COMPREHENSIVE FRAMEWORKS FOR DECISION MAKING SUPPORT IN MEDICAL EQUIPMENT MANAGEMENT

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By

Neven Saleh Khalil Saleh

A Thesis Submitted to the Faculty of Engineering, Cairo University

In Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

IN

SYSTEMS AND BIOMEDICAL ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
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Summary:

Throughout medical equipment life cycle, hospitals need to take decisions on medical equipment management based upon a set of different criteria. In fact, medical equipment acquisition, preventive maintenance, and replacement are considered the most important phases, accordingly a properly planned management for these issues is considered a key decision of medical equipment management. In this thesis, a set of frameworks were developed regarding acquisition, preventive maintenance, and replacement to improve management process of medical equipment. In practice, quality function deployment was proposed as a core method around which the frameworks were developed.

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ABBREVIATIONS

AAMI	Association for the Advancement of Medical Instrumentation
ABC	Activity Based Costing
ACO	Ant Colony Optimization
ACS	Ant Colony System
AHP	Analytical Hierarchy Process
AMD	Actual Maintenance Duration
ANN	Artificial Neural Network
AS	Ant System
ASHE	American Society of Hospital Engineering
BMET	Biomedical Engineering Technician
BPMN	Business Process Modeling Notation
CE	Clinical Engineering / Clinical Engineer
CGA	Canonical Genetic Algorithm
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
CMS	Medicare & Medicaid Services
COG	Center of Gravity
CT	Computerized Tomography
DNA	Deoxyribonucleic Acid
ECRI	Emergency Care Rescue Institution
ERPS	Equipment Replacement Planning System
FIS	Fuzzy Inference System
FL	Fuzzy Logic
FMEA	Failure Modes and Effect Analysis
FTA	Failure Tree Analysis
GA	Genetic Algorithm
HDO	Healthcare Delivery Organizations
HEI	Health Equipment Information
HOQ	House of Quality

HTM	Healthcare Technology Management
LOF	Likelihood of Occurrence
LOS	Level of Severity
MCDM	Multi- Criteria Decision Making
MDA	Medical Devices Agency
MEMP	Medical Equipment Management Program
MOM	Mean of Maxima
MRI	Magnetic Resonance Imaging
NHPP	Non-Homogenous Poisson Process
NICU	Neonatal Intensive Care Unit
PBMA	Program Budgeting Marginal Analysis
PM	Preventive Maintenance
QFD	Quality Function Deployment
RCM	Reliability Centered Maintenance
RL	Risk Level
RLC	Risk Level Coefficient
RMD	Recommended Maintenance Duration
RPN	Risk Priority Number
SPMS	Sequential Preventive Maintenance Schedule
STEEP	Safe, Timely, Effective, Efficient and Patient- centered
TJC	The Joint Commission
TSP	Traveling Salesman Problem
UML	Unified Modeling Language
VOC	Voice of Customers
VOE	Voice of Engineers
WHA	World Health Assembly
WHO	World Health Organization

To the spirit of my beloved mother

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*First I thank **God** who supplied me with faith and success.*

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ABSTRACT

Throughout the medical equipment life cycle, hospitals need to take decisions on medical equipment management based on comprehensive and reliable information. In fact, acquisition, preventive maintenance, and replacement of medical equipment are considered the most important phases of medical equipment management. A properly planned policy for these issues is a key part of medical equipment management. In this thesis, we focus on how to develop a comprehensive framework for acquisition, preventive maintenance, and replacement of medical equipment considering a set of criteria that impact the decision making to improve the management system of medical equipment.

In the literature, we can find methods and tools that handle management of medical equipment for various stages, but with a little regard to present a comprehensive framework. Quality Function Deployment (QFD) is one of total quality management tools that could be used to translate customer requirements into appropriate technical or service specifications. It is used mainly in manufacturing and production areas. Literature review reveals that QFD is rarely considered for medical equipment management, despite its several advantages. In this study, we propose QFD as the core method around which the comprehensive framework is constructed.

In acquisition stage we focus on the purchasing process. One of the main challenges of purchasing medical equipment is how to give any purchasing request a reasonable priority among different requests especially with limited resources. In this thesis, QFD integrated with fuzzy logic provide an answer to this question by building a framework based on a set of technical, safety, and financial criteria that impact on the purchasing of medical equipment. Using this framework, the priority is classified into five classes; very high, high, medium, low, almost no. To validate the proposed model, we collected twenty purchasing requests in a public Egyptian hospital and compared the priority list of these requests with the one approved by the

hospital. The results demonstrated the ability of the proposed model to address the requests priority in consistent way.

Since preventive maintenance (PM) is a core function of clinical engineering, it is essential to prepare a PM plan starting from a well-organized inventory. We propose a 3-domain framework employing QFD as a new concept to identify the priority of devices that requires PM. The framework consists of a requirement domain, a function domain, and a concept domain. The requirement domain is the house of quality matrix. The second domain is the design matrix. Finally the concept domain gives a priority index that contains the critical criteria for PM prioritization with their weights. According to the final scores of criteria, prioritization of medical equipment is obtained.

The proposed model was tested on a set of data includes 200 pieces of medical equipment of 70 different types belonging to 32 different departments of two public Italian hospitals in Piedmont province during one year (2012). The model's solution proposes classification of PM priority into five categories; very high, high, medium, low, and minimal. According to the final results, the investigated devices are categorized as: 15% needs very high PM, 19% should be included as high priority, 30% should be considered for medium priority, 27% as low priority, and 9 % have no need for PM, except for visual checking only. The plan was approved by the clinical engineer working for the two hospitals.

As PM is expensive, it is important to decide when it should be performed. Optimizing PM is an old problem that was discussed extensively in the literature. The problem is that most of proposed models, if not all, tend to optimize the intervention durations and frequency of PM with a little or no regard to optimizing the schedule of devices themselves considering their PM priority. This study presents a solution to the problem of seeking the optimal devices schedule for PM using Ant Colony Optimization (ACO) algorithm. We developed two versions of the algorithm to increase model complexity step by step. Both algorithms are starting from a prioritized medical equipment list, and

differ in heuristic function. The first algorithm takes into account only device priorities, while the second one considers also its location. An experimental case study was conducted on a prioritized list of 182 pieces of medical equipment. The results indicate the effectiveness of ACO algorithm for this kind of problems.

Medical equipment replacement is often a complex issue to model since it embraces a high number of problems. In this thesis, we propose the QFD technique to manage this critical stage exploiting a set of indicators that impact directly or indirectly the replacement decision. The output of our proposed QFD is a prioritized list of medical equipment that reflects their need for replacement. Moreover, the devices that require replacement are optimized using Genetic Algorithm (GA) considering the available budget to maximize the number of replacements. The proposed QFD-GA is evaluated through a data set of sixty pieces of medical equipment in a public Egyptian hospital. Results manifest the robustness of the proposed model since it can efficiently address the replacement priority into one of four subcategories; very high, high, medium, and no need and simultaneously maximize medical equipment requires replacement considering the budget constraint.

In conclusion, we can say that QFD proved to be a good method to design a comprehensive framework for medical equipment management that guide clinical engineering department in decision making.

PREFACE

Most of the chapters presented in this thesis are the extensions of the following journals and conferences articles, which are published or submitted during my PH.D. study,

Journal Articles

1. N. Saleh, S. Rosati, A. Sharawi, M. Abdel Wahed, and G. Balestra, "An Optimal Scheduling for Medical Equipment Preventive Maintenance Over a Finite Horizon Using Ant Colony Algorithm". *Medical & Biological Engineering & Computing*. (Submitted in November 2013).

2. N. Saleh, S. Rosati, A. Sharawi, M. Abdel Wahed, A. Petti, D. Puppato and G. Balestra, " Preventive Maintenance Prioritization Index of Medical Equipment Using Quality Function Deployment". *IEEE Journal of Biomedical and Health Informatics.* (Accepted in July, 4th, 2014).

3. N. Saleh, A. Sharawi, M. Abdel Wahed, and G. Balestra, " A Conceptual Priority Index for Management of Purchasing Medical Equipment in Hospitals". *Journal of Engineering and Technology Management*. (Submitted in August, 2014).

Conferences Proceedings

1. N. Saleh, S. Rosati, A. Sharawi, M. Abdel Wahed, A. Petti, D. Puppato and G. Balestra, " A New Approach for Preventive Maintenance Prioritization of Medical Equipment" *Proceeding of XIII Mediterranean Conference on Medical and Biological Engineering and Computing,* Seville, Spain, Sep. 2013, pp. 1059-1062.

