) = V(C_{7M} \geq C_{1M}, C_{2M}, C_{3M}, C_{4M}, C_{5M}, C_{6M}, C_{8M})$ =min (0.1545,0.1248,0.0865,0.0649,0.3100,0.5006) =**0.0649**
$d'(C_{8M}) = V(C_{8M} \geq C_{1M}, C_{2M}, C_{3M}, C_{4M}, C_{5M}, C_{6M}, C_{7M})$=min (0.1597,0.1311,0.0949,0.0747,0.3096,0.4896,0.9552) =**0.0747**
$d'(C_{21A}) = V(C_{21A} \geq C_{22A}, C_{41A}, C_{42A}, C_{81A}, C_{82A},)$ =min (1,1,1,1,1) =**1**
$d'(C_{22A}) = V(C_{22A} \geq C_{21A}, C_{41A}, C_{42A}, C_{81A}, C_{82A},)$ =min (0.98, 1, 1, 1, 1) =**0.98**
$d'(C_{41A}) = V(C_{41A} \geq C_{21A}\ C_{22A}, C_{42A}, C_{81A}, C_{82A})$ =min (0.94,0.96,1,1,1) =**0.94**
$d'(C_{42A}) = V(C_{42A} \geq C_{21A}, C_{22A}, C_{41A}, C_{81A}, C_{82A},)$ =min (0.67, 0.66, 0.70, 1, 1) **=0.66**
$d'(C_{81A}) = V(C_{81A} \geq C_{21A}, C_{22A}, C_{41A}, C_{42A}, C_{82A})$ =min (0.074,0.0178,0.01248,0.29102,1)= **0.01248**
$d'(C_{82A}) = V(C_{82A} \geq C_{21A}, C_{22A}, C_{41A}, C_{42A}, C_{81A})$=min(0.066,0.01377,0.00858,0.2554,0.85244)=**0.00858**

Then, the weight priority vectors are obtained by using the following equation:

$$W' = \left(d'(C_1), d'(C_2), d'(C_3), \ldots . d'(C_n)\right)T - - - Equation: 15$$

Therefore, the weight vectors are generated as:

$W_M' = (d'(C_{1M}), d'(C_{2M}), d'(C_{3M}), d'(C_{4M}), d'(C_{5M}), d'(C_{6M}), d'(C_{7M}), d'(C_{8M}))^T$

$W_A' = (d'(C_{21A}), d'(C_{22A}), d'(C_{41A}), d'(C_{42A}), d'(C_{81A}), d'(C_{82A}))^T$

Step Eight: The prioritized weight vectors obtained for both main and sub-criteria are:

$W_M' = (0.9948, 1, 0.9724, 0.9516, 0.7297, 0.4857,$ **0.0649**$, 0.0747)^T$

$W_A' = (1, 0.98, 0.94, 0.66,$ **0.01248**$, 0.00858)^T$

Step Nine: The normalized weight vectors obtained as follows and he scores should be normalized with the cumulative sum equal to 1. The normalized criteria values are depicted in Fig. 13 & Fig 14.

$$W_M = \frac{W'_M}{\sum_{i=1}^{n} d'(C_i)} - - - Equation: 16$$

$$W_M = (0.1886, 0.1896, 0.1843, 0.1804, 0.1383, 0.0920, 0.0123, 0.0141)^T$$

$$W_A = \frac{W'_A}{\sum_{i=1}^{n} d'(C_i)} - - - Equation: 17$$

$$W_A = (0.2776, 0.2721, 0.2610, 0.1832, 0.0035, 0.0023)^T$$

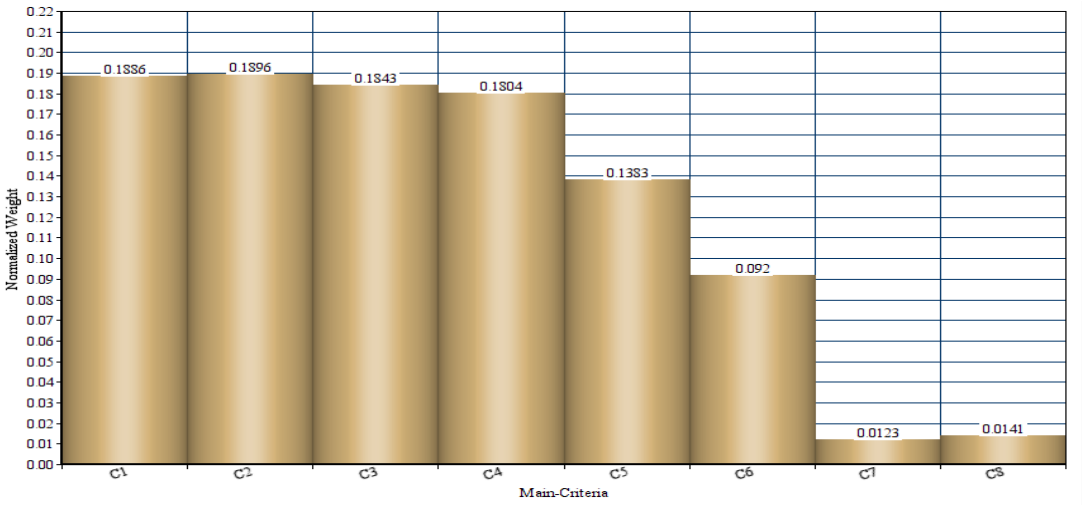


Figure 13: Normalized weights for main criteria.

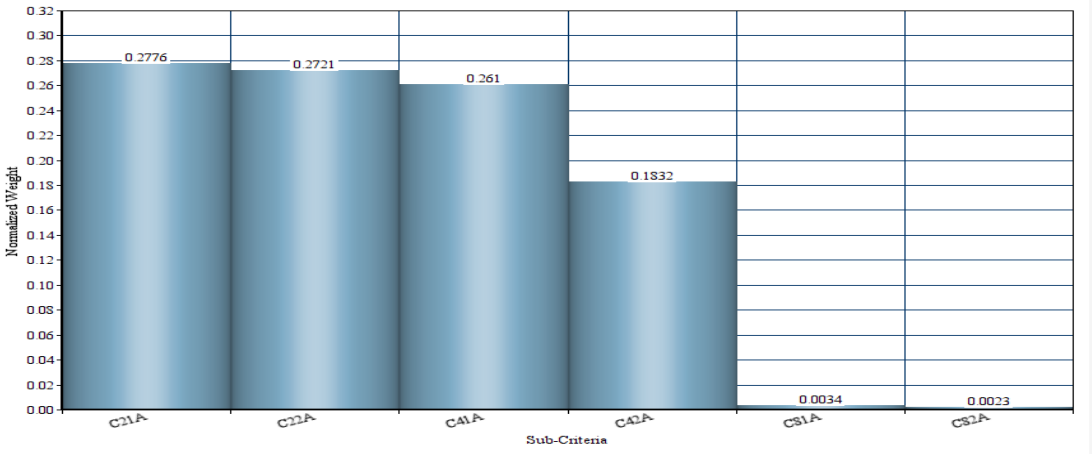


Figure 14: Normalized weights for sub criteria

3.11 Equipment Replacement Priority Weight Determination

The Equipment Replacement Priority Weight (ERPW) approach was applied for the purpose of identification and prioritization of the list of medical equipments while Tabu search algorithm was used to solve the resulting optimization problem. Total equipment importance weight is obtained from result analysis of individual equipment weight and equipment criteria weight is obtained from experts, which is, evaluated for

each technical criterion against other criteria. *Eqn.* 18 computes the resultant relative weights to identify and prioritize influential equipments.

$$\begin{aligned}\text{ERPW} = (C_{1M} \times W_{1M} + C_{2M} \times W_{2M} + C_{21A} \times W_{21A} + C_{22A} \times W_{22A} + C_{3M} \times W_{3M} + C_{4M} \times W_{4M} + C_{41A} \\ \times W_{41A} + C_{42A} \times W_{42A} + C_{5M} \times W_{5M} + C_{6M} \times W_{6M} + C_{7M} \times W_{7M} + C_{8M} \\ \times W_{8M} + C_{81A} \times W_{81A} + C_{82A} \times W_{82A}) \times X_i - - - - - Equation: 18\end{aligned}$$

Where X_i depicts the i^{th} device. Figure 17 presents the equipments weight histogram distribution.

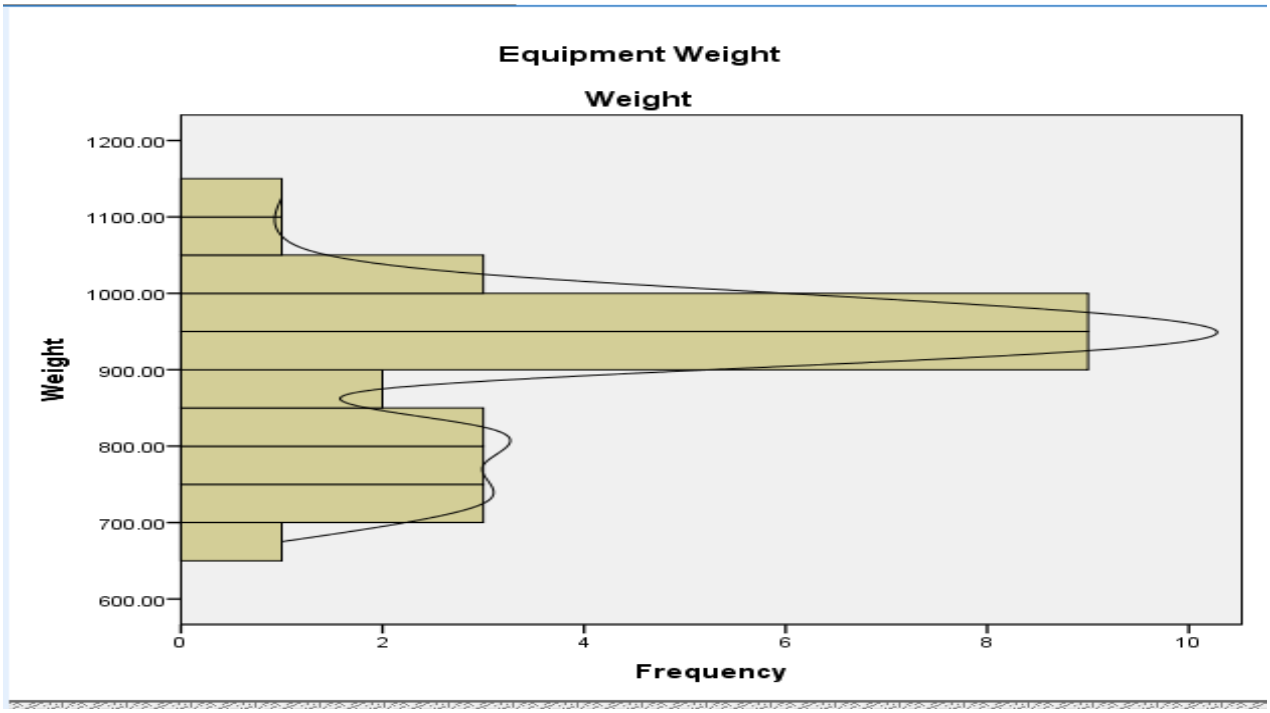


Figure 15: Equipment weight histogram distribution.