2. N. Saleh A. Sharawi, M. Abdel Wahed, and G. Balestra, "Application of Quality Function Deployment and Genetic Algorithm for Replacement of Medical Equipment", *Proceeding of 7th Cairo International Biomedical*

Engineering Conference (CIBEC 2014), Cairo, Egypt, Dec.2014. (Accepted in October 13, 2104)

Chapter 1

Introduction

1.1 Introduction

Health care ranges from the fight against diseases to the maintenance of physical and mental functioning, and its delivery largely depends upon technology, especially medical technology. Health care systems everywhere face the STEEP test of being Safe, Timely, Effective, Efficient, and Patient-centered [36]. To achieve these objectives, hospitals should establish and regulate medical equipment management program (MEMP). A well-organized program will have a significant impact on the hospital's bottom line, which is highly desirable outcome overtime.

As medical technology continues to evolve, so does its impact on patient outcome, hospital operations, and financial efficiency. The ability to plan for this evaluation and its subsequent implications has become a major challenge in most decisions of healthcare organizations and their related industries.

Therefore, there is a need to adequately plan for and apply those management tools that optimize the deployment of medical technology and the facilities that house it. In addition, the plans provide a means for interaction through which likely future needs are identified [15].

Cost-effective and efficient decisions could be made after understanding and implementing medical equipment management excellence in healthcare organizations. Management excellence is the balance of planning, resources, performance, monitoring, and costs to reach to the optimal solutions for all phases in medical equipment life cycle [104]. Therefore, the proper decisions along medical equipment management are vital features for this process.

1.2 Problems Definition

The medical equipment management cycle from the user's perspective starts at the planning and acquisition phase, through the training and usage process, being maintained, and then replacement or disposal phase after it has reached the end of its useful life [36]. By regarding those activities in management process, we can realize that the most important stages requiring proper planning for decision making assumed to be acquisition, maintenance(preventive maintenance), and replacement or disposal of medical equipment. For instance, to identify a reasonable priority index that should be used as a guide for approving some decisions is a crucial phase for these issues.

Considering the acquisition process, it is clear that if equipment purchases are realized without making an evaluation of requirements and getting cooperation of the hospital management, then the purchasing items could be so far from meeting the hospitals real need [57]. Moreover, traditionally, the decision to use a new technology is based on the desires of the physicians and the added benefit to patient care, with its financial impact often a secondary consideration [79]. Therefore, it is essential to have a systematic and a comprehensive acquisition program to prevent a number of potential

problems. One of the most important problems that could arise is the improper purchasing process of medical equipment in public hospitals.

In developing countries the situation has became scary, since some studies conducted by international agencies such as World Health Organization (WHO) have shown that 25 – 50% of all health equipment cannot be used in healthcare for different reasons [111], one of them is the improper planning in acquisition process and imperfect selection of medical equipment.

Moving to another point, the appropriate maintenance of medical equipment, including performance inspection and preventive maintenance is fundamental in mitigating clinical risks caused by adverse events in hospitals. Planning a maintenance program is a part of a broader effort to establish a comprehensive program for healthcare technology management. Usually, this planning includes a review of critical factors. The challenge for planners is to balance these factors to design a maintenance program that is appropriate and cost-effective for their situation [109].

Although maintenance strategies and techniques have been significantly improved in the last two decades, most of hospitals and healthcare organizations do not benefit from maintenance excellence. Unnecessary and excessive preventive maintenance could be also loss-making likewise inadequate level of maintenance. The time, which is spent doing the unnecessary preventive maintenance (PM), is robbing an organization of a fraction of one of its most vital resources [104].

However, in Egypt, most, if not all healthcare organizations include their medical equipment in their maintenance program regardless the actual need for maintenance and just follow manufacturers' recommendations for preventative maintenance. Current maintenance strategies employed in hospitals and healthcare organizations have difficulty in identifying a proper prioritized list of devices to reduce specific risks and applying optimal scheduling for preventive maintenance.

Maintenance prioritization is a crucial task in healthcare systems, especially when there are more maintenance work orders than available people or resources that can handle those [78]. Maintenance executed in a random sequence or in an ad hoc sequence could potentially not only waste the labor and resources, but also could increase risk level of some devices. Consequently, it is important to decide when preventive maintenance should be carried out as well as identifying the optimal scheduling for medical equipment.

Optimizing PM interval and activities is an old problem that is discussed extensively in the literature. Several models were developed in order to optimize maintenance interval, considering both costs and reliability. As PM is expensive it is important to decide when it should be performed. Accordingly, optimizing the intervention sequence is crucial to reduce the costs, the labors, and the time spent in going through the departments by the technicians.

Practically, planning process in hospitals tended to focus on current or short-term needs with little or no consideration of future requirements such replacement of medical equipment. According to hospitals, provided equipment poses no clinical or safety risks to patients or staff, it was rarely replaced at the end of its recommended useful life. Forward replacement planning is an essential requirement of any healthcare organization especially with growing competitive market and fast technological evolution. An equipment replacement plans help to guide the decision makers on potential future spending obligations relating to medical devices.

In fact, most hospitals do not have sufficient capital funds to approve all equipment replacement requests. Typically, a capital planning process yields executive decisions for replacing technology, which are not technical, standardized or performance-based. These decisions are typically based on subjective reasons rather than firsthand knowledge, experience or scientific analysis. Equipment is more often than not; replaced after it fails at a critical time or when it is discovered during service that parts and manufacturer

support are not available. In some hospitals, replacement is also recommended as soon as new technology becomes available even if the existing equipment is still effective. As a result, the overall productivity of the healthcare system is significantly reduced due to ill-conceived expenditures on replacing devices that may still viable rather than focusing on devices that need to be replaced [84].

1.3 Research Motivations

The research reported in this thesis aims to address these gaps in the most important stages of medical equipment management life cycle and proposes methods to improve current strategies in healthcare organizations. It is clear that the common challenge for the previous three stages is to prepare a well-organized plan that can identify a convenient list of prioritized medical equipment relied on influential criteria in order to guide the decision makers approving appropriate decisions for various situations.

In that case, we proposed a new model to produce a convenient priority index for these stages. Then the priority model is integrated with other different models forming new frameworks for different targets. In application, and according to our research, considering the first stage; purchasing of medical equipment, we proposed a framework consisting of two models. The first one is proposed to conclude the most important criteria that should be regarded. The second model is developed based on the resultant important criteria of the first one to classify the purchasing requests according to their priorities.

In the second stage, preventive maintenance, we divide it into two issues. We first propose a prioritization model which can be used to decide what medical devices should be included in the hospital's maintenance management program. Then we develop an optimal scheduling algorithm for medical equipment preventive maintenance with two versions starting with the output prioritized list of the first model. Our observations on data set let us to decide what assumptions should be made for both algorithms.

In the last stage, replacement of medical equipment, we adopt new approach to solve the problem of replacement. We present a new policy by proposing new framework including two models. The first model is to provide a prioritized list of equipment to decide what devices should be included for replacement. The second one is to optimize the resultant list according to the degree of priority taking into account the funding constraint. Therefore, a new algorithm is formulated in order to maximize the number of devices require replacement with respect to the available budget.

Taking into consideration the study motivation, the main contributions of this research can be listed as

- Presenting a new approach for prioritization a list of medical equipment.
- Proposed new frameworks are demonstrated for medical equipment management.
- New scheduling algorithms are developed for preventive maintenance.
- New algorithm for replacement optimization is introduced.

The thesis is structured as follows. Chapter 2 presents a general overview for medical equipment management and their typical life cycle as well as the management systems and common medical equipment management systems. Chapter 3 explains the proposed methods and materials, which are utilized in this study to develop the frameworks. The first proposed framework for prioritization of purchasing requests of medical equipment and its results is presented in chapter 4. Chapter 5 illustrates the second framework that proposes models for prioritization and scheduling of preventive maintenance as well as the results of both of them. The last framework is presented for prioritization and optimization of medical equipment replacement, and the applications are described in chapter 6. Finally, the conclusions and some guidelines for future work are given in chapter 7.

Chapter 2

Medical Equipment Management Overview

2.1 Chapter Outlines

This chapter presents an overview of medical equipment management covering a wide spectrum of basic concepts and principles including typical management life cycle, currently used systems for management and the required standards and regulations for medical equipment management. In section 2, we illustrate the main concept of healthcare technology management, medical equipment management, definition and role of medical equipment, and the classification of essential medical equipment. In section 3, a typical life cycle of medical equipment management is covered in details in subsection 3.1, whereas the different management systems are given according to literature with illustrative examples in subsection 3.2. Finally, the regulations and standards for medical equipment management referred to two of well known organizations are presented in subsection 3.3.