Table 14 presents a summary of the equipment weights generated from the data collected by the questioner respondents and the corresponding ERPW values while Table 15 presents the aggregated criteria weight generated by experts. The final prioritized list of equipments is depicted in Fig. 16 (considering the 35 medical equipments included in the current study). Table 16 presents the prioritized equipments using their relative ERPW.

x_i	Description	W_{1M}	W_{2M}	W_{21A}	W_{22A}	W_{3M}	W_{4M}	W_{41A}	W_{42A}	W_{5M}	W_{6M}	W_{7M}	W_{8M}	W_{81A}	W_{82A}	ERPW
1	Audiometer	71	63	15	20	69	70	65	57	66	81	52	71	23	17	106.031
2	Stethoscope	76	71	19	18	74	72	69	61	69	85	59	65	19	12	112.876
3	Pulse Oximeter	100	108	31	17	85	79	75	77	85	104	59	66	22	16	139.258
4	Ultrasonic Nebulizers	130	96	28	26	74	74	81	74	86	96	65	78	24	22	142.01
5	Ophthalmoscope	69	73	18	4	54	68	56	62	74	79	57	77	27	18	100.555
6	Sphygmomanometer	81	72	22	23	88	72	73	68	86	94	58	74	26	21	124.446
7	Mini-Shaker for immunology	68	91	24	24	83	76	75	71	86	116	77	75	23	18	129.551
8	Laboratory Medical Centrifuge	102	94	30	28	78	76	79	72	79	126	76	76	28	18	139.562
9	Laboratory Microscope	65	76	24	14	64	51	54	52	68	69	53	62	18	11	99.1214
10	Hot Air Oven	104	81	27	26	72	66	73	79	81	103	70	76	27	19	130.99
11	Vertical/Horizontal High Pressure Sterilizer autoclave	116	92	26	25	70	75	69	73	77	108	71	86	30	23	133.98
12	Freezer	64	65	11	14	87	62	66	63	77	107	47	59	21	8	109.237
13	Hematology Analyzer	102	90	32	24	82	68	70	77	79	123	79	85	33	21	136.043
14	Clinical Chemistry	100	96	29	25	84	75	72	74	82	128	85	65	20	17	138.46
15	X-ray	119	95	32	30	93	72	79	77	79	116	77	79	26	20	146.149
16	Computed Tomography(CT)	105	85	27	15	71	70	68	73	75	98	79	62	26	17	125.693

	Scanner															
17	Magnetic Resonance Image(MRI)	102	86	31	22	67	70	79	75	72	111	87	78	24	25	131.948
18	Ultrasound	102	91	32	32	80	78	79	75	89	134	83	74	32	9	144.086
19	Anesthesia Machine	170	109	28	32	81	74	73	75	77	118	78	78	34	13	153.989
20	Defibrillators	146	116	29	26	93	86	91	78	82	118	87	73	18	22	159.757
21	Operating Table	61	70	22	20	71	73	65	65	73	102	62	69	26	15	112.792
22	Surgical Light	97	82	29	17	73	71	66	61	75	83	65	70	22	23	121.104
23	Diathermy	135	91	23	13	83	75	72	72	84	101	56	78	28	21	136.287
24	ECG Machine	107	99	29	26	86	79	70	77	89	116	79	80	23	27	141.774
25	Mechanical Ventilator	170	103	28	24	94	78	74	76	82	118	83	74	24	21	154.917
26	Infusion Pump	150	94	22	19	90	71	75	76	79	120	76	67	24	11	144.235
27	Bedside Monitor	88	84	25	19	92	80	86	71	71	120	73	75	33	12	134.428
28	High Pressure Suction	94	86	24	16	88	78	73	76	76	121	73	81	26	21	132.135
29	Oxygen Concentrator	170	113	28	28	92	87	91	83	93	139	97	73	22	16	168.469
30	Slit Lamp	72	72	22	19	66	72	67	72	75	97	79	70	26	18	115.723
31	Infant Incubator	165	104	28	25	88	73	73	68	76	114	77	69	24	21	149.36
32	Baby Warmer	146	94	29	24	82	84	69	66	77	115	63	66	28	10	143.358
33	Flat Bed	63	77	17	19	78	73	73	68	76	89	71	74	26	15	116.164
34	Autoclave	116	93	29	24	88	72	78	80	78	107	60	73	26	11	140.825
35	Stretcher Wheeled	63	75	21	16	66	61	58	55	66	89	50	59	20	12	103.526

Table 14: Equipment weight generated by respondent.

Normalized Weight	W_{1M}	W_{2M}	W_{21A}	W_{22A}	W_{3M}	W_{4M}	W_{41A}	W_{42A}	W_{5M}	W_{6M}	W_{7M}	W_{8M}	W_{81A}	W_{82A}
Value	0.1886	0.1896	0.2776	0.2721	0.1843	0.1804	0.2610	0.1832	0.1383	0.0920	0.0123	0.0141	0.0035	0.0023

Table 15: The aggregated criteria weight generated by experts.

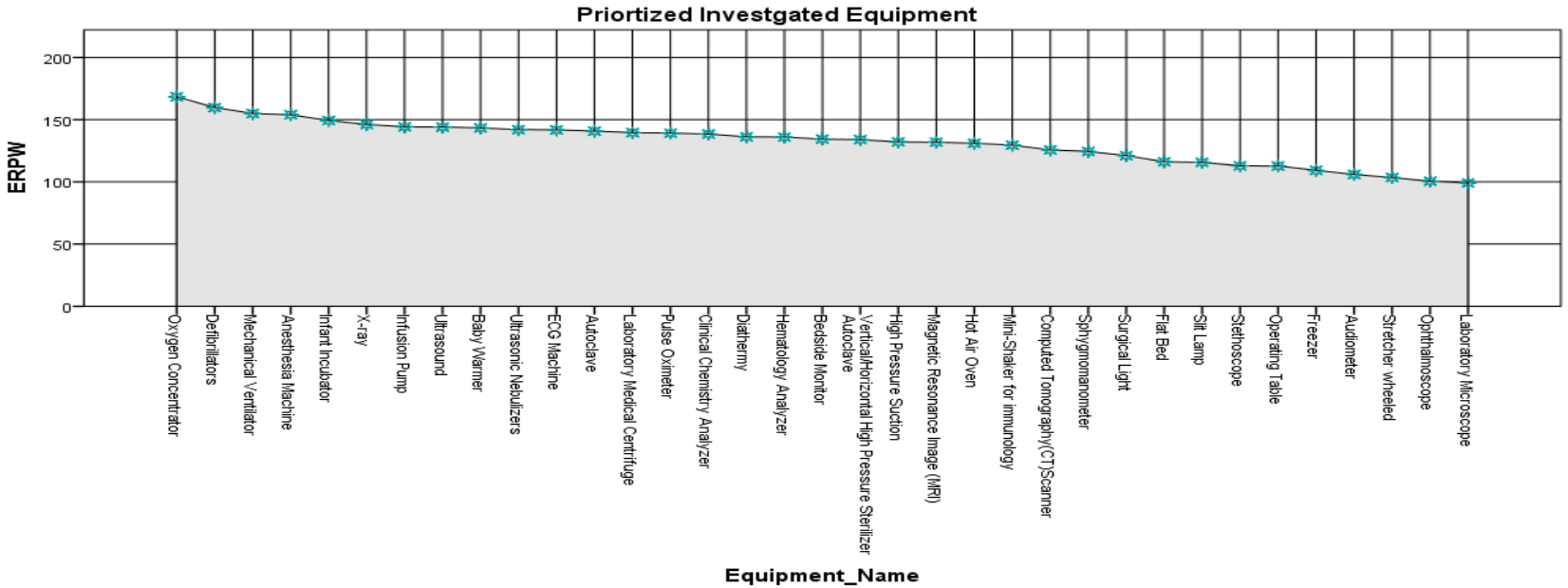


Figure 16: Prioritized equipments.

Equipment Name	ERPW		Prioritized Equipment Name	ERPW	Ranking	B(30%XTEP)=$**59,189.99** EP($)
Audiometer	106.03		Oxygen Concentrator	168.47	1	345.00
Stethoscope	112.88		Defibrillators	159.76	2	2985.9
Pulse Oximeter	139.26		Mechanical Ventilator	154.91	3	6608.00
Ultrasonic Nebulizers	142.01		Anesthesia Machine	153.99	4	11326.5
Ophthalmoscope	100.56		Infant Incubator	149.36	5	2960.00
Sphygmomanometer	124.45		X-ray	146.15	6	26965.00
Mini-Shaker for immunology	129.55		Infusion Pump	144.24	7	331.4
Laboratory Medical Centrifuge	139.56		Ultrasound	144.09	8	36503.8
Laboratory Microscope	99.121		Baby Warmer	143.35	9	2468.9
Hot Air Oven	130.99		Ultrasonic Nebulizers	142.01	10	142.27
Vertical/Horizontal High Pressure Sterilizer autoclave	133.98		ECG Machine	141.77	11	1642
Freezer	109.24		Autoclave	140.82	12	28225.7
Hematology Analyzer	136.04		Laboratory Medical Centrifuge	139.56	13	329.6
Clinical Chemistry	138.46		Pulse Oximeter	139.26	14	76.52
X-ray	146.15		Clinical Chemistry Analyzer	138.46	15	9382
Computed Tomography(CT) Scanner	125.69		Diathermy	136.28	16	4063.5
Magnetic Resonance Image(MRI)	131.95		Hematology Analyzer	136.04	17	6520
Ultrasound	144.09		Bedside Monitor	134.42	18	552.5
Anesthesia Machine	153.99		Vertical/Horizontal High Pressure Sterilizer autoclave	133.98	19	17335.8
Defibrillators	159.76		High Pressure Suction	132.13	20	1904.1
Operating Table	112.79		Magnetic Resonance Image(MRI)	131.95	21	619500.00
Surgical Light	121.1		Hot Air Oven	130.99	22	8545.7
Diathermy	136.29		Mini-Shaker for immunology	129.55	23	715.6
ECG Machine	141.77		Computed Tomography(CT) Scanner	125.69	24	737069
Mechanical Ventilator	154.92		Sphygmomanometer	124.45	25	40.63
Infusion Pump	144.24		Surgical Light	121.104	26	1892.5
Bedside Monitor	134.43		Flat Bed	116.16	27	186.7
High Pressure Suction	132.14		Slit Lamp	115.72	28	3194
Oxygen Concentrator	168.47		Stethoscope	112.88	29	86.52
Slit Lamp	115.72		Operating Table	112.79	30	5734.3
Infant Incubator	149.36		Freezer	109.24	31	2766.4
Baby Warmer	143.36		Audiometer	106.03	32	350.00
Flat Bed	116.16		Stretcher Wheeled	103.52	33	519.2
Autoclave	140.82		Ophthalmoscope	100.56	34	12300.00
Stretcher Wheeled	103.53		Laboratory Microscope	99.121	35	299.7

Table 16: Prioritized equipment using their relative ERPW.

3.12 Tabu Search Framework

The objective of the Tabu search was to assign and plot a pair of nodes (golden-rigs) of medical equipments to be replaced with a minimum distance; the golden-rigs are a set of medical equipments that need to be replaced based on their replaced priority index number and their objective functions. Based on the paired golden-rigs, the Tabu search algorithm draws a straight line from node to node until it makes a closed-loop (for our case the shortest Hamiltonian distance among the possible feasible solutions). The method assumes a standard symmetric TSP with an entire graph where the triangle inequality applies. Figure 17 presents the x-y coordinates of the different equipments based on their ERPW and objective functions.

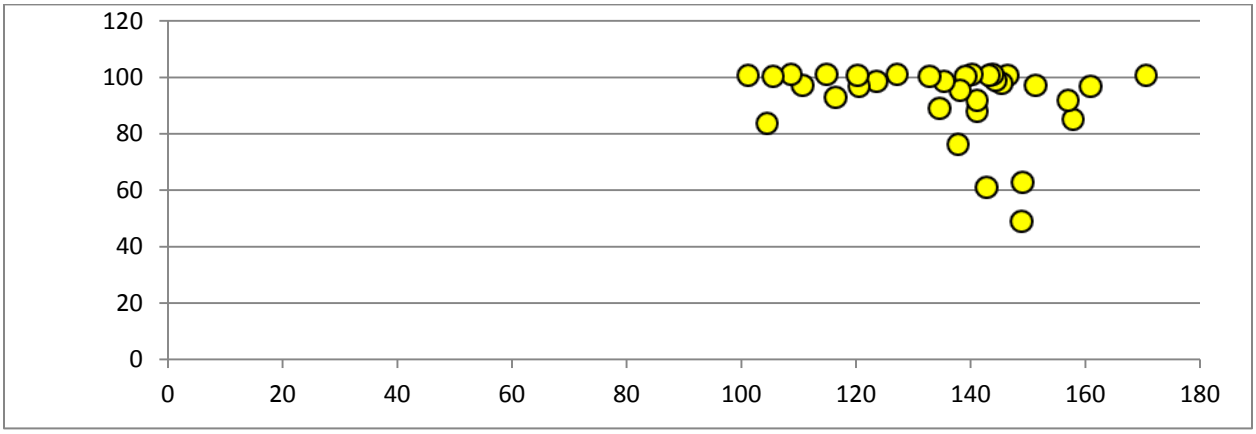


Figure 17: Equipment x-y coordinates based on their ERPW and objective function

3.13 Tabu Search Algorithm Model

Tabu search algorithm (TSA) is a searching technique based on the Travelling Salesman Problem Distance Calculation (TSPDC) and assumes that a salesman has to return to the node where he starts the tour; this node is usually referred to as base point and the assumption is called closed tour (Hamilton). For a closed tour, any node can be selected as the starting node. The tour can go in either direction (as the Euclidian distance is symmetric). The TSPDC has wide variety of applications, particularly in combinatorial optimization problems and they were proved to be able to provide near optimal solutions in reasonable time . The purpose of the Tabu search in the current study was to optimize list of prioritized inventory medical equipments. It considers the prioritized weights (ERPWs) and the available replacement budget of the hospital. Tabu search requires formulation of the objective function.

To optimize devices according to the available budget, there is a need to estimate prices of new devices. In order to develop the objective function, the following parameters were considered: *R* is the total calculation result of hospital budget and estimated price, E_P is the equipment replacement cost (estimated price of the medical equipment), *B* is available budget of the hospital and *K* the price constraint.
Then the proposed objective function of the optimization model is given by e*qn*. 19:

$$R = \left(\frac{B - Ep}{B}\right) K - - - Equation: 19$$

$$\text{where } k = \begin{Bmatrix} 1 \; if \; E_P \leq B \\ 0 \; if \; E_P > B \end{Bmatrix}$$

3.14 Travelling Salesman Problem Distance Calculation (TSPDC)

In graph theory, minimum distance problem is an example of minimum distance searching between specified pair of vertices. In a network, edge weight is usually represented as a crisp real number. Euclidean version of the TSPDC finds the shortest closed path (tour) through group points in a plane. That is the minimum distance that passes through every point and returns to the origin.

TSPDC is basically a combinatorial optimization setup that is defined to finding the minimum cost route, distance or time in a undirected graph from an initial starting point, covering all points (vertices) in the graph exactly once, and coming to a stop at the initial starting point i.e. the starting node and destination node are identical nodes. Travelling salesman problems can be either *symmetric* or *asymmetric.* In symmetric problems, the cost of an edge is independent of the travel direction (i.e., cost of travelling from city A to city B is same as travelling from city B to city A). In asymmetric problems, cost of an edge may be dependent on direction of travel (i.e., cost of travelling from city A to city B is not same as with that of travelling from city B to city A). The replacement problem in the current study is assumed symmetric.

3.14.1 Definitions

If there are n equipments, they are numbered from 1 to n. The distance between the equipments is stored in an exceedingly two-dimensional n x n array, D, where D_{ij} is the distance between equipments *i* and j.

3.14.2 Complexity

Given *n,* the number of equipments to be visited, the overall number of possible routes covering all equipments is given as a collection of possible feasible solutions of the TSP and is the factorial (*n*-1)!. In

the current study, use of the symmetric travelling salesman problem is assumed for solving the replacement problem. Let $V= \{v_1 \ldots\ldots, v_n\}$ be a group of equipments to replace, $A= \{(r, s): r, s \varepsilon V\}$ be the edge set and $d_{rs}=d_{sr}$ be a distance measure related to edge (r, s). The optimization problem is then finding a minimal length closed tour that visits each equipment once. Every equipment is assigned by a coordinate (X_i, Y_i) and d_{rs} is the Euclidean distance between r and s.

3.14.3 Objective Function Formulation

Consider the following fuzzy travelling salesman problem:

$$Min\ \tilde{z} = \sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{c}_{ij}\, \tilde{x}_{ij};\ [\text{i=1, 2, 3…n; j=1, 2, 3…n}] - - - \textit{Equation: 20}$$

Subject to the constraints: i) $\sum_{i=1}^{n} \tilde{X}_{ij} = 1; j = 1,2, \ldots., n$; ii) $\sum_{j=1}^{n} \tilde{X}_{ij} = 1; i = 1,2, \ldots., n$

Where $\tilde{X}_{ij} = \begin{Bmatrix} 1; \text{if the salesman travel from node i to node } j \\ 0; \text{otherwise} \end{Bmatrix}$,

$\tilde{c}_{ij} = \text{Distance going from node i to node } j$ and $\tilde{z} = \text{The total minimum cost of the matrix.}$

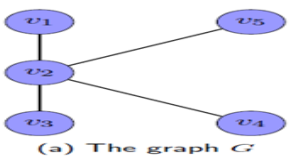
The TSP is defined on a complete undirected graph $G = (V, E)$ where the set $V=[1,. . . , n]$ is the vertex set and $E=\{(i , j): i , j \varepsilon V, i <j\}$ is an edge set. A cost matrix $C = (c_{ij})$ is defined on E. The cost matrix satisfies the triangle inequality whenever $c_{ij} \leq c_{ik} + c_{kj}$, for all i, j, k. In particular, this is the case of planer problems for which the vertices are points $P_i= (X_i, Y_i)$ in the plane, and

$$c_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2} - - - \textit{Equation: 21}$$

is the Euclidean distance. Triangle inequality holds if C_{ij} is length of the shortest path from i to j on G.

3.14.4 Distance Matrix

Let G be a connected graph set of vertices $V(G) = \{v_1, v_2, v_3 \ldots., v_n\}$ and c_{ij} represents minimum route length between vertices v_i and v_j. Then the distance matrix G denoted by $D(G)$ is an n x n matrix whose $(i, j)^{th} = c_{ij}$. It is symmetric and has trace (the sum of elements on the main diagonal) is equal to zero. An example is shown in Fig. 20 showing a graph and its distance matrix.



(a) The graph G

$$D(G) = \begin{array}{c} \\ v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{array} \begin{array}{c} \begin{array}{ccccc} v_1 & v_2 & v_3 & v_4 & v_5 \end{array} \\ \begin{pmatrix} 0 & 1 & 2 & 2 & 2 \\ 1 & 0 & 1 & 1 & 1 \\ 2 & 1 & 0 & 2 & 2 \\ 2 & 1 & 2 & 0 & 2 \\ 2 & 1 & 2 & 2 & 0 \end{pmatrix} \end{array}.$$

(b) Distance matrix $D(G)$

Figure 18: A graph and its distance matrix.

3.14.5 Optimization Problem

This is about optimizing (minimizing or maximizing) of an objective function subject to given constraints. The objective function and/or the constraints could be linear or non-linear. The optimization problem is thus about determining closest or optimal solution (minimal cost, maximal profit, minimal error, optimal design etc). ERPW is a common identification technique for establishing a medical equipments prioritization model while Tabu search is used to solve the resulting optimization problem.

3.14.6 Combinatorial Optimization

Combinatorial optimization deals with optimizing problems with disordered variables . There are many known combinatorial optimization problems like production scheduling, machines sequencing, transportation planning form incorruptible codes and the like . The equipment prioritization model in the current study is also categorized under combinatorial optimization.

3.14.7 Heuristics

Heuristic originated from the Greek 'Heuriskein' meaning to discover or explore. The term heuristics is often employed in combinatorial optimization. Heuristic techniques search for an optimal solution at an inexpensive computational cost without having the ability to ensure either feasibility or optimality or perhaps in some cases to state how near optimal a particular feasible solution is .

3.14.8 Meta-Heuristics

Meta-heuristics is a heuristic approach that suits a specific problem by providing a solution beyond that is generated through the traditional heuristics. One main aspect of meta-heuristic is to escape from local optima using a special procedure. The Tabu search is based on meta-heuristics. It involves use of adaptive memory, use of neighborhood exploration and the number of current solutions is carried from one iteration to the next. Tabu search is a meta-heuristic local optimal solution tool and has been successfully applied in practical combinatorial optimization problems including travelling salesman problem, various graph problems and is successful in obtaining optimal or near-optimal solutions. The Tabu search algorithm is an iterative technique that starts with an initial feasible solution and attempts to determine a better solution. The Tabu search is characterized by the capability to escape local optima by using short-term memory structure in recent solutions. Additionally, Tabu search allows checking previous solutions and that leads to an improved solution. Tabu search includes a flexible structure by intensification and diversification of the searching process to obtain an optimal solution for a given problem. In general, it is a neighborhood-search algorithm, which searches for sequence of solutions and

moves to best neighbor of existing solution in a relatively short running time. Tabu search uses a 2-opt exchange mechanism for searching a better solution.

3.14.9 Initial Solution

Any random and feasible solution can be used as an initial solution and TS succeeds to a better solution no matter how far away is the initial from the optimal. A very simple way to generate an initial solution for the medical equipment prioritization problem we have is to randomly put the equipments sequentially.

3.14.10 Tabu Length

Tabu length is the number of steps of Tabus. For example, giving Tabus X a number 1 (Tabu length) means Tabus X is forbidden within the next 1 iteration. After one iteration, Tabus X will be released. Generally, when the Tabu length is high, it results in increased computational time.

3.14.11 Neighborhood

The Tabu search method essentially depends on neighborhood. Neighborhood is defined as a move in a set to some distance without leaving the set. A new solution is obtained when a neighborhood is carried on a pair wise exchange (permuting two successive operations) of any two nodes or replacing the node in the solution with another node and converging to the local optimum. The neighborhood move point is defined by using the operations of moving, swapping, and replacing but the number of nodes remains the same. Neighborhoods usually have a feasible solution. The node with the smallest value of the objective function is selected from the neighborhood to perform the swap or exchange within the heuristic. In Tabu search, we use dynamic ways to define neighborhoods. To avoid cycling in search space, we use recency based memory (short-term). Recency-based memory is used to eliminate recently visited solutions.

3.14.12 Adaptive Memory

To perform an intelligent search on equipment replacement problem, the primary requirement is to possess the data of the past moves of the process. Therefore, Tabu search incorporates memory to store the history of the past actions performed at the time of the search process. It uses a versatile memory structure to store the history. By using the memory in Tabu, the search algorithm to store history faces the challenge regarding the space for storing. The memory stores the record information about solution attributes that change in moving from one solution to different. Memory structures are classified into *short-term memory* and *long-term memory*. Each memory has its own special strategies and provides different solutions. Memory structures are utilized to change the neighborhood of the present solution to get a new solution at different states of the Tabu iteration.

3.14.13 Responsive Exploration

The Tabu search process uses recorded history in an efficient way. Intelligent search responsive exploration is crucial decision during the search process. Tabu search uses strategic restraints and inducements on neighborhood solution by using Tabu conditions and aspiration levels. Responsive exploration uses direct search in promising way to find good solution. The search process is focused on good regions and good solution features by using intensification process. Using diversification process, search process is extended to explore promising new regions.

3.14.14 Move Mechanism

In Tabu search, new solutions are generated by applying a moving mechanism from the current solution. Move is defined as replacing new edge in a neighborhood or swapping edges. All moves applied to this solution are stored in candidate list. Each move generates new solution. Tabu search seeks to select a move that generates an improved solution or a move in a new direction. There are two forms of edge swaps, static edge swap and dynamic edge swap. The algorithm first determines all possible move edges and store them in a candidate list. Then the best move is selected from the candidate list to get a replacement solution iteratively.

3.14.15 2-Opt

2-Opt arbitrarily omits two edges from generated tours so that it reconnects and creates two new paths. This is done if the new tour is shorter than the older one so that this can be continued until no further improvement is possible.

3.14.16 Tabus

Solution in an edge or a node becomes restricted for subsequent search iteration defined by Tabus. Tabus prevent cycling when applying move mechanisms in current neighborhood solution. Tabus is often stored in short-term memory called *Tabu list* (list of possible moves not performed on the solution). In the Tabu list, only fixed and limited quantity of information is recorded (Tabu length). It can record complete solutions but it requires plenty of memory storage to do so making it expensive to check whether a move is Tabu or not. Edges in the list are removed by the FIFO (first in first out) technique. The Tabu list is updated based on current solutions obtained. The Tabu list operates like a short-term memory to prevent search from endlessly cycling between same solutions and the goal of Tabu list is to permit good moves in each iteration without revisiting solutions already encountered.

3.14.17 Stopping Criterion

To get possible feasible solution in a reasonable time, Tabu search needs termination criterion. Stopping criterion is used to determine when the search has to end. There are four most typically used stopping criteria in Tabu search: Number of iterations performed since best solution last changed is larger than a pre-specified maximum number of iterations; Maximum allowable number of iterations reached (or a set amount of CPU time); Stop after some number of iterations without an improvement in objective function value; or Stop when objective function reaches a pre-specified threshold (tolerance) value.