2.2 Healthcare Technology Management

Healthcare Technology Management (HTM) activities offer a range of solutions to address healthcare requirements and to improve quality while reducing cost. HTM is defined as a systematic process in which qualified health care professionals, typically clinical engineers, in partnership with other health care leaders plan for and manage health technology assets to achieve the highest quality care at the best cost. The goal of health care technology management (HTM) is to optimize the acquisition and utilization of technology, to achieve maximum beneficial impact on health outcomes at the national level [36].

2.2.1 Definition of Medical Equipment

The literature provides us with a number of definitions for the term "medical equipment". A more selective definition can be found in the relevant health equipment information (HEI) publication of the Medical Devices Agency (MDA) of the department of health in London [86] , which states that the term medical equipment comprises: *any device instrument, apparatus, implement , material ,substance or other article(used singly or in combination) together with any accessory thereto , which is intended by the manufacturer for diagnosis, prevention, monitoring treatment or alleviation of human disease or injury as well as investigation or modification of human anatomy or of human physiological process; which does not achieve its principal intended action by pharmaceutical means, but which may be assisted in its functioning by such means(MDA) :* health equipment information issue 98:28).

Medical equipment is ranking from small and simple devices such as sphygmomanometer to complex and big devices such as magnetic resonance imaging (MRI). This ranking is as a result of differences in utilized technologies and intended applications. This means that medical equipment acquisition costs can range from few thousands of dollars to millions of dollars. It is therefore, a vital importance that healthcare organizations manage their

assets to keep their expenditures under control as well as assure the quality of healthcare delivery.

2.2.2 Role of Medical Equipment

Medical equipment plays an important role in health care delivery; it contributes to the advancement of health care in many ways for different clinical stages. It is essential element in healthcare technology management. Recognizing the important role of medical devices in health technologies, the World Health Assembly (WHA) adopted resolution WHA 60.29 in May 2007. The resolution covers issues arising from the inappropriate deployment and use of health technologies, and the need to establish priorities in the selection and management of health technologies, especially medical devices [108].

Today's medical environment is highly dependent on various types of medical equipment [21] to complete the diagnosis for patients with care. Medical equipment should be what the health care practitioner wants them to do (effectiveness) and not do what the practitioner does not want them to do (safety); these are the two sides of the coin of clinical engineering [80, 39]. Medical devices are progressively being deployed to increase the capabilities of health diagnostic and treatment services. On the other hand, the potential to manage and maintain medical equipment in most developing countries remain rather weak [104].

2.2.3 Essential Medical Equipment

Basic medical equipment is widely used in the healthcare facilities. This essential equipment is supportive to provide primary healthcare to the public. World Health Organization (WHO) classifies essential medical equipment in four main categories [104]. The list given in each category includes the examples of devices required for a specified health service delivery. The type of equipment is significantly dependent on the local health practice, physical characteristics and culture of the population.

1. **Diagnostic imaging equipment:** Diagnostic imaging equipment is used to take pictures, which help physicians to diagnose a patient's medical condition

- Diagnostic X-ray equipment
- Ultra-sound equipment

2. Laboratory equipment: A variety of laboratory equipment is used for analysis or measurement purposes.

- Microscope
- Blood counter
- Analytical balance
- Colorimeter/spectrophotometer
- Centrifuge
- Water bath

3. General electro-medical equipment

- Portable electrocardiograph
- External defibrillator
- Portable anesthesia unit

4. Other support equipment

- Operating theatre table
- Delivery table
- Autoclave for general sterilization
- Electrical power regulator

2.3 Medical Equipment Management

Medical technology management is one of the most important segments of the healthcare system. Medical equipment management is the most important feature of this process. Medical Equipment Management (MEM) takes place within a context of human, material, structural, organizational and financial resources [86]. The effectiveness of a medical equipment management system can be measured in terms of operational performance of the stock of medical equipment which is being managed.

The medical equipment management is a process through which help hospitals to develop, monitor and manage their equipment to promote the safe, effective and economical use of equipment and keeping in a good working order [36]. The purposes of medical equipment management plans are to minimize the risks associated with medical equipment by ensuring that all items of equipment are maintained, in a clean, safe and serviceable condition; raise the level of healthcare delivery and finally cost control for medical equipment [8, 39]. This is achieved by; selection of equipment, acceptance of equipment, utilization, training and certification of selected operatives, timely servicing and maintenance, and disposal or replacement of medical equipment.

Responsible organizations should therefore setup and regularly review medical equipment management to ensure that whenever a medical device is used it is suitable, used in accordance with the manufacturer’s instructions, maintained in a safe and reliable condition, and disposed appropriately at the end of its useful life [69]. Based on the interpretation of the literature and existing studies, it appears that medical equipment life cycle can be regarded as a logical sequence of medical equipment management activities. Each activity or stages in the management process is dependent on and linked up with other activities [86].

2.3.1 Medical Equipment Management Life cycle

A systematic way to manage medical equipment is to study and optimize all phases in the useful life of the medical equipment, or study and optimize the technology life cycle [16]. The life cycle management approach, was originally developed for major medical equipment, also applies to non major but essential medical devices and may be extended to additional devices [36]. The typical life cycle of a medical device has the stages shown in Fig 2.1.

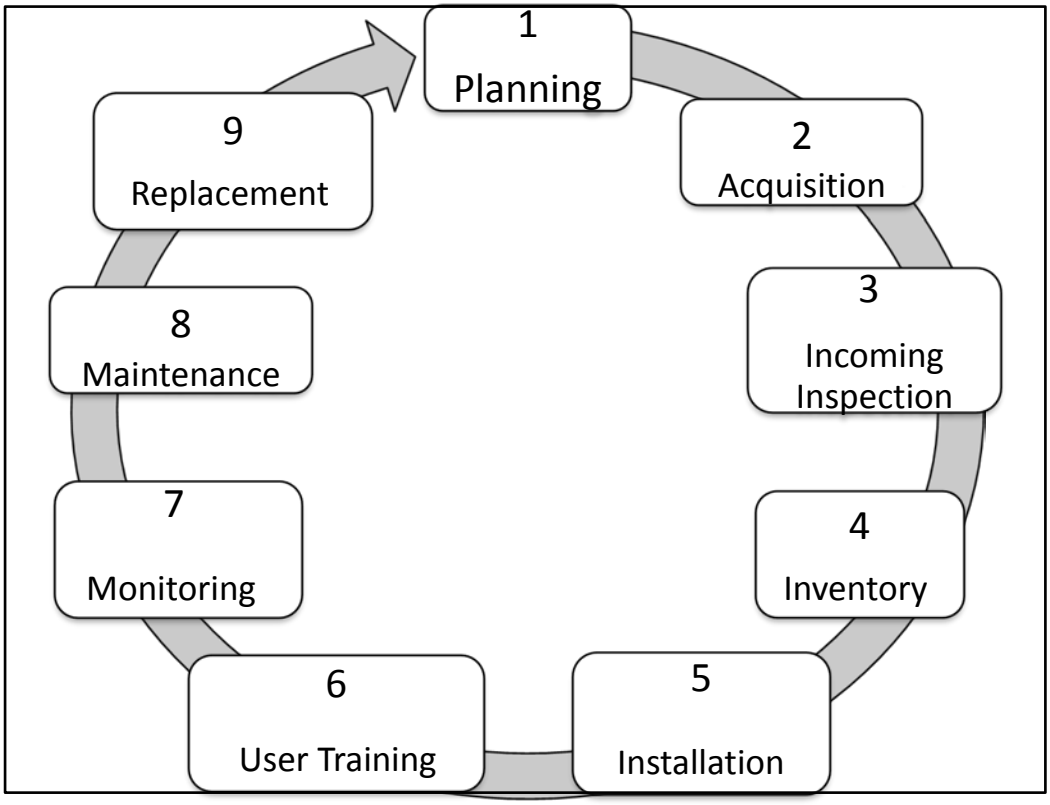


Fig 2.1 Life cycle management of medical equipment

2.3.1.1 Planning

Planning process is an important aid in decision-making; it provides essential information. In other words, it provides technology vision where healthcare facility should position itself; it can specify the following conditions in order to aid the decision-making process [36].

-Demonstrated needs and benefits

-Available qualified users

-Confirmed maintenance services and support

-Adequate environment support

-Regulatory compliance

The previous conditions are simple and should be applied to any routine acquisition of a medical device. A policy on medical device acquisition includes meeting these conditions as prerequisites to acquisition will reduce medical device problems later in the life cycle of the device. For example appropriate financial planning for a medical device can ensure optimum position for operating and service costs of this device.