3.14.18 Aspiration Criteria

Tabus sometimes may prohibit attractive moves, even when there is no danger of cycling, or they will cause an overall stagnation of the searching process. Therefore, it is necessary to use some conditions to cancel Tabus. These conditions are called *aspiration criteria.* It is a sensitive key to consider Tabu search because this defines the flexibility of the Tabu search algorithm. By default, the aspiration criterion is to pick the least Tabu, one if all the available moves are in the Tabu lists. There are mainly two types of aspirations: move aspiration and attribute aspiration. Attribute aspiration criteria use revoke active Tabu status of attributes. Move aspiration criteria use revoke solution's Tabu classification .

3.15 Algorithm Development

The algorithm starts with a Tabu List. New Tabu lists are generated by calculating euclidian distance from the objective function, then searching a new neighborhood that contain Tabu lists shorter in distance than the previous neighborhood. The process repeats until a given stopping criteria is met or acceptable feasible optimal solutions are found. The Tabu search algorithm utilized in the current study follows the procedures listed in the following pseudo code and the flow chart is depicted in Fig. 19.

Algorithm 1 Pseudo-code for the proposed Tabu Search Algorithm

```
BEGIN
tabu_list:= [];
S: = initial solution; //generate an initial solution
S*:= S;
REPEAT
Find the best admissible solution S1 that belongs to Neighborhood of S
if f( S1) > f(S*) then S*:= S1;
Update TL (insert the move from S to S1 in TL ) //Tabu list tabu_list;
S: = S1;
UNTIL stopping-criteria =true //Until stopping criterion;
RETURN S*
End;
```

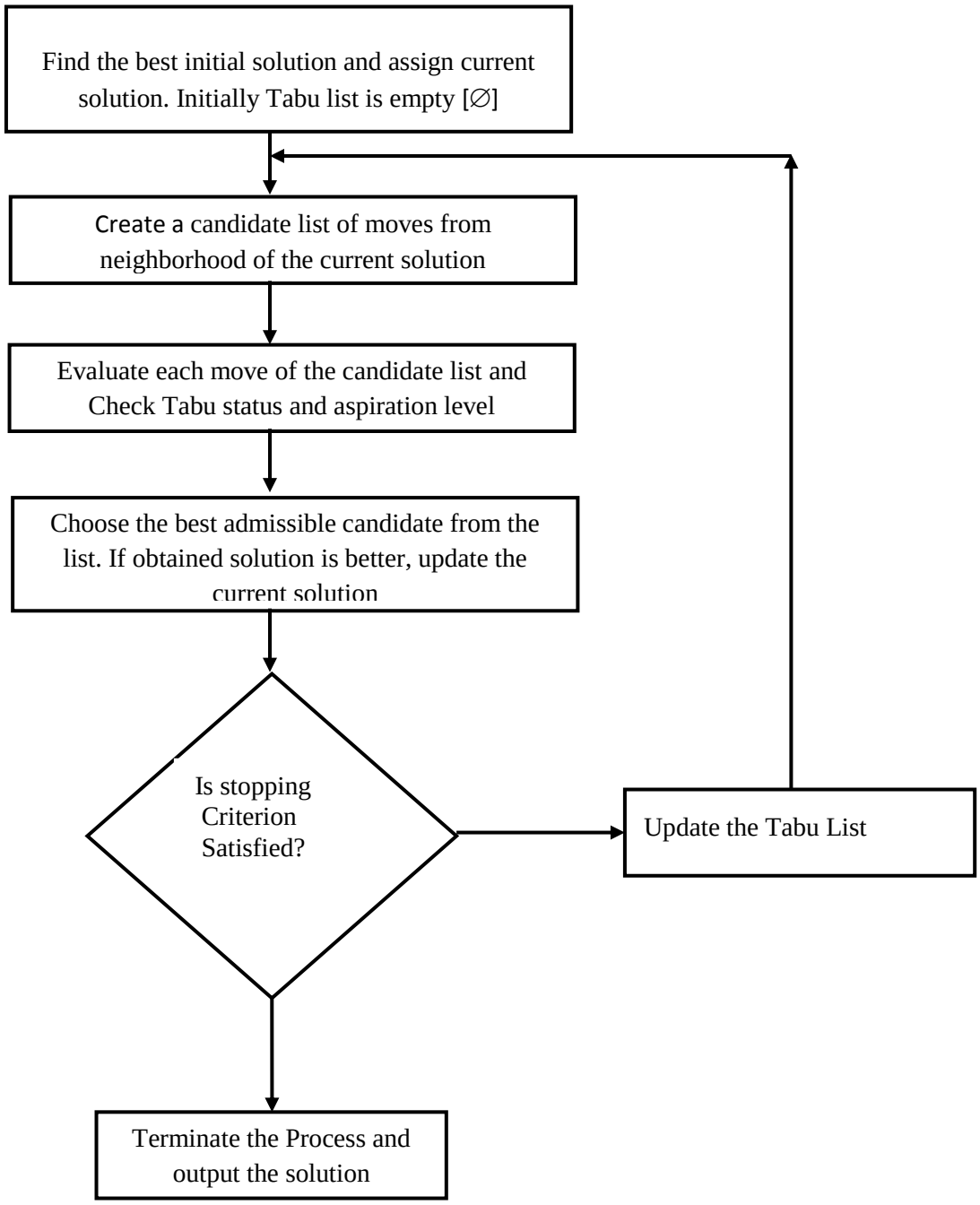


Figure 19: Flow chart for Tabu search algorithm.

3.16 Parameters Adaption

Tabu search is problem-specific and its parametric structure is affected by its parameter settings such as initial solution, neighborhood structure, Tabu length, aspiration criteria, intensification, diversification

and number of iterations. To optimize the number of equipment replacements, parameters of the Tabu search should be optimized to increase solution accuracy.

3.17 Software Development for Tabu Search Algorithm

The Tabu search algorithm was developed on a Mathlab (R2015a) platform (the Mathlab code is presented in Appendix 4). Table 14 lists the system requirements. The Hamilton cycle, a closed loop (undirected) scheme, was used to generate feasible optimal solutions. The algorithm involves iterative identification of vertex/node values and displays each iterative solution using a graphical user interface (GUI). A snapshot of the GUI output at a certain iterative stage has been shown in Fig. 20.

32-Bit and 64-Bit Mathlab and Simulink Product Families				
Operating Systems	Processors	Disk Space	RAM	Graphics
Windows 10 Windows 7 Service Pack 1 Windows XP Service Pack 3 Windows Server 2012	Any Intel or AMD x86 processor supporting SSE2 instruction set*	1 GB for Matlab only, 3–4 GB for a typical installation	2 GB	No specific graphics card is required. Hardware accelerated graphics card supporting OpenGL 3.3 with 1GB GPU memory recommended.
License Management • Some license types require a license server running FLEX net 11.11, which is provided by the Math Works installer. A license server that is serving multiple releases of MATLAB must use the version of FLEX net shipped with the latest release of MATLAB being served. • TCP/IP is required on all platforms when using a license server.				

Table 17: 32-Bit and 64-Bit Mathlab and Simulink Product Families.

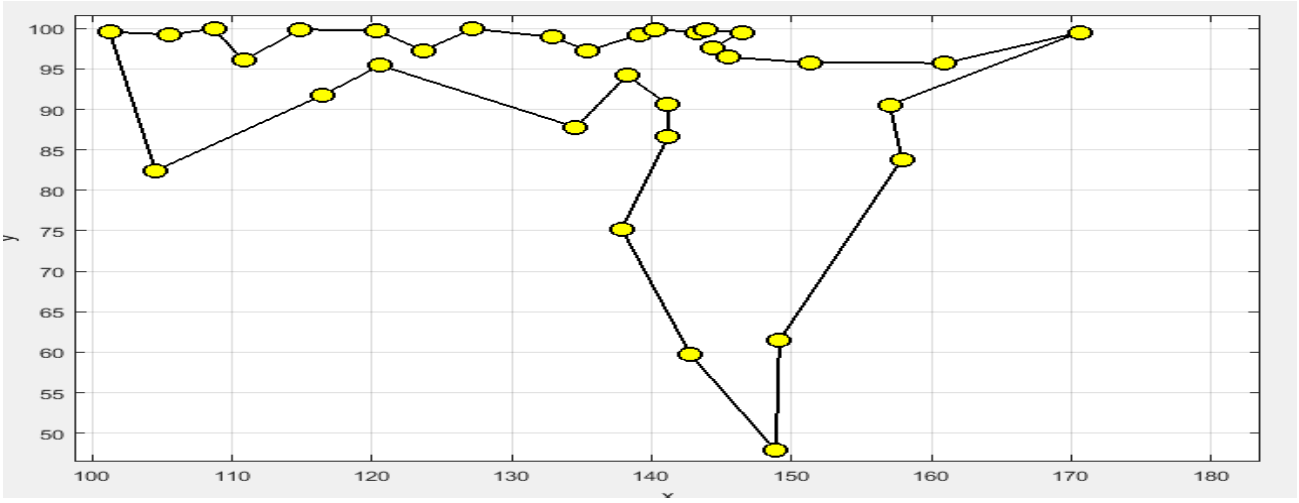


Figure 20: GUI output for proposed Tabu search algorithm with tolerance value 0.0001.

Chapter Four
4 Results and Discussion

Model validation was implemented by employing a data set of medical equipment at selected governmental hospitals in Addis Ababa and an Egyptian Hospital. Data set in the case of Addis Ababa includes 35 medical equipments that belong to different departments. Data set for the Egyptian hospital includes 60 pieces of medical equipments from 12 different departments. In the case study for Addis Ababa, final score for each device was calculated as equipment replacement priority weight (ERPW) where devices with higher ERPW are given higher priority for replacement and devices with lower ERPW take lower priority for replacement.

Qualitative and quantitative approaches were used as optimized medical equipment replacement tools. Data gathering techniques: questionnaires, direct interviews and observations were implemented. The participants were selected by purposive sampling technique. Around 278 questionnaires were distributed among hospitals and there were 241 respondents. The data showed that 85% of the participants agreed that there is a major gap in optimized medical equipment replacement. Furthermore, 73% of the respondents agreed that hospitals do replace their medical equipment before reaching their optimal replacement period. Around 81% of the respondents agreed that the hospitals do not have an efficient replacement methodology.

Model structure includes fourteen quantitative and qualitative replacement factors descending as main and sub-criteria, which can affect the replacement decision. Each medical equipment is assessed with respect to every criterion and ranked with respect to the criteria independent of other devices. This study presents an optimized replacement tool that can inform the hospitals how and which medical equipment in need of replacement in a clear methodological way. The proposed framework is divided into two models: the TFN-AHP model and Tabu search.

4.1 Results of the TFN-AHP Model

Equipment priority replacement support model was built using TFN-AHP multi-criteria approach based on the decision-makers preferences. The proposed TFN-AHP results were based on equipment priority replacement weight, which indicates priority level for the investigated devices. In order to obtain the priority score for the investigated devices, the proposed method classified data set into 3 categories: Raw

data, Score data and Final score data. Raw data includes the basic information like replacement price and replacement criteria. Score data is based on data ration, expert judgment evaluation and equipment evaluation based on their threshold values. Final score data translates the derived data into final score. In order to compute the equipment priority replacement weights for the investigated devices, we apply the data as mentioned above on the proposed TFN-AHP.

4.2 Mathlab and Excel Outputs for Tabu Search

Tabu search model was used to optimize the prioritized replacement equipment by considering their priority weight and the available replacement budget. For the purpose of this research, it assumes the available replacement budget is 30% of the estimated investigated equipment price. Tabu search is a local search technique and, in the current study, made use of the Hamilton cycle. The results revealed that the best maximum solutions are obtained when the tolerance value is 0.0001 and the Tabu length multiplication factor is 0.5. Given N number of equipments, the Tabu search outputs $2N$ number of possible optimal solutions. Results showed that all optimum solutions exclude expensive devices that consume a large amount of available budget (MRI and CT). The Tabu result revealed that 25 medical equipment (out of 33) are ready to get replaced. The replacement criteria were identified based on respondent's questioner assessments; ten factors were associated with technical matters, three factors associated with financial, and one factor associated with administrative.

The study utilized prioritization and optimization tools in order to design and develop a working decision support system for equipment replacement planning in government hospitals in Ethiopia. The model can classify equipments in high priority for replacement in different groups and provides decision-makers with the required tools that help to monitoring medical equipment status and remove/replace it from inventory at the right time. The model was tested on equipments within four randomly selected device categories.

In general, replacing equipment in a correct timing will prevent extraordinary expenses and it is important to have a well-organized replacement plan and will identify list of medical equipment required to replace based on their real needs. In practice, this implies to prepare a replacement plan based on a set of technical, financial, and safety criteria to provide a reasonable priority replacement weights for devices that require replacement and optimize them to generate an optimal list of medical equipment replacement list.

Once the replacement prioritization solution is optimized by the Tabu search algorithm, a shortest closed loop path will be generated and is called Hamilton cycle. This cycle usually contains similar distance of different series of feasible sequence numbers. For the purpose of this research, obtained Hamilton cycle contains 33 nodes (medical equipment). The Hamilton cycle has vertex and edge. The cycle can be written as **G (V, E),** where **V** is nothing but it contains equipment weights and its estimated price and **E** measures the distance from one node to another node. Once the equipments are optimized near their optimal solution, we have a total of *2N* solutions where *N* is number of equipment or nodes. In our case *N* is 33, therefore the total number of solutions is 66. All the 66 generated optimal solutions have equal Hamilton path distances. For example, the first two generated optimal solutions with Hamilton path distance 239.4630 are:

➔21 26 28 32 33 31 30 29 27 25 24 23 22 20 18 14 13 10 11 9 7 5 1 2 3 4 6 8 12 19 15 17 16= (Hamilton path distance=**239.4630)**

➔3 2 1 5 7 9 11 10 13 14 18 20 22 23 24 25 27 29 30 31 33 32 28 26 21 16 17 15 19 12 8 6 4 = (Hamilton path distance=**239.4630)**

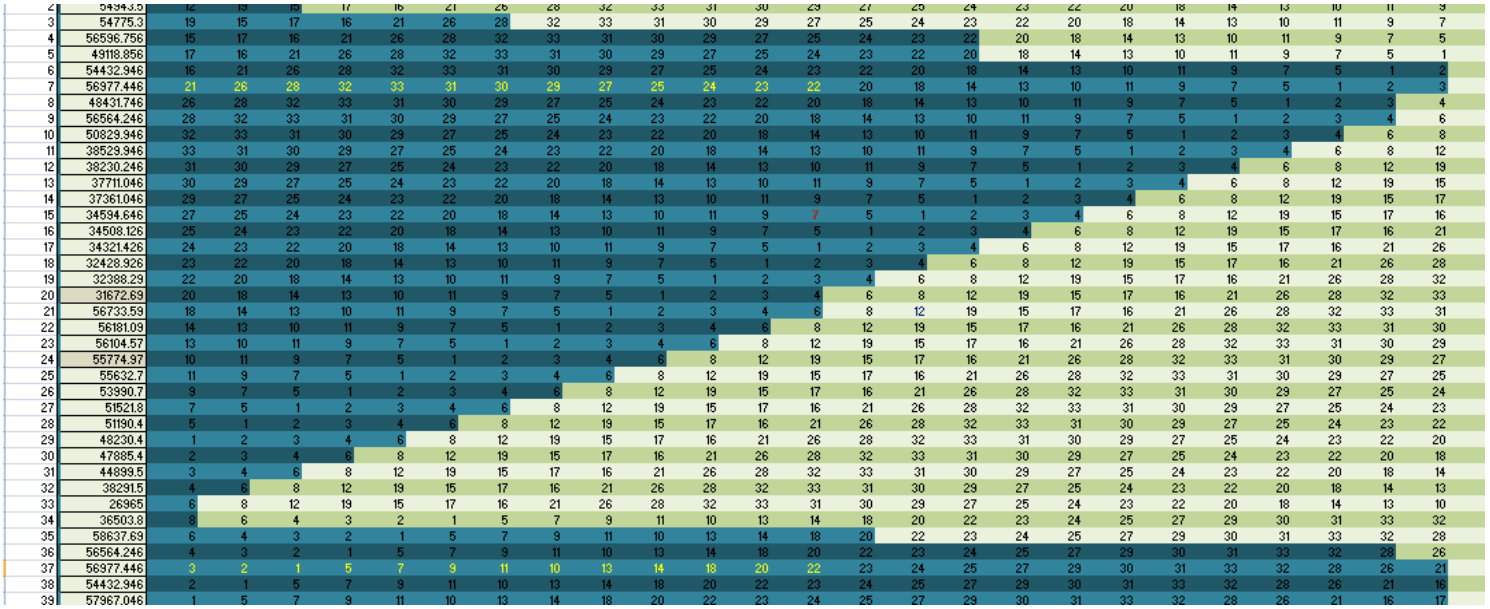


Figure 21: different sequence order numbers analyzed by excel spreadsheet.

Even though the Hamilton path distances are the same, the orders of each individual sequence is unique. All 66 Hamilton path sequence orders are exported into an excel spreadsheet for further ranking filtrations. The excel output shown in Fig. 21 depicts such. As it could be seen on the figure, the

following three sequences have the highest equipment in need to replace according to the hospital available budget:

- A=[16,21,26,28,32,33,31,30,29,27,25,24,23,22,20,18,14,13,10,11,9,7,5,1,2],3,4,6,8,12,19,15,17
- B=[21,26,28,32,33,31,30,29,27,25,24,23,22,20,18,14,13,10,11,9,7,5,1,2,3],4,6,8,12,19,15,17,16
- C=[3,2,1,5,7,9,11,10,13,14,18,20,22,23,24,25,27,29,30,31,33,32,28,26,21],16,17,15,19,12,8,6,4
- D=[2,1,5,7,9,11,10,13,14,18,20,22,23,24,25,27,29,30,31,33,32,28,26,21,16],17,15,19,12,8,6,4,3
- E=[1,5,7,9,11,10,13,14,18,20,22,23,24,25,27,29,30,31,33,32,28,26,21,16,17],15,19,12,8,6,4,3,2

The number of equipments to replace based on the available hospital budget in all of the five cases (A, B C, D or E) is 25. This result alone cannot lead us the right decision to make regarding the final list of equipments to replace. We still have five optimal solutions. We still need a way to differentiate the above five optimal results and pick the best. The technique applied to do so in the current thesis study was equipment risk category scoring scheme (High-Risk devices=3, Medium-Risk devices=2, Low- Risk devices=1). Based on this scoring technique, the following outputs were obtained for the total risk factor (TRF) calculation: A: TRF = 50, B: TRF = 51, C: TRF = 51, D: TRF = 50, E: TRF = 49.

TRF value of sequence B and C appeared to be ('slightly') higher than that of A , D and E while there is a tie between B and C sequences. That shows that another method which could differentiate all the five sequences with equal TRF outputs should be developed. The other method utilized was the so called *50 plus 1* rule that is based on "mission criticality (Equipment Function)". Mission criticality is defined in terms of medical equipments functionality and it measures the effect of medical equipments on patients and other hospital services. In this regard, the Fennigkoh and Smith model was utilized. This model reflects equipment scoring technique based on their mission criticality (see Table 18).

Category	Function Description	Point score
Therapeutic	Life support	10
	Surgical and intensive care	9
	Physical therapy and treatment	8
Diagnostic	Surgical and intensive care monitoring	7
	Additional physiological monitoring and diagnostic	6
Analytical	Analytical laboratory	5
	Laboratory accessories	4
	Computers and related	3
Miscellaneous	Patient related and other	2

Table 18: Devices' mission criticality .

The 50 plus 1 rule offered the following results:

A: Mission criticality using 50 plus 1 rule for 25 equipments = 51;

B: Mission criticality using 50 plus 1 rule for 25 equipments = 49;

C: Mission criticality using 50 plus 1 rule for 25 equipments = 91;

D: Mission criticality using 50 plus 1 rule for 25 equipments = 83; and

E: Mission criticality using 50 plus 1 rule for 25 equipments = 80.

Based on the principle of equipment mission criticality (Life Support, Thearuptic, Diagnostic, Analytical and Miscellaneous) using the 50 plus 1 rule, equipments in C sequence outperformed equipment sequences in A,B,D and E. Therefore the final order of equipments that require replacement is: **C**=[3,2,1,5,7,9,11,10,13,14,18,20,22,23,24,25,27,29,30,31,33,32,28,26,21],16,17,15,19,12,8,6,4.

Table 19 lists all 33 prioritized medical equipment data. Note that according to the hospital available budget, the only equipments possible to replace using the traditional replacement approach is just 7. Table 20 presents the 25 selected equipments (shaded) extracted using the Tabu search algorithm.

Sequence number	Description	**Budget =59,190.00**
		Estimated Price ($)
1	Oxygen concentrator	345
2	Defibrillators	2985.9
3	Mechanical Ventilator	6608
4	Anesthesia Machine	11326.5
5	Infant Incubator	2960
6	X-ray	26965
7	Infusion Pump	331.4
8	Ultrasound	36503.8
9	Baby Warmer	2468.9
10	Ultrasonic Nebulizers	142.27
11	ECG Machine	1642
12	Autoclave	28225.7
13	Laboratory Medical Centrifuge	329.6
14	Pulse Oximeter	76.52
15	Clinical Chemistry	9382
16	Diathermy	4063.5
17	Hematology Analyzer	6520
18	Bedside Monitor	552.5

19	Vertical Pressure sterilizer	17335.8
20	High Pressure Suction	1904.1
21	Hot Air Oven	8545.7
22	Mini-Shaker	715.6
23	Sphygmomanometer	40.63
24	Surgical Light	1892.5
25	Flat Bed	186.7
26	Slit Lamp	3194
27	Stethoscope	86.52
28	Operating table	5734.3
29	Freezer	2766.4
30	Audiometer	350
31	Stretcher Wheeled	519.2
32	Ophthalmoscope	12300
33	Laboratory Microscope	299.7
		197300.00

Table 19: Prioritized medical equipment data.

Sequence number	Description	**Budget =59,190.00**
		Estimated Price ($)
3	Mechanical Ventilator	6608
2	Defibrillators	2985.9
1	Oxygen concentrator	345
5	Infant Incubator	2960
7	Infusion Pump	331.4
9	Baby Warmer	2468.9
11	ECG Machine	1642
10	Ultrasonic Nebulizers	142.27
13	Laboratory Medical Centrifuge	329.6
14	Pulse Oximeter	76.52
18	Bedside Monitor	552.5
20	High Pressure Suction	1904.1
22	Mini-Shaker	715.6
23	Sphygmomanometer	40.63
24	Surgical Light	1892.5
25	Flat Bed	186.7
27	Stethoscope	86.52
29	Freezer	2766.4
30	Audiometer	350
31	Stretcher Wheeled	519.2
33	Laboratory Microscope	299.7
32	Ophthalmoscope	12300
28	Operating table	5734.3

26	Slit Lamp	3194
21	Hot Air Oven	8545.7
16	Diathermy	4063.5
17	Hematology Analyzer	6520
15	Clinical Chemistry	9382
19	Vertical Pressure sterilizer	17335.8
12	Autoclave	28225.7
8	Ultrasound	36503.8
6	X-ray	26965
4	Anesthesia Machine	11326.5

Table 20: The 25 selected equipments (shaded) extracted using the Tabu search algorithm.

4.3 Case Study: Egyptian Hospital

In order to further test the performance of the proposed optimized replacement scheme, another case study was done. The case study considered the prioritization of medical equipments found in an Egyptian hospital with basic information and the equipments are sorted according to their replacement score based on the QFD method as shown in Table 21. Note that according to the hospital available budget, the only equipments possible to replace using the traditional replacement approach is just only 3.

Sequence number	Description	**Budget =144,660.00**
		Estimated Price ($)
1	Bilirubinometrt	18000
2	Ventilator	70000
3	Infusion Pumb	6700
4	Incubator	90000
5	Blood gas analyzer	130000
6	Pulse Oximeter	12000
7	Monitor	40500
8	Mobile x-ray	115000

Table 21: Sample score data for equipment replacement in the case of an Egyptian Hospital.

Using the above table replacement sample scored data, the proposed TSPDC optimization technique was applied in order to generate the possible series of feasible optimal solution/s by forming the closed loop (undirected) Hamilton cycle and the output is depicted in Fig. 22.