2.3.1.2 Acquisition

Acquisition process subdivided into evaluation and procurement. *Evaluation proces*s includes considering some factors such as safety, performance, maintenance and manufacturer which should be reviewed in order to fulfill the requirements. In the *procurement process*, conditions can be included in the purchase order to specify that the supplier must apply operating and service manuals, operation and service training and essential spare part. Other special requirements also can be specified here such as payment.

2.3.1.3 Delivery and Incoming Inspection

Clinical Engineering (CE) ensures an incoming inspection on equipment includes verification of accessories, manuals, electrical safety and operation in accordance with all applicable policies [36]. Incoming equipment should be carefully checked for possible shipment damage and compliance with specifications in the purchase order.

2.3.1.4 Inventory and Documentation

Medical device inventory and documentation system can provide information to support different aspects of medical equipment management. One important

aspect is consideration for standardization. Important parameters to be tracked in association with each device in the inventory are the model, serial number, warranty expiration date, risk of the device, type of device, ownership information, maintenance scheduling information and purchase information.

2.3.1.5 Installation, Commissioning and Acceptance

Installation and commissioning can be carried out by in-house technical staff if they are familiar with a given item of equipment. If the installation and commissioning are needed by the suppliers, in-house technical staff should monitor this process. Installation process should be compatible with standard policies for medical equipment installation.

2.3.1.6 Training of Users and Operators

To reduce the possibility of equipment malfunction following service or repair, all personnel involved in maintaining and servicing equipment must be trained to appropriate standards for the work they are carrying out [8]. Operator error is a leading cause of device malfunctioning especially in developing countries. Incorrect use of devices also will greatly increase maintenance problems. Training of users should be monitored from vendor to ensure the maximum skill level that is required for operating a device. The training should include all user's staff as needed, such as clinical staff and technical staff, also the training performance should cover all aspects of device use.

2.3.1.7 Monitoring of Use and Performance

One common mistake is to believe that the warranty period is covered by the supplier, so no in-house technical attention is necessary. In-house technical staff should become the link between user and supplier and should observe any supplier's technical staff. This also will provide a learning opportunity for the in-house technical personnel. This performance should be also documented in the service history of the device by in-house technical staff [36].

2.3.1.8 Maintenance and Service

Equipment maintenance involves all activities relating to provide an adequate level of service and limiting downtime of medical devices. Maintenance and service activity is required in order to ensure the devices are kept functioning within the limits imposed by the test criteria and to return devices to the required level of functioning after breakage or other failure. The primary goal of maintenance activity is to reduce or, if possible, to eliminate the need of repairs. “Maintain” comes from Latin "to hold in one's hand" meaning to protect and look after. "Repair" on the other hand, means to return things to the way they were, to make better, or to fix [36].

Traditionally, equipment maintenance is categorized as Preventive Maintenance (PM) and Corrective Maintenance (CM). *Preventive maintenance* procedures are actions that are necessary or desirable in order to extend the operational intervals between failures to extend the life of equipment or to detect and correct problems that are not apparent to the user. *Corrective maintenance* procedures are any services that involve medical equipment repair. Specific services include repair performed by in-house personnel or vendors, repairs completed during the warranty period, repairs as a result of a hazard notification, repairs resulting from user error and repairs performed under a service contract [36].

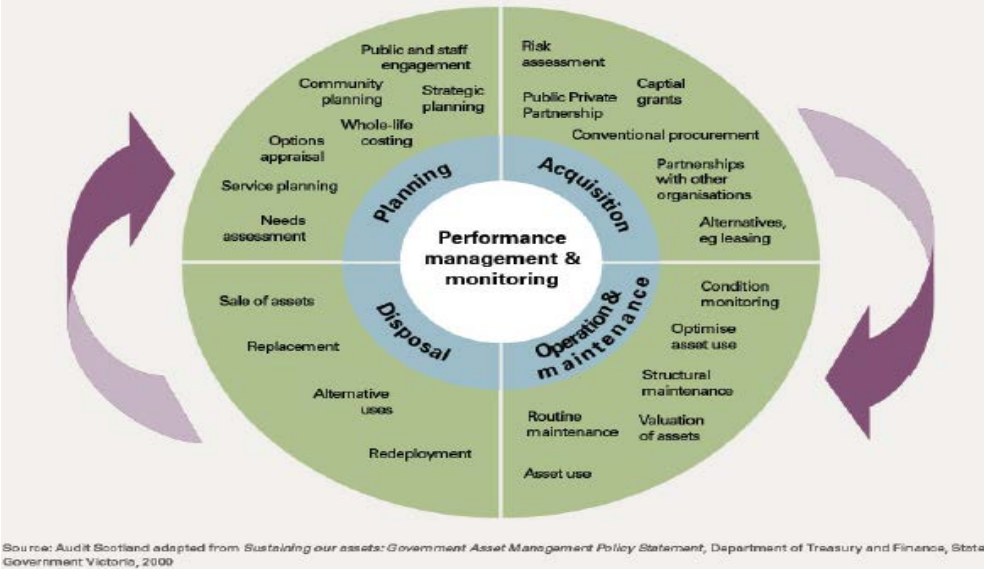
2.3.1.9 Replacement or Disposal

All equipment reaches the point in its life where the cost-benefit ratio goes to the negative because of decreased reliability, increased downtime, safety issues, compromised care, increased operating costs, changing regulations, or simply obsolescence. At that point replacement action must be considered. The majority of medical equipment in developing countries is old and that spare parts are often in short supply, some old units can be dismantled to provide spare parts for similar units [36].

Disposal of equipment must follow safety procedures in order to protect people and the environment. The ideal health care technology replacement planning system would be facility-wide covering all clinical equipment; would utilize accurate, objective data for analysis; would be flexible enough to incorporate non equipment factors; and would be futuristic by including strategic planning relating to clinical marketplace trends and hospital strategic initiatives relating to technology. The plan should encompass many factors relating to cost-benefit analysis, safety, support, standardization and clinical benefits. Equipment replacement planning is an important part of the technology planning process.

2.3.1.10 Important Stages

According to the life cycle of medical equipment management, the key elements of operational management that require decision support are, planning, acquisition, operation and maintenance, and disposal or replacement as shown in Fig 2.2 [82]. There are, however, problems with life cycle development methodology, because it doesn't support well the typical design situation where users don't quite know their needs at the beginning and developers don't quite understand user's needs.



Source: Audit Scotland adapted from *Sustaining our assets: Government Asset Management Policy Statement*, Department of Treasury and Finance, State Government Victoria, 2000

Fig 2.2 Detailed issues with decision key elements in medical equipment management life cycle [82].

2.3.2 Medical Equipment Management Systems

It is now universally accepted that to assure patient safety, medical devices must be correctly managed and used, and that the quality of healthcare delivery is related to the suitability of the available technology [8]. Delivering healthcare to patients is a complex endeavor that is highly dependent on information [12]. All equipment management systems provide basic features that consist of record keeping, scheduling, and basic reporting functions. Management systems must contain valuable information that can be used to improve management of and level of service performance [73].

General equipment information includes manufacturer, model number, and serial number. Equipment management information includes facilities asset management tracking number, department using the equipment, equipment category type, and risk assessment. Additional helpful equipment information includes acquisition date, acquisition value, warranty period, and warranty expiration date. One should capture this basic information for all equipment that is supported in management program. There is a core set of data that are helpful in managing performance of a program. In addition to providing an equipment history for review, and allow categorization of services provided, these data sets should enable the following data to be captured; work categories, equipment identification, in-house support, vendor supports, parts, user identification, date/time indicators, problem descriptions, and solution descriptions [36].

According to literature, there are many systems for management of medical equipment programs [112]. The common classification for medical equipment management systems is either paper-based system or computer-based system. Nowadays, as a software programs are widespread in all management activities, the computer-based programs are considered a common attribute and the back bone of management.

2.3.2.1 Paper – Based Management Systems

Although the computers become an essential part of our daily life, still paper-based methods are adopted in medical equipment management systems until now especially in developing countries. In [63], the authors classified the medical equipment management systems in to four main categories

- User based system (activities are initiated by user request).
- Paper based filling system (each device has its own file).
- In-house developed computer-based system (tailor-made solution).
- Off -the- shelf system (computerized system and maintenance package).

By comparing these management systems with eight criteria, producing a range of scores as shown in Table 2. The scores points range from full compliance to non compliance. High scores indicate most appropriate management systems. User system is appropriate for areas that don't have basic utility infrastructural elements, while the paper-based system is appropriate if compliance with standards and legal requirements are adopted. The authors conclude that the paper-based system is an appropriate system for developing countries.

Table 2.1 Compliance Scores for the Equipment Management Systems [63]

Equipment Management Systems				
Evaluation Criteria	**User-driven**	**Paper-based**	**In-house developed**	**Off-the- shelf**
Environmental conditions	3	3	1	1
Customer support	3	3	1	1
User competence	3	3	1	2
Language	3	3	1	1
Culture	2	1	2	2
Financial	3	3	1	1
Maintenance	3	3	1	1
System flexibility	2	3	2	3
Total	**22**	**22**	**10**	**12**

2.3.2.2 Computer – Based Management Programs

Medical equipment is quickly becoming less manageable by traditional methods. Most healthcare delivery organizations (HDO) must manage tens of thousands of medical devices representing numerous makes and models. Traditionally medical devices have functioned as stand alone or perhaps locally networked without the capability to transmit information outside of their own realm [36].

Computerization of medical equipment management systems becomes a common attribute in the management aspect. Computerization of the all stages of medical equipment management life cycle and their related activities facilitates the management and tracking of information related to different stages. Also, it allows considering reasonable decisions in the management process as well as controllable assessment.

Literature provides us with a numerous variety of computer – based management programs for medical equipment. *Mobarek et al* [72] developed a computerized management systems for medical equipment considering all stages of life cycle and for various categories of hospitals. The research deals with all different phases of the design, implementation, and evaluation of a fully automated clinical engineering technical management system, for Jordan Ministry of Health (MOH).

In another example, *Abayazeed et al* [3] presented a survey on computerized management programs for medical equipment. In this survey, the authors classified all computer – based management systems into three main categories as illustrated in Table (2.2)

- Full range: service nearly all tasks of HTM
- Computerized Maintenance Management System (CMMS)
- Discrete component of HTM spectrum : one or more functions

Table 2.2 Survey of Computerization Systems for Healthcare Management Systems [3]

Processes	No. of papers	General	For a specific department
Full range	4	1	3
Procurement of medical technology	2	---	2
Inventory management	4	1	3
Maintenance management	1	0	1
Preventive maintenance	3	3	---
Technology replacement	2	2	---

2.3.3 Medical Equipment Management Standards

Yet many countries lack access to high-quality devices and equipment that are suitable for their specific epidemiological needs. This is particularly true in developing countries, where health technology assessments are rare and where little regulatory controls exist to prevent the importation or use of substandard devices. With the vast majority of devices in developing countries being imported, this leaves them prey to unscrupulous market influences and puts patients' lives at risk [20].

The ideal conditions that will ensure the safety and performance of medical devices require shared responsibility by all stakeholders. This need for cooperation is illustrated in Fig 2.3. The circle formed by the stakeholders illustrates the shared responsibility. The diamond handshake symbolizes cooperation and two-way communication (2-way arrow), and the star highlights how the fundamental elements for cooperation function best when all stakeholders communicate with each other [20].

Standards can establish a wide range of specifications for products, processes, and services. The specifications are prescriptive specifications obligate product characteristics, design specifications set out the specific design, performance specifications that a product meets a prescribed test, and management specifications set out requirements for the processes and procedures [20].

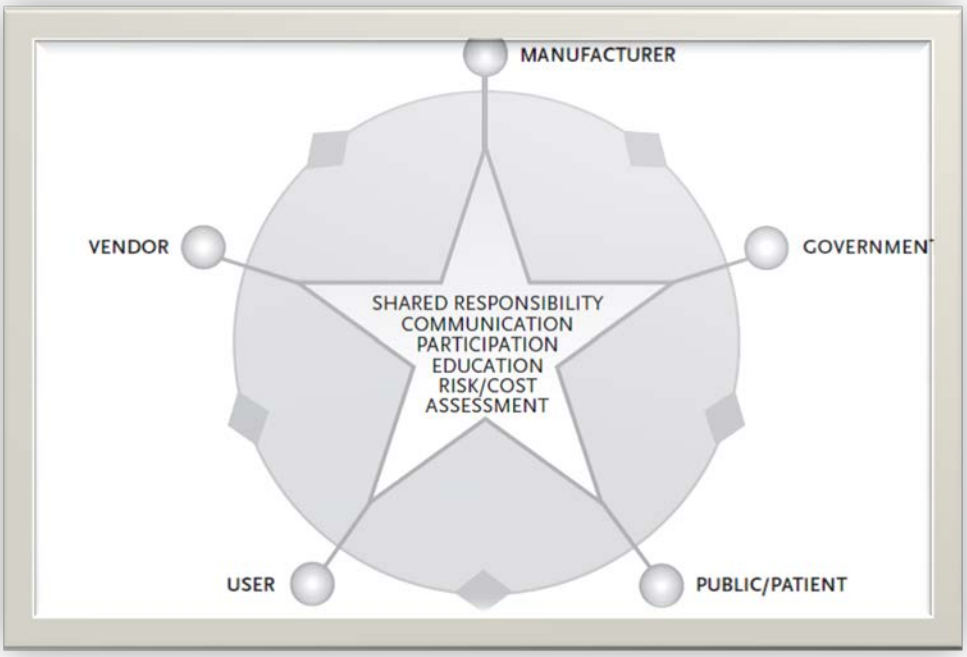


Fig 2.3 Ideal conditions for ensuring the safety and performance of medical devices [20]

2.3.3.1 Joint Commission Standards for Medical Equipment

Hospitals are expected to maintain equipment inventories and documentation of their maintenance activities. In such instances, hospitals should be in compliance with the most stringent maintenance requirements. In accordance with the life cycle phases of medical equipment, biomedical/clinical engineers should comply continuously with two primary medical equipment standards of The Joint Commission (TJC) [104, 112], EC.02.04.01 and EC.02.04.03. Standard EC.02.04.01 must be used by healthcare organizations to manage safety and security risks. Standard EC.02.04.03 presents guideline to inspects,

tests, and maintains medical equipment. The elements of performance for these two standards are as follows (TJC, 2008):

Standard *EC.02.04.01*: The organization manages safety and security risks.

1. The organization has a systematic approach to selecting and acquiring medical equipment.

2. The organization maintains either a written inventory of all medical equipment or a written inventory of selected equipment categorized by physical risk associated with use and equipment incident history. The organization evaluates new types of equipment before initial use to determine whether they should be included in the inventory.

3. The organization identifies the activities for maintaining, inspecting, and testing for all medical equipment on the inventory. Organizations may use different maintenance strategies based on the type of equipment. **Strategies must include defined intervals for inspecting, testing, and maintaining equipment on the inventory**. Defined intervals are based on criteria such as manufacturers' recommendations, risk levels, and current organization experience. In addition, predictive maintenance, reliability centered maintenance, interval-based inspections, corrective maintenance, or metered maintenance (means maintaining according to the working age of a device) may be selected to ensure reliable performance.

4. The organization identifies frequencies for inspecting, testing, and maintaining medical equipment on the inventory based on criteria such as manufacturers’ recommendations, risk levels, or current organization experience.

5. The organization monitors and reports all incidents in which medical equipment is suspected in or attributed to the death, serious injury, or serious illness of any individual, as required by the Safe Medical Devices Act of 1990.

6. The organization has written procedures to follow when medical equipment fails, including using emergency clinical interventions and backup equipment.

7. For organizations that provide the technical component of advanced diagnostic imaging and elect to use The Joint Commission CMS imaging supplier accreditation option (Joint Commission Accreditation Ambulatory Care, 2010): The organization identifies activities and frequencies to maintain the reliability, clarity, and accuracy of the technical quality of diagnostic images produced.

Standard *EC.02.04.03*: The organization inspects, tests, and maintains medical equipment.

1. Before initial use of medical equipment on the medical equipment inventory, the organization performs safety, operational, and functional checks.

2. The organization inspects, tests, and maintains all life-support equipment. These activities are documented.

3. The organization inspects, tests, and maintains non–life-support equipment identified on the medical equipment inventory. These activities are documented.

4. The organization conducts performance testing of and maintains all sterilizers. These activities are documented.

5. The organization performs equipment maintenance and chemical and biological testing of water used in hemodialysis. These activities are documented.

Visual and operational check of the equipment's safety and functionality typically performed at the beginning of the day or work period, or just before using equipment on a patient.