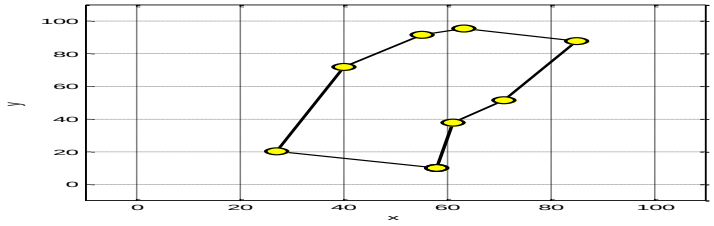


Figure 22: Hamilton cycle output using the proposed Tabu search algorithm with tolerance value of 0.0001 for the case of an Egyptian hospital.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1																				
2			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3	EP		345	2985.9	11326.5	6608	2960	26965	36503.8	2468.9	1642	142.27	329.6	28225.7	9382	6520	76.52	552.5	4063.5	173355.8
4	Erisk		3	3	3	3	3	3	2	3	3	2	1	2	1	1	1	2	2	2
5	Mission Criticality		10	9	10	10	9	6	6	8	6	2	5	2	5	5	2	6	7	2
6	Seq_No																			
7	1	59480.5	23	22	21	19	16	15	11	10	9	8	5	2	1	4	3	6	7	12
8	2	59353.3	22	21	19	16	15	11	10	9	8	5	2	1	4	3	6	7	12	18
9	3	58637.7	21	19	16	15	11	10	9	8	5	2	1	4	3	6	7	12	18	13
10	4	58306.3	19	16	15	11	10	9	8	5	2	1	4	3	6	7	12	18	13	14
11	5	56402.2	16	15	11	10	9	8	5	2	1	4	3	6	7	12	18	13	14	17
12	6	55849.7	15	11	10	9	8	5	2	1	4	3	6	7	12	18	13	14	17	20
13	7	55773.2	11	10	9	8	5	2	1	4	3	6	7	12	18	13	14	17	20	25
14	8	55443.6	10	9	8	5	2	1	4	3	6	7	12	18	13	14	17	20	25	27
15	9	55301.3	9	8	5	2	1	4	3	6	7	12	18	13	14	17	20	25	27	32
16	10	53659.3	8	5	2	1	4	3	6	7	12	18	13	14	17	20	25	27	32	33
17	11	51190.4	5	2	1	4	3	6	7	12	18	13	14	17	20	25	27	32	33	31
18	12	48230.4	2	1	4	3	6	7	12	18	13	14	17	20	25	27	32	33	31	30
19	13	45244.5	1	4	3	6	7	12	18	13	14	17	20	25	27	32	33	31	30	29
20	14	44899.5	4	3	6	7	12	18	13	14	17	20	25	27	32	33	31	30	29	28
21	15	52142.3	3	6	7	12	18	13	14	17	20	25	27	32	33	31	30	29	28	26
22	16	63468.8	6	7	12	18	13	14	17	20	25	27	32	33	31	30	29	28	26	24
23	17	64729.5	7	12	18	13	14	17	20	25	27	32	33	31	30	29	28	26	24	23
24	18	28225.7	12	18	13	14	17	20	25	27	32	33	31	30	29	28	26	24	23	22
25	19	0	18	13	14	17	20	25	27	32	33	31	30	29	28	26	24	23	22	21

Figure 23: Different sequence order number analyzed by excel spreadsheet in the case of Egyptian Hospital.

Further ranking filtration done using excel offered the results shown in Fig. 23. The Hamilton cycle contains 8 nodes (medical equipment). A total number of possible solutions is then 16. The proposed Matlab based Tabu search algorithm generated the following two optimal solutions with equal Hamilton path distances (226.1566).

→5 4 2 1 3 6 7 8 = (Hamilton path distance=**226.1566)**

→4 2 1 3 6 7 8 5 = (Hamilton path distance=**226.1566)**

According to the excel output shown in Fig. 23, the following sequences have the highest equipment in need of replacement based on the hospital's available budget:

⇨ A. [2 1 3 6] 7 8 5 4
⇨ B. [1 3 6 7] 8 5 4 2
⇨ C. [7 6 3 1] 2 4 5 6
⇨ D. [6 3 1 2] 4 5 8 7

Hence, 4 equipments need to be replaced but 4 possible choices exist to do so:

A: Equipment to replace = 4,

B: Equipment to replace = 4,

C: Equipment to replace = 4, and

D: Equipment to replace = 4.

Then the total risk factor scores were computed (High-Risk devices = 3, Medium-Risk devices = 2, Low-Risk devices = 1) and the results were:

A: TRF = 10,

B: TRF = 9,

C: TRF = 9 and

D: TRF = 10.

Again, the computed TRF values could not lead to a unique optimal solution. For this reason, the 50 plus 1 approach was utilized based on the equipments mission criticality and the following results were obtained:

A: Mission criticality based on 50 plus 1 rule for 8 equipments =27.

D: Mission criticality based on 50 plus 1 rule for 8 equipments =13.

Therefore**,** equipment sequence in **A** is the most preferable sequence chosen and hence the final replacement sequence is A**=** [2 1 3 6] 7 8 5 4. The result show that the number of equipments prioritized to be replaced using the Tabu search algorithm (which is 4) is quite close to what is computed using the traditional approach (which is 3).

Chapter Five
5 Conclusion and Future Works

Replacing equipment in correct timing prevents extraordinary expenses and contributing to generalized reduction in maintenance, repair, and operating costs. Therefore, a more efficient budget application will be possible and, as result, medical service will improve. Delay of treatment due to equipment downtime, even for short periods, can have very serious implications in quality of healthcare services provided. The main intent of the current study was to develop a decision-supporting system for equipment replacement in order to increase equipment replacement planning practices in health-care provisions. It is understandable that effective equipment replacement practices result in increased value of health service provision. Principal proposition of this research was first to assess existing replacement practices in governmental hospitals in Ethiopia and be able to propose a working system to address gaps observed. The study involved different elements of the replacement process including equipment service and support, equipment function, cost benefits, clinical efficiency, user errors, and reliability to find out their optimal combination during the replacement system design.

The model was applied on selected 35 different categories of equipments. In principle, the model can be applied to a wide array of equipment database in a given hospital set up. The proposed replacement process was based on a multi-criteria priority and optimization methodology exercised in fields of decision analysis. The multi-criteria medical equipment replacement model appeared to offer an effective means of identifying and prioritizing devices in need of replacement. Medical equipment replacements can thus be quantitatively prioritized allowing hospitals to purchase medical equipments needed to support their services.

Traditionally, equipment replacement is handled in hospitals (particularly those in low resource settings) substantially based on common sense rather than on an active policy (several parameters and replacement criteria). The proposed TFN-AHP model prioritizes medical equipments in need of replacement. The proposed model uses both relative and absolute measurements to determine weighting values for all criterions for evaluating the equipments. Relative measurement was applied in order to maintain the consistent criteria weights as a result the proposed model was able to integrate into a medical equipment management system in the hospitals to prioritize the medical equipments for replacement.

There are number of issues that still require further investigations with the optimal replacement scheme. One is testing it on a large data set by including more types of medical equipments. Data was collected only from few hospitals while increasing the samples could enhance the usability of the method. Comparing the performance of the Tabu search algorithm against other optimization tolls could also be beneficial. Supporting tools for equipment replacement do not have to be inbuilt a general way, for all kinds of equipments. To build and apply a replacement tool per a particular type of equipment will be an advantage, as it allows building a more detailed and sophisticated substitution criteria.

References

[1] O'Keeffe K, "Medical Device Regulation: An Introduction for the Practicing Physician"2004 Feb 17 WHAnn Intern Med, Maise, pp. 296-302.

[2] Polisena J, Jutai J, Chreyh R. "A proposed framework to improve the safety of medical devices in a Canadian hospital context". *Med Devices (Auckl)*, 16 May 2014, pp. 39-147.

[3] O'Keeffe K. "The rise of medtech" WH Ann Intern Med, Jun 10, 2011.

[4] Jahnke, David, "Medical Equipment Replacement Strategy," IEEE, May 2005, pp. 80-84.

[5] "The Future of the Public's Health in the 21st Century", Washington (DC): National Academies Press (US); 2002.5, The Healthcare Delivery System. [Online]: Available www.ncbi.nlm.nih.gov/books/NBK221227.

[6] Douglas D.Gransberg,"Major Equipment Life-cycle Cost Analysis, Minnesota department of transportation," Principal Investigator Institute for Transportation lowa State university, April 2015, MN/RC 2015-16.

[7] Lynette J,Brian P, "A Better Approach To Equipment Replacement", HealthCare financial management association, May 16, 2018.

[8] Thimbleby H, "Technology and the future of healthcare," *J Public Health Res*. 2013 Dec 1; 2(3):e28. Published 2013 Dec 1.

[9] Fennigkoh.L, "A medical equipment replacement model.", J. Clin. Eng., vol. 17, pp. 43–47, 1990.

[10] Rodziewicz T L, Hipskind J E,"Medical Error Prevention" StatPearls, Treasure Island (FL): StatPearls Publishing; 2020 Jan: https://www.ncbi.nlm.nih.gov/books/NBK499956/

[11] Jay M, "Public health methodology environmental and systems issues", 2012, pp. 290-300.

[12] K. L. Carleton, J. D Enderle, K. T. Jensen and Q Zhu,"Development of an Equipment Replacement Planning Tool for the Veterans Administration,"2007 IEEE 33rd Annual Northeast Bioengineering Conference, Long Island, NY, 2007, pp. 275-276.

[13] Polisena J, Jutai J, Chreyh R.," A proposed framework to improve the safety of medical devices in a Canadian hospital context", *Med Devices (Auckl)*. 2014; 7:139-147. Published 2014 May 16.

[14] Saaty "A scaling method for priorities in hierarchical structure," *Journal of Mathematical Psychology*, vol. 15, 1977, pp. 234–281.

[15] Z.P.Fan,J.Ma,and Q.Zhang,"An approach to multiple attribute decision making based on fuzzy preference information on alternatives," *Fuzzy Sets and System*s, vol.131, no.1, pp.101-106, 2002.

[16] T.L.Saaty,"A Scaling Method For Priorities in Hierarchical Structure," Journal of Mathematical Psychology, vol 15, 1977, pp. 234-281, https://doi.org/10.1016/0022-2496(77)90033-5

[17] Malaysiana,K.Berkumpulan,M.Proses,H.Analisis,K.P.Keutamaan,A.H.Process, and D.E.Analysis,"Group Decision via Usage of Analytic Hierarchy Process and Preference Aggregation Method," , 2012, vol. 41, no.3, pp. 361-366.

[18] A.K.Verma,A.Srividya and R.S PrabhuGaonkar,"Fuzzy Reliability Engineering Concepts and Applications," Narosa Publishing House Pvt.Limited, 2007.

[19] Liang, X.Zhao, X.Wang, M.Li, Z,"Small and Medium-Sized Enterprises Sustainable Supply Chain Financing Decision Based on Triple Bottom Line Theory Sustainability," 2018, 10, pp. 42.

[20] A.K.Verma,A.Srividya and R.S Prabhu.G,"FuzzyReliablity Engineering Concepts and Applications," Narosa Publishing House Pvt.Limited, 2007.

[21] Deng.H, "Multi-criteria analysis with fuzzy pairwise comparison, *"International Journal of Approximate Reasoning*, vol. 21, no. 3, 1999, pp. 215–231.
[Online] Available: https://doi.org/10.1016/S0888-613X(99)00025-0

[22] Zhu, K.J, Jing, Y. and Chang, D. Y, "A Discussion on Extent Analysis Method and Applications of Fuzzy AHP," *European Journal of Operational Research*, 1999, pp. 450-456.

[23] Molly.G,"The Future of Healthcare:9 capabilities for Post-Reform Success", January 23rd, 2012.

[24] https://www.ecri.org/press/fda-medical-device-servicing-report.

[25] Dondelinger.R, "A Simple Method of Equipment Replacement Planning. Biomedical instrumentation & technology / Association for the Advancement of Medical Instrumentation" (2003). pp. 3-35.

[26] Tobey.C "Medical equipment replacement: Planning, Factors, Methods and outcomes" A practicum for biomedical engineering & Technology Management Issues, ,Technical service program. University of Vermont, 29, Nov. 2018.