2.3.3.2 Centers for Medicare & Medicaid Services Standards

In a December 2, 2011 Memorandum [S&C: 12-07-Hospital], Medicare & Medicaid Services (CMS) provided a clarification for hospital equipment maintenance requirements. In their memorandum summary [103] they stated the following:

A) Alternate equipment maintenance schedules <u>permitted</u> in some instances: Hospitals may adjust maintenance, inspection, and testing frequencies for some facility and medical equipment below those recommended by the manufacturer, based on an assessment by qualified personnel of the risk to patient and staff health and safety.

- Manufacturer-recommended maintenance frequency is required for:
  1- All equipment critical to patient health and safety.
  2- Any new equipment until a sufficient amount of maintenance history has been acquired.

At a minimum, *critical equipment* includes, but is not limited to, life-support devices, key resuscitation devices, critical monitoring devices, equipment used for radiologic imaging, and other devices whose failure may result in serious injury to or death of patients or staff.

B) Alternative equipment maintenance methods <u>are not permitted</u>: hospitals must continue to follow the manufacturer's recommended techniques for maintaining equipment, even if the hospitals alter the frequency of maintenance activities.

Chapter 3

Materials and Methods

3.1Chapter Outlines

This chapter aims to explain the methods and materials that we use to propose and develop different methodologies. In this study, we propose a common model that could be combined with other methods to get out different frameworks for intended management stages, which is stated in section 3.2. We suggested using quality function deployment as common model for prioritization of medical equipment in various stages of management. An overview of quality function deployment and the rules of construction are covered in details in section 3.3. In section 3.4, the second method, fuzzy logic is described with most important features and construction principles. Ant colony optimization method is used also in this study, thus a brief history and the principles of development are given in details in section 3.5. In section 3.6, the guidelines of genetic algorithm optimization method are provided. Finally, how to visually represent process modeling is presented in section 3.7.

3.2 Introduction

The goal of this study is to develop new frameworks for medical equipment management to support the decision makers in any healthcare organization. As mentioned in chapter 1, the main challenge for different stages of management life cycle is to identify a prioritized list of medical equipment to employ it in consistent way for different implementations. The literature is rich with different methodologies in order to produce a proper list of devices for different purposes in medical equipment management.

Most, if not all, of the developed models did not consider the effective role of healthcare participants starting from patients to the general administrator of the hospital in management process. In other words, in every stage of medical equipment management, there are other actors rather than clinical engineers that could influence management strategy by their roles, desires, and visions. Taking into account healthcare participants requirements in developing comprehensive policies for medical equipment management is rarely considered in literature. Therefore, in order to overcome this omission, we are eager to find out a new method that consider the requirements of healthcare providers in different departments who have direct or indirect interface with medical equipment to improve the overall management system by regarding their needs.

Literature review provides us with a qualitative management tool called *Quality Function Deployment* (QFD). The main task of this tool is to improve the characteristics of products or services depending on the requirements of the customers. The applications and contributions of this method are mainly in the industry. Several models were developed for various intended applications utilizing this method. In healthcare sector, particularly in medical equipment management, quality function deployment is seldom used. Accordingly, we decided to exploit this method as it is presenting new concepts in management process and quality assurance for medical equipment in prioritization process.

A number of QFD extensions or modifications have been developed to make QFD more representative and workable [67]. As we propose three important stages to be managed in this research, we develop three models that handle the output of QFD in order to execute intended specific application for every stage. Hence, we suggest other three methods to integrate with QFD model to formulate a final framework to each stage. Method selection has been carried out considering the desired application. The principles and concepts of each method are described in details in the following sections.

3.3 Quality Function Deployment

Quality Function Deployment (QFD) is one of the Total Quality Management (TQM) quantitative tools and techniques that could be used to translate customer requirements and specifications into appropriate technical or service requirements. Quality function deployment was conceived in Japan at the end of the 60's by Yoji Akao. Professor Mizuno first used QFD in 1972 to Mitsubishi's Kobe shipyard site to design super tankers [27].

The Japanese phrase ″品質　機能　展開", means "hinshitsu kino tenkai" refers to "Quality Function Deployment", where function refers to the analysis of the business process in order to improve the quality of the development process of products and services. In the 1970's it was used by Toyota to investigate rust prevention in vehicles and has been introduced by car manufacturers worldwide to help increase customer satisfaction levels [51].

In 1986, Ford motor company and Xerox were the early users of QFD that initiated the use of QFD concept in the USA. Since then, QFD has been developed and broadly used in various industries such as automotives, electronics, banking, insurance, healthcare, utilities, food processing, aerospace, software engineering, construction , and marketing [27]. The Cadillac car model 1992, considered one of the great car models that had

attracted many customers at that time, this car model has been planned and designed using QFD technique.

There is no single or unique definition of QFD, but several definitions, for example; Akao defines QFD [4] as being "*a method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demands into design targets and major quality assurance points to be used throughout the production stage* ". Cohen (1995) in [26] defined it as "a *method for structured product planning and development that enables a development team to specify clearly the customer's wants and needs, and then to evaluate each proposed product or service capability systematically in terms of its impact on meeting those needs"*.

Benefits obtained from the successful adoption of QFD practices have been reported as an increased level of team working including providing a communication platform for current engineering, a reduced time to market, a reduced amount of re-work, and an increase in quality of the product, speeding up changes during different stages, as well as reducing costs of design and meeting satisfaction of customer requirements [4, 46, 99].

3.3.1 Quality Function Deployment Phases

Quality function deployment is a technique that links an organization with its customers. Hence, it is essential to know the customer's needs or Customer Voice (VOC) or WHATs which they can be involved from the first stage of the planning process. This implies implementing (Technological Voice) or HOWs to satisfy the customer's requirements [4, 33, 99]. Thus QFD provides the systematic method to support the process of design decision making.

Typically, a QFD system can be broken into *four* inter-linked phases to fully deploy the customer needs phase by phase [4, 11, 19, 46, 51, 99]. In QFD, each phase's important outputs (HOWs), generated from the phase's inputs (WHATs), are converted into the next phase as its inputs (new WHATs) as

depicted in Fig 3.1. So each phase can be described by a matrix of "WHATs" and "HOWs", which is easy and convenient to deal with in practice [17].

The four QFD phases include phase I, House of Quality (HOQ) or product planning to translate customer needs into product design attributes; phase II, design deployment or parts deployment that translate important technical measures into parts characteristics; phase III, process planning to translate important parts characteristics into process operations; and finally phase IV, production planning to translate key process operations into day to day production requirements [4, 14, 17, 99]. Fig 3.2 illustrates the basic concepts of four QFD phases.

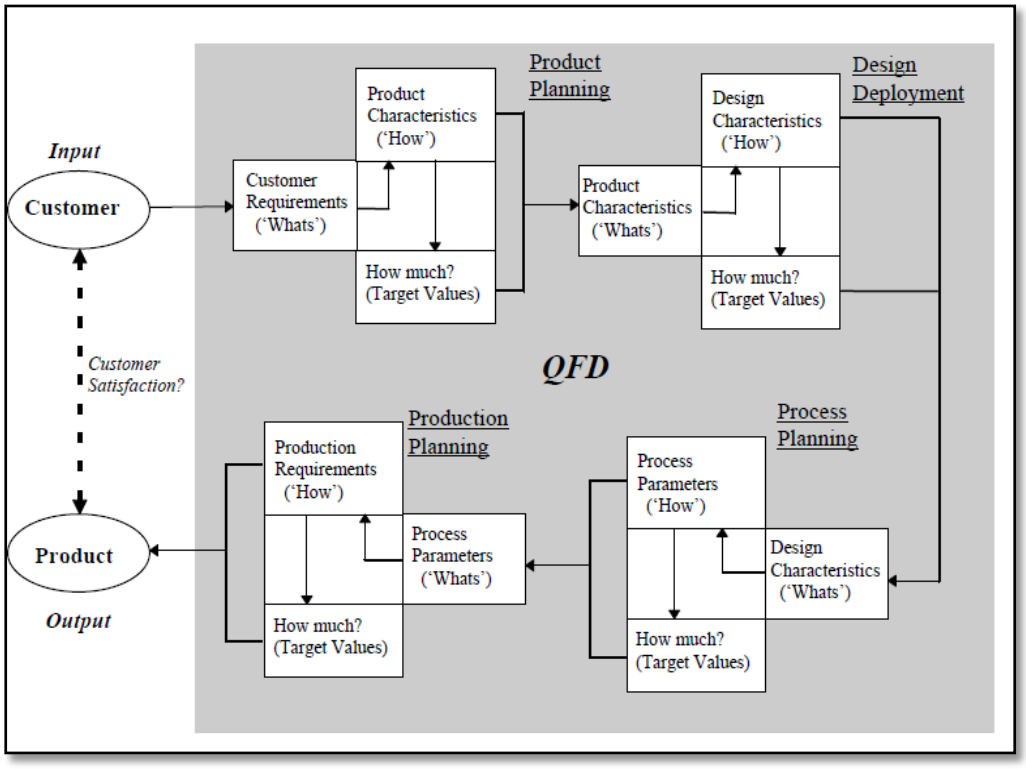


Fig 3.1 QFD process configuration including four main phases [4]

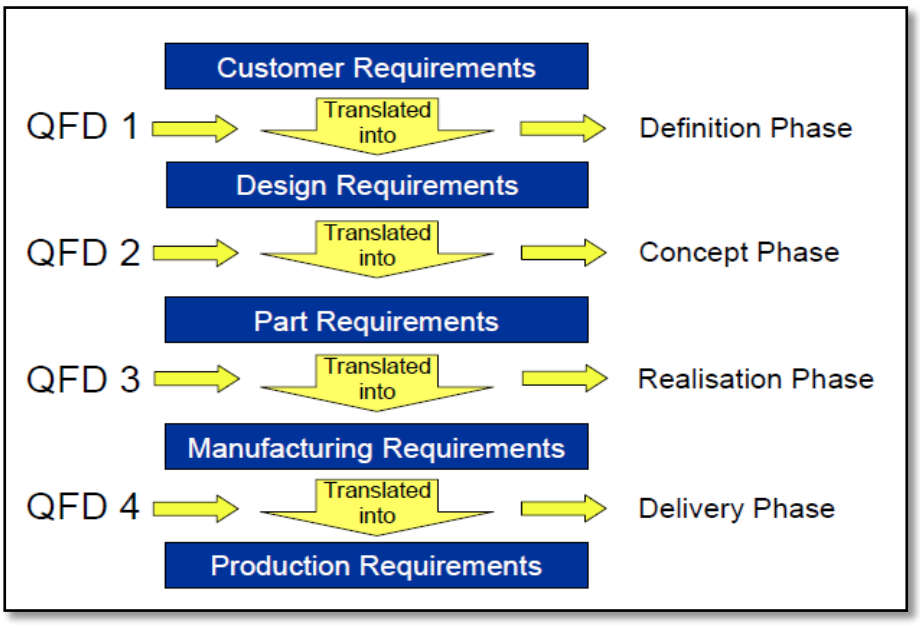


Fig 3.2 Main concepts of four phases for QFD [14]

Among the various stages, the HOQ is the most commonly used stage and its aim is to reflect customer desires. The HOQ is a matrix that determines the relationships between customer needs (WHATs) and design characteristics (HOWs). Its "roof" indicates how design characteristics interact. .In practice, the other matrices are rarely used because the work involved in their construction can consume as much as 80% of a company's employees [26].

3.3.2 House of Quality

The House of Quality (HOQ) is the first matrix used in the process, displays the voice of the customer needs against the technical responses to meet them [35]. In other words HOQ links the voice of customer (VOC) to the voice of engineers (VOE) through which process and production plans can be developed in the other phase of the QFD system. A house of quality (HOQ) involves the collection and analysis of VOC which includes the customer needs for a product, customers' perceptions on the relative importance of these needs and the relative performance of the producing company and its main competitors on the needs.

It also requires the generation and analysis of the "voice of the technician" which includes the technical measures converted from the customer needs, technician's evaluations on the relationship between each customer needs and each technical measure, and the performance of the relevant companies in terms of these technical measures [17]. Based on the literature review for QFD, the main rooms of HOQ have different names. Figure 3.3 illustrates an example for schematic diagrams of HOQ. It consists of several sub-matrices (chambers) joined together in various ways; each matrix contains information related to the others.

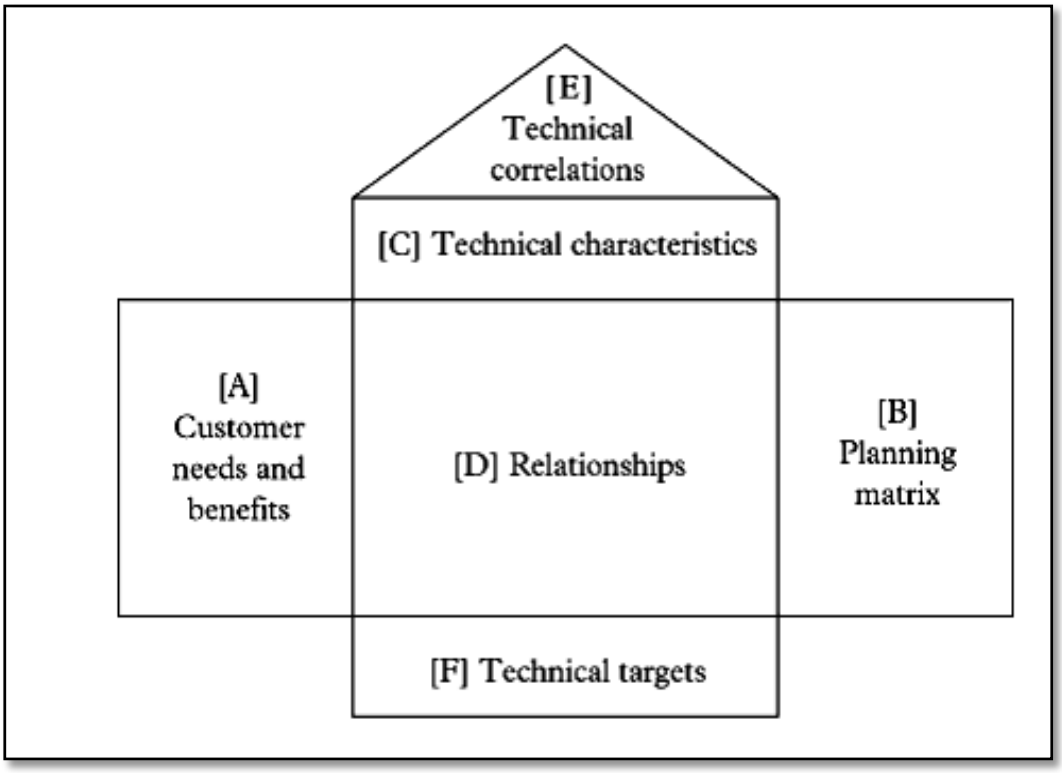


Fig 3.3 House of Quality main room's configuration [26]

Section "A" of Fig 3.3 contains a list of the customer wants and needs. Sometimes it is also called "voice of the customer" or "WHATs". Section "B" is the planning matrix which usually includes the following information; importance to customers, competitive benchmarking, sales point and final priorities. Section "C" lists the technical characteristics of a product or the "HOWs". Section "D" is the relationship matrix which indicates how much each "HOW" affects each "WHAT". Section "E", the roof of the HOQ, contains the technical correlations that capture the trade-off between pairs of "HOWs". Section "F", considered as the last room, and contains the technical matrix with information on technical priorities [4, 17, 19, 26]. Sometimes it also includes technical benchmarks, technical difficulties, estimated cost, targets, and other related information [99].

3.3.3 House of Quality Construction

The process of constructing the HOQ is different from the construction of a real house. According to many works for HOQ construction, the most common popular method is summarized in the next steps;

A. Define the customer requirements (WHATs)
B. Define the technical requirements or the technical characteristics (HOWs)
C. Based on the competitive assessment, develop the planning matrix
D. Develop the relationship matrix between WHATs and HOWs
E. Develop the roof or the correlation matrix
F. Develop the technical targets matrix

3.3.3.1 Customer Requirements (WHATs)

At first the customers of a product or a service concerned should be identified. The customer requirements or needs could be identified based on questionnaire or reported survey on customer complaints. Sometime customer's needs are general, vague and very difficult to implement it directly. If there are many

customer needs, grouping them into meaningful categories is necessary for easy understanding and analysis.

Kano's model as shown in Fig 3.4 is an example for identifying customer's needs. Basically, the function of Kano's model [33] is the belief that the product/service criteria which have the great influence on the customer's satisfaction can be distinguished. Accordingly, there are three kinds of customer's requirements, *performance*, *basic*, and *emotional*. The requirements that mentioned directly by the customers will be called "performance requirements", the requirements that the customers can't verbalize it but they are essential for production or services are "basic requirements", while "the emotional requirements" reflect the needs that the customer has not appreciated before.