[27] Noor, Majid & Chawla, Seema & Magray, Dr. (2016). Integration of Healthcare System with its Experts for Improving the Life Expectancy of Medical Devices : A Review. International Journal of Scientific Research in Science and Technology. 2. 223-231.

[28] https://harmonyhomemedical.com/blogs/news/all-types-of-medical-equipment.

[29] Robert M. Dondelinger ,"Clinical Engineering Management, A Simple Method of Equipment Replacement Planning" CBET-E,USA, June 2017.

[30] Mohammed.F, Amr.S,*"* Prioritize Medical Equipment Replacement Using Analytical Hierarchy Process**,"** *Biomedical Engineering and systems, Faculty of Engineering* Cairo University, Egypt, Feb. 2015.

[31] C. L. Yeo, "Medical Equipment Analysis and Planning," *Seminar of Medical Equipment Management for Hospital Management*, Biomedical Engineering Department, Ministry of Public Health, Thailand, 2-4 May, 2005.

[32] Rajasekaran.D, "Development of an Automated Medical Equipment Replacement Planning System in Hospitals," Bioengineering Conference, Proceeding of the IEEE 31st Annual Northeast, April 2005, pp. 52–53.

[33] Taylor.K and Jackson.S, "A Medical Equipment Replacement Score System," *Journal of Clinical Engineering*, January/March 2005, pp. 37–41.

[34] Yatsenko.Y, Hritonenko.N, "Properties of Optimal Service Life under Technological Change," *International Journal of Production Economics*, 2008, vol. 114, pp. 230-238.

[35] Miguel.C and Rodriguez.D, "A Neural-Network-Based Model for the Removal of Biomedical Equipment from a Hospital Inventory," *Journal of Clinical Engineering*, July/September 2006, pp. 140–144.

[36] Rajasekaran.D, "Development of an automated medical equipment replacement planning system in hospitals," Proc. IEEE 31st Annu. Northeast Bioeng. Conf. 2005, pp. 1–3.

[37] Vesely.E and Goldberg.F, "Fault Tree Handbook," *U.S. Nuclear Regulatory Commission*, NUREG-0492, U.S.A, 1981.

[38] Miguel.C, Rodriguez.D, Sanchez.M.C and L.M. Lic Gonzalez, "An Event Tree-Based Mathematical Formula for the Removal of Biomedical Equipment from a Hospital Inventory," *Journal of Clinical Engineering*, Winter 2002, pp. 63–71.

[39] Ouda.K, Mohamed.A, and Saleh.N, "A simple quantitative model for replacement of medical equipment proposed to developing countries," *5th Cairo Int. Biomed. Eng. Conf. CIBEC,* 2010, pp. 188–191.

[40] Mummolo.G, Ranieri.L, Bevilacqua.V, and Galli.P, "A Fuzzy Approach for Medical Equipment Replacement Planning," *Proc. Third Int. Conf. Maint. Facil. Manag*, 2007,pp. 229–235.

[41] Mohammed. F, Amr. S, "Prioritize Medical Equipment Replacement Using Analytical Hierarchy Process," *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)* ,vol. 10, Issue 3 Ver. II, May – Jun. 2015, pp. 55-63.

[42] Malaysiana.S,Berkumpulan.K, Proses.M, Analisis.H, Keutamaan.K,"Group Decision via Usage of Analytic Hierarchy Process and Preference Aggregation Method," vol. 41, no. 3, pp. 361–366, 2012.

[43] Sloane.B, Liberatore.M,Nydick.R,Luo.W, and Chung.Q, "Using the analytic hierarchy process as a clinical engineering tool to facilitate an iterative, multidisciplinary, micro economic health technology assessment," *Comput. Oper. Res*, vol. 30, 2003,pp. 1447–1465.

[44] Pecchia.L,Martin.J,Ragozzino.A, Vanzanella.C, Scognamiglio.A,Mirarchi.L, and S. P. Morgan, "User needs elicitation via analytic hierarchy process (AHP). A case study on a Computed Tomography (CT) scanner," *BMC Med. Inform. Decis. Mak.*, 2013, vol. 13, pp. 22-24.

[45] Dondelinger.R,"CLINICAL ENGINEERING MANAGEMENT, A Complex Method of Equipment Replacement Planning, *An Advanced Plan for the Replacement of Medical Equipment,*" CBET-E *of BI&T*, vol. 37, no.6, 2003, p. 433.

[46] David L., "Web Database Applications with PHP and MySQL", 2nd Edition, 2014.

[47] Fennigkoh.L, "A medical equipment replacement model," *J. Clin. Eng*., vol. 17, 1990, pp. 43–47.

[48] Taylor.K and Jackson.S, "A medical equipment replacement score system," *J. Clin. Eng.,* vol. 30, no. March 2005, pp. 37–41.

[49] FENNIGKOH.L" A Medical Equipment Replacement Model," Clinical engineering, St Luk Wiscomil, 2008, pp.15-25.

[50] Hopp.W,and Nair, S. "Timing equipment replacement decisions due to discontinuous technological change", *Nat~al Research Logistics* 38, 1991, pp 203-220.

[51] Dondelinger, R.M., "A Simple Method of Equipment Replacement Planning", *Biomedical Instrumentation & Technology*, vol. 37, no. 6, 2003.

[52] Saleh.N, "Comprehensive Frameworks for Decision Making Support in medical equipment management", 2014.

[53] Rajasekaran.D, "Development of an Automated Medical Equipment Replacement Planning Systems in Hospitals," *Proceeding of IEEE 31st Annual Northeast Bioengineering Conference,* 2005, pp. 52-53.

[54] Mehrjerdi.Y, "Quality Function Deployment and Its Extensions", *International Journal of Quality & Reliability Management*, vol. 27, no.6, 2010, pp. 616-640.

[55] Miroslav.G "Estimation of Medical Equipment Prices - a Case Study of Tomotherapy Equipment in the Czech Republic", *Journal of Business Economics and Management,* vol 18, no.6, 2017, pp 1193-1211.

[56] Democratic of Ethiopia Ministry of Health, "Ethiopian Hospital Services Transformation Guidelines", and August 2010

[57] Federal Democratic Republic of Ethiopia Central Statistical Agency, "Population Projection of Ethiopia for All Regions, At "Wereda" level from 2014 - 2017", August 2013.

[58] T. L. Saaty, "The Analytic Hierarchy Process" .McGraw-Hill, New York, 1980

[59] Deng.H "Multi-Criteria analysis with fuzzy pairwise comparison" *International Journal of Approximate Reasoning,* vol 21, no 3, pp.215-231.

[60] Tesfamariam and Sadiq (2006) based on Saaty scale, Kaufmann, & Gupta, 1988.

[61] T.Saaty "The analytic hierarchy process" Newyork.1980

[62] T. L. Saaty, "A scaling method for priorities in hierarchical structure, *"Journal of Mathematical Psychology*, vol. 15, pp. 234–281, 1977.

[63] Vaidya.K,"Analytic hierarchy process:an overview of applications," *European Journal of Operational Research*, vol 169, 2006, pp. 1-29.

[64] Chang.D,"Applications of the extent analysis method on fuzzy AHP," *European Journal of Operational Research*, vol. 95, 1996, pp. 649-655.

[65] Machani.M., and Nourelfath,M., "A Genetic Algorithm for Integrated Production and Preventive Maintenance Planning in Multi-State Systems", *Proceedings of the 8th Conference of Modeling, and Simulation*, MOSIM'10, Hammamet, Tunisia, May, 2010

[66] Bakar, S. and Ibrahim, M., "Optimal solution for travelling salesman problem using heuristic shortest path algorithm with imprecise arc length*", American Institute of Physics Conference Series* 2017, vol. 1870, no. 1

[67] Per.Mattsson,"the asymmetric traveling salesman problem", Uppsala University, Turkey 22 October 2010.

[68] Glover, Fred and Laguna, Manuel, *Tabu Search*, 1997, Kluwer Academic Publishers, Boston.

[69] J. Dreo, A. Petrowski, P. Siarry, E. Taillard, "*Metaheuristics for Hard Optimization*, Methods"

[70] Graham L.," *Handbook of Combinatorics*, Chapter 28," 1995

[71] Reeves.M, Colin. R, "Modern Heuristic Techniques for Combinatorial Problems," 1993.

[72] Fred G. and Rafael M.,"Tabu Search," *Leeds School of Business, University of Coloradoe*, Valencia

[73] Crown W., Buyukkaramikli N., "Constrained Optimization Methods in Health Services Research—An Introduction: Report 1 of the ISPOR Optimization Methods Emerging Good Practices Task Force**,"** *Value in Health*, vol.20, March 2017, Issue 3, pp. 310 – 319.

[74] Glover S. & Laguna M., "Tabu Search", 1999

Appendix 1: First Questioner

Addis Ababa University
Addis Ababa Institute of Technology
School of Multidisciplinary, Center of Biomedical Engineering

My name is Henok Hussien, MSc student at the center of Biomedical Engineering in Addis Ababa University, Institute of Technology. Currently I am undertaking research in the field of '*Medical Equipment Replacement'* for the partial fulfillments of the requirement for Masters of Science in Biomedical Engineering. The aim of the survey is to assess and determine factors that affect the replacement process. And designing decision support system for medical equipment replacement.

- Objective of the Survey
  - To assess the current scenario of medical equipment replacement practices in hospital.
  - To identify major challenges in medical equipment replacement system.

- Research Question
  - How medical equipment replacement process is conducted?
  - Does hospital in Ethiopia replace their medical equipment according to their replacement plan?
  - What is the gap between traditional medical equipment replacement and optimization medical equipment replacement?

This study is for only decision-making purpose. Respondents are requested to give genuine answer. It is enough writing your institute name in the beginning of the questionnaire. I promise to treat all information you provide as strictly. Your cooperation and assistance is highly valued.

To make it clear to you about the concept of medical equipment replacement, short clarifications on the whole essence of the key terms are provided in below.

Medical Equipment Replacement:-All equipment reaches the point in its life where the cost-benefit ratio goes to negative and decreased reliability, increased downtime and increased operating costs as a result equipment is become obsolescence. At that point, replacement must be considered.

Questioner Organization

Part I:-General Information of Respondents
Part II:-Requirement Factors for Medical Equipment Replacement Process.
Part III:-Equipment Replacement Decision Making.

Lot No: _____
Part I: - General Information of Respondents
1. Hospital/Institution Name: [_____]
2. Gender: ◯Male ◯ Female
3. What is your professional?
◯Biomedical Engineer◯Medical Director (MD)◯ Doctor ◯Nurse◯ Laboratory- Technologist.
◯Radiologist Pharmacist Technician◯ Others (Please specify)[_____]
4. How long have you been working in the hospital/institution?

◯ <1 year ◯ 1-2 years ◯ 2-3 years ◯ 3-4 years ◯ >4 years

5. What is your education status?

◯ Diploma ◯ First Degree ◯ Master Degree ◯ PHD ◯ Others, (Please Specify)[_____]

6. What is your role in the hospital?

◯ Equipment User ◯ Medical Director ◯ Hospital Manager ◯ Other (please specify)[_____]

7. How many beds are in your hospital?

◯ <50 ◯ 50-250 ◯ 250-500 ◯ >500 ◯ don't, know

8. Do you have a well established biomedical engineering?

◯ Yes ◯ No

Part II: Requirement Factors for Medical Equipment Replacement Process.

9. The following items are factors that affect medical equipment replacement process. *Tick all that apply*.

List of items measuring appropriateness of medical equipment replacement		Alternative Response				
		Agree	Fairly agree	Strongly agree	Disagree	Strongly disagree
A	Technical Factors					
	How much do you agree that the following factors affect replacement process?					
1	Increase technological obsolescence					
2	Increase physical deterioration					
3	Increase failure rate					
4	Increase standardization					
5	Low availability of backup equipment					
6	Poor inventory management system					
B	Equipment Support and Service					
1	End of manufacture support					
2	Equipment functional life is exceeded					
3	Poor Maintenance practices					
4	Increase the cost of maintenance					
5	Increase downtime					
C	Cost Benefits					
1	Increase the cost of operating it become sufficiently high					
2	Increase revenue associated with new technology					
3	Increase of purchase costs due to devices are replaced too early					
4	Increase costs of part inventory					
5	Capital budget(money limitation)					
6	Increase labor costs					
D	Availability					
	How much do you agree that the following item affect replacement process?					

1	Spare part availability					
2	Speed of obtaining the spare parts					
E	Sustainability and User training					
	How much do you agree that the following item affect replacement process?					
1	Increase house and overseas training for technical staff					
2	Increase the cost of inventory management					
3	Increase training time for users					
4	Increase user problem recalls and alerts					
5	Increase user errors					
F	Clinical Safety and Preferences					
	How much do you agree that the following item affect replacement in clinical efficiency?					
1	Increase regulatory requirement					
2	Decrease patient care					
3	Reduce technical and procedural skill					
4	Lack of essential safety features					
5	Increase regulatory prohibition					
6	New performance requirement					
7	Lower clinical competency					
8	Make operational procedures complex					
9	Challenges to improve staff performance					
10	Confused users to adapt different equipment					

Part III:-Equipment Replacement Decision Making

10. Does your hospital have medical equipment replacement decision support system? *Yes/No*, if ‘’*Yes*’’ is it web based, desktop application or any other?

11. The followings are lists of items that challenge decision makers during medical equipment replacement decision-making process. *Tick that exist*.

Items	Agree	Fairly agree	Strongly agree	Not agree	Strongly not agree
Physician preference					
A tradeoff between cost policies and high quality level of service					
Manager-supplier relationship					
Public procurement law					
Lack of communication and collaboration					
Negative attitude					
If other please specify……..					

Appendix 2: Second Questioner

Expert Survey Questioner

The main objective of this survey is to score each criterion based on the following table. The outcomes of the survey are going to use only for research purpose to design and develop an optimized medical equipment replacement-planning scheme. Respondents requested to give genuine answers by comparing each criterion according to their importance with other criteria.

Verbal variable	Fuzzy number	Scale of the corresponding number
Equal importance	$\tilde{1}$	(1, 1, 1)
Intermediate values between two adjacent judgments	$\tilde{2}$	(1, 2, 3)
Weak importance	$\tilde{3}$	(2, 3, 4)
Intermediate values between two adjacent judgments	$\tilde{4}$	(3, 4, 5)
Strong importance	$\tilde{5}$	(4, 5, 6)
Intermediate values between two adjacent judgments	$\tilde{6}$	(5, 6, 7)
Extreme importance	$\tilde{7}$	(6, 7, 8)
Intermediate values between two adjacent judgments	$\tilde{8}$	(7, 8, 9)
Absolute more importance	$\tilde{9}$	(8, 9, 9)

The following factors identified by the preliminary survey that can affect the replacement process:-

C_1=Equipment Risk Level
C_2=Equipment Adaption (Technology and Physical Status)
C_3=Frequency Usage
C_4=Reliability
C_5=Equipment Economic Life
C_6=Maintenance Cost
C_7=User Errors
C_8=Manufacturer Support

1. How important is "Equipment Risk Level (C_1)" when it compared with "Equipment Risk Level (C_1)"? Manufacturer Support (C_8)"?
9. How important is "Equipment Adaption (Technology and Physical Status)
16. How important is "Frequency Usage (C_3)" when it is compared with "Frequency Usage (C_3)"?
22. How important is "Reliability (C_4)" when it compared with "Reliability (C_4)"?
28. How important is "Equipment Economic Life (C_5)" when it compared with "Maintenance Cost (C_5)"?
31. How important is "Maintenance Cost (C_6)" when it compared with "Maintenance Cost (C_6)"?
34. How important is "User Errors (C_7)" when it compared with "User Errors (C_7)"?
36. How important is "Manufacturer Support (C_8)" when it compared with "Manufacturer Support (C_8)"?

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
C_1	(1,1,1)							
C_2		(1,1,1)						
C_3			(1,1,1)					
C_4				(1,1,1)				

C_5					(1,1,1)			
C_6						(1,1,1)		
C_7							(1,1,1)	
C_8								(1,1,1)

Appendix 3: Third Questioner

Survey on Medical Equipment Replacement Planning

1. Objective of the Survey

The main objective of this survey is to score the medical equipments based on the identified criteria list. The outcomes of the survey are going to be used only for research purposes to design and develop an optimized medical equipment replacement planning scheme. Respondents are requested to give genuine answers. Short clarifications on the whole essence of the key terms used in the survey are provided below.

2. Medical Equipment Replacement: All equipment reaches the point in its life time where the cost-benefit ratio goes to negative with decreased reliability, increased downtime and increased operating costs and as a result equipment become obsolete. At that point, replacement must be considered. The following criteria were identified based on the preliminary assessment carried out in this research based on questioners distributed to respondents including doctors, nurses, biomedical engineers and other health professionals.

- ✓ Equipment Risk Level (C_1): three groups of equipments are identified with respect to their risk levels. Those categorized as high risk devices are those used in life support, key resuscitation, critical monitoring, energy emitting and other devices whose failure or misuse is reasonably likely to seriously injure patients or staff (Example: Anesthesia units and vaporizers, Defibrillators, Oxygen monitors and Analyzers). Those considered medium risk devices include diagnostic instruments whose misuse, failure or absence (Example: out of service with no replacement available) would have a significant impact on patient care, but would not be likely to cause direct serious injury. While those under low risk device category are devices whose failure or misuse is unlikely to result in serious consequences.

The risk levels are grouped into five in this survey: Death, Injury, Misdiagnosis, Equipment Damage and No risk.

- ✓ Equipment Adaption (C_2): this criterion includes two sub-criteria (Technology Obsolescence and Physical deterioration).
  - ✓ Technology Obsolescence (C_{21}): is when technologies (Service/product) are in perfectly working condition, but are no longer relevant to the people who were once users of that technology. This happens when the technology is progressing fast, newer and better equipment are being developed.
  - ✓ Physical Deterioration (C_{22}): equipment has become worn out.
- ✓ Frequency Usage (C_3): Number of hours counted in a day when equipment is under usage.

- ✓ Reliability (C_4): measures the capacity of equipment to operate without failure for a time interval when put into service and operated correctly. Tracking equipment reliability is one of the challenges in equipment replacement process. There are two sub-criteria:
  - Failure rate (C_{41}): The number of times the equipment is out of service in a year.
  - Down time (C_{42}): The duration in which the equipment is out of service due to failures.
- ✓ Equipment Economic Life (C_5): This is the reaming age of the device. It measures period over which equipment is expected to be usable, with normal repairs and maintenance and expressed usually in number of years.
- ✓ Maintenance Cost (C_6): The summation of repair cost, purchase cost, spare part cost spent in a year.
- ✓ User Errors (C_7): Describes faults from the user of the equipment. It may be caused by psychological factors such as tiredness or stress, physical factors such as insufficient skills in use of mental or hands, training and also negligence.
- ✓ Manufacturer Support (C_8): Technical, consultancy and spare parts support given to purchase.

3. Filling the Questioner: scores (weights) have been given per each criteria and sub-criteria in the table below to help you fill the questioner.

Criteria	Description	Threshold	Score
C_1	Equipment Risk Level	Death	5
		Injury	4
		Misdiagnosis	3
		Equipment Damage	2
		No risk	1
C_2	Equipment Adaptation (Technology and Physical Status)	Obsolete	4
		Adequate	3
		Current	2
		Latest	1
	Technology Obsolescence (C_{21})	Yes	1
		No	0
	Physical Deterioration (C_{22})	Yes	1
		NO	0
C_3	Frequency Usage	≥8 hrs/day	3
		6≤FU<8hrs/day	2
		6hrs< per/day	1
C_4	Reliability	Below Average	3
		Average	2
		Above Average	1
	Failure Ratio (C_{41})	High	3
		Moderate	2
		Low	1
	Down Time (C_{42})	High	3
		Moderate	2
		Low	1
		Reaming Age > 80 %	3

C_5	Equipment Economic Life	50% < Reaming Age ≤80%	2
		Reaming Age ≤ 50 %	1
C_6	Maintenance Cost	Extensive	5
		A above average	4
		Average	3
		Below average	2
		Minimal	1
C_7	User Errors	Technical & Procedure Skills	3
		Physiological	2
		Absence of safety	1
C_8	Manufacturer Support	unavailable	3
		Some	2
		Available	1
	Vendor Support (C_{81})	Yes	0
		No	1
	Alternative Support (C_{82})	Yes	0
		No	1

Questioner

Equipment / Criterion	C_1	C_2	C_{21}	C_{22}	C_3	C_4	C_{41}	C_{42}	C_5	C_6	C_7	C_8	C_{81}	C_{82}
Aluminum Pinard Fetal Stethoscope														
Stethoscope														
Pulse Oximeter														
Ultrasonic Nebulizers														
Ophthalmoscope														
Sphygmomanometer														
Mini-Shaker for immunology														
Laboratory Medical Centrifuge														
Laboratory Microscope														
Hot Air Oven														
Vertical/Horizontal High Pressure Sterilizer Autoclave														
Freezer														
Hematology Analyzer														

Clinical Chemistry Analyzer														
X-ray														
Computed Tomography (CT) Scanner														
Magnetic Resonance Image (MRI)														
Ultrasound														
Anesthesia Machine														
Defibrillators														
Operating Table														
Surgical Light														
Diathermy														
ECG Machine														
Mechanical Ventilator														
Infusion Pump														
Bedside Monitor														
High Pressure Suction														
Oxygen Concentrator														
Slit Lamp														
Infant Incubator														
Baby Warmer														
Flat Bed														
Autoclave														
Stretcher, wheeled														

Appendix 4: Matlab Code

Matlab Code

```
% OPTIMIZED MEDICAL EQUIPMENT REPLACMENT SYSTEM-------->
% TRAVELLING SALESMAN PROBLEM DISTANCE CALCULATION----->
% TABU SEARCH ALGORITHM-------------------------------->
% HENOK HUSSIEN---------------------------------------->
clc;
clear;
close all;
%% Problem Definition
model = TspModel();       % Create TSP Model
CostFunction=@(tour) RouteLength(tour, model);    % Cost Function

ActionList=ActionList(model.n);    % Action List
nAction=numel(ActionList);              % Number of Actions

 %% Tabu Search Parameters
 it=0;
 tol=0.00001;                  %%Tolerance limit
 error=1;                      %% Error definition
 TL=round(0.5*nAction);        %% Tabu Length

%% Initialization

% Create Empty Individual Array
empty_indi.Pos=[];
empty_indi.Cost=[];

% Create Initial Solution
sol=empty_indi;
sol.Pos=randperm(model.n);
sol.Cost=CostFunction(sol.Pos);

% Initialize Best Solution Ever Found
BestSol=sol;

% Array to Hold Best Costs
BestCost=zeros(TL,1);

% Initialize Action Tabu Counters
TC=zeros(nAction,1);

%% Tabu Search Main Loop
 z1=realmax;
 z2=eps;
 count=0;
%for it=1:MaxIt
tic;
while(error>tol)
    count=count+1;
    bestnewsol.Cost=inf;
```

```
    % Apply Actions
    for i=1:nAction
        if TC(i)==0
            newsol.Pos=DoAction(sol.Pos,ActionList{i});
            newsol.Cost=CostFunction(newsol.Pos);
            newsol.ActionIndex=i;

            if newsol.Cost<=bestnewsol.Cost
                bestnewsol=newsol;
            end
        end
    end

    % Update Current Solution
    sol=bestnewsol;

    % Update Tabu List
    for i=1:nAction
        if i==bestnewsol.ActionIndex
            TC(i)=TL;               % Add To Tabu List
        else
            TC(i)=max(TC(i)-1,0);   % Reduce Tabu Counter
        end
    end

    % Update Best Solution Ever Found
    if sol.Cost<=BestSol.Cost
        BestSol=sol;
    end
     z1=z2;
    z2=BestSol.Cost;

     error=abs((z1-z2)/(z2));

     it=it+1;

    % Save Best Cost Ever Found
    BestCost(it)=BestSol.Cost;

    disp(BestSol.Pos)
    disp(z1)
    disp(z2)
    disp(error)
   toc;
    % Show Iteration Information
    disp(['Iteration ' num2str(it) ': Best Cost = ' num2str(BestCost(it))]);

    % Plot Best Solution
    figure(1);
    PlotSolution(BestSol, model);
    pause(0.01);

    % If Global Minimum is Reached
    if BestCost(it)==0
```

```
        break;
    end

end

BestCost=BestCost(1:it);

%% Results

figure;
plot(BestCost,'LineWidth',2);
xlabel('Iteration');
ylabel('Best Cost');
grid on;
```