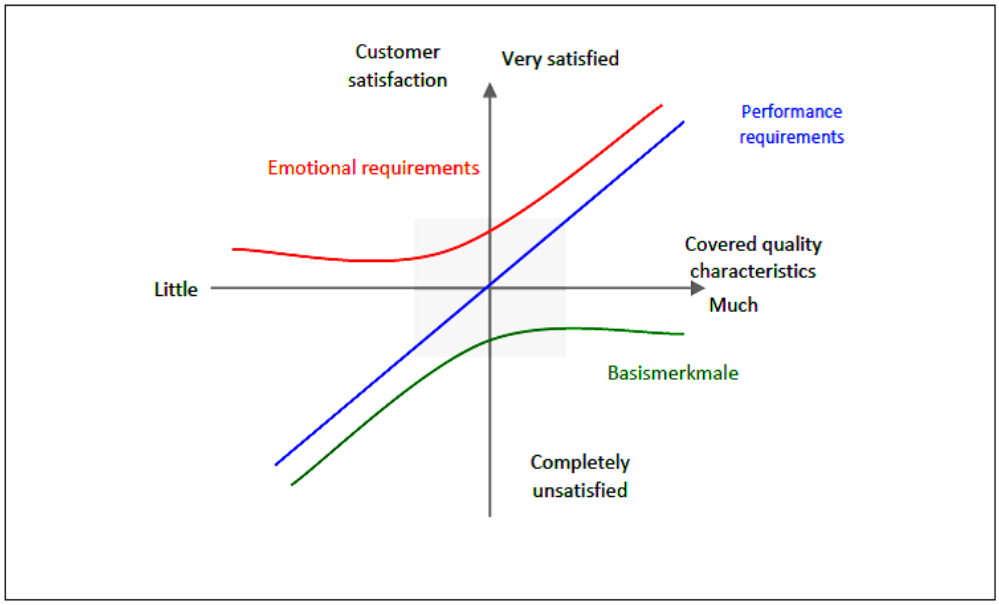


Fig 3.4 Kano's model for customer's requirements [33]

3.3.3.2 Technical Requirements (HOWs)

After definition of customer's requirements, the technical requirements should be developed to meet the customer's needs. The “HOW” are the design requirements of the service; it is necessary to define how each customer’s

requirement will be satisfied by the service [33]. These are measurable features that can be evaluated at the end of the development process. Sometimes technical requirements also are classified into categories to guide engineering needs.

3.3.3.3 Planning Matrix

The planning matrix is a tool to help the product development team to systematically re-prioritize customer needs [99]. This part describes customer perceptions of competing products with regard to meeting their needs. Competitive benchmarking is also carried out here. Usually the customers assess the relative performance of the company's product and its main competitors utilizing the 5-point Likert scale in which 1 is not important at all through to 5 which is very important [26]. Sometimes scales such as a 9-point scale from 1 to 9 or 100-point scale from 1 to 100 also could be used [17]. The following steps describe how to construct the planning matrix [17, 19, 26]

1. Allocate the importance scale for customer needs based upon their satisfaction using a 5-point scale.
2. Allocate the customer satisfaction with the investigated product or service using a 5-point scale.
3. Allocate the customer satisfaction with the other competitors using a 5-point scale.
4. Allocate the planned goal for investigated product or service using a 5-point scale.
5. Calculate the improvement ratio by dividing the planned goal scores to customer satisfaction with investigated product or service scores.
6. Calculate the absolute weight by multiplying the improvement ratio by the importance scores.
7. Calculate the relative weight by dividing each absolute weight score by total summation of the absolute weight.

8. Rank (prioritize) the customer requirements according to the relative weight values to get the degree of importance for customer needs.

3.3.3.4 Relationship Matrix

The relationship matrix is the center of HOQ which indicates how each technical requirement affects each customer requirements. In other words, the matrix identifies the level of relationship between each WHAT and each HOW [4, 19, 46, 99]. Usually, the relationship is expressed using three levels scores, weak relation, medium relation, and strong relation. Fig 3.5 depicts a relationship matrix with symbols of relation levels. Cohen (1995) [26, 46] proposed the use of the following scale: 9-strongly linked, 3-moderately linked and 1-possibly linked.

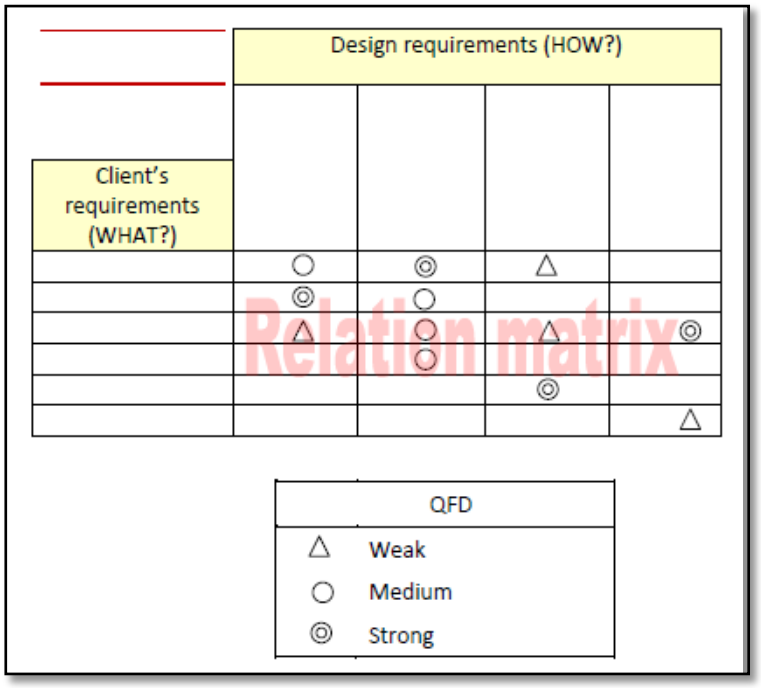


Fig 3.5 A general relationship matrix with symbols for HOQ [33]

3.3.3.5 Correlation Matrix (The Roof)

The roof matrix is a matrix indicating the relationships between technical characteristics (HOWs). It is a good indicator of future design trade-off that

may have to be made [99]. For each pair of technical requirements, the QFD team must answer the following question: does improving one requirement cause deterioration or improvement in another requirement?. The answer of this question is the correlation matrix. The symbols that are used for this matrix; ++ for strong positive, + for positive, - for negative, -- for strong negative [4, 33] as shown below in Fig 3.6.

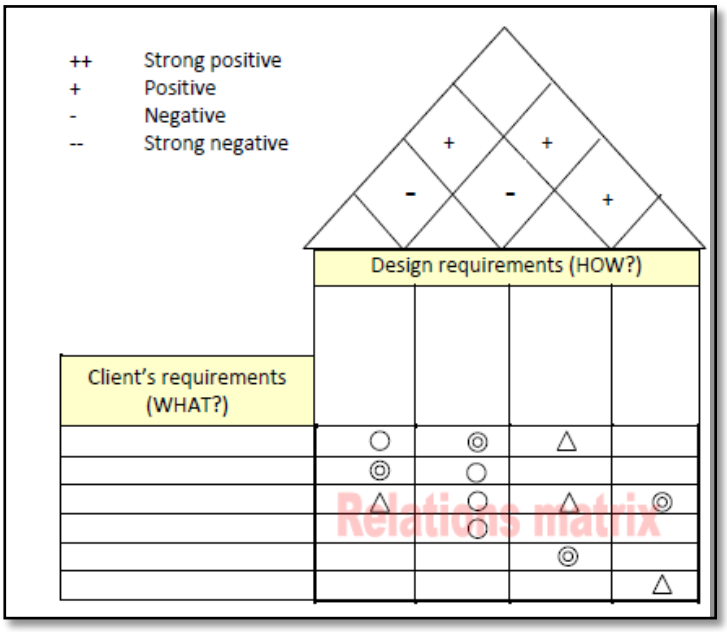


Fig 3.6 A general correlation matrix (the roof) of HOQ [33]

3.3.3.6 Technical Target Matrix

The goal of this matrix is to compare the most important customer requirements against the most relevant technical characteristics to verify customer satisfaction. Accordingly, this section contains the most important and useful information. The priority of each technical characteristic [99] provides a rank ordering of the technical characteristics. The target values represent "how much" for the technical descriptors [46], and can then act as a base-line to compare against. The following steps summarize how to develop the technical target matrix [4, 26].

1. **Calculate the absolute weight using Equation 3.1**

$$\mathbf{AW} = \sum_{i,j=1}^{m,n} \boldsymbol{D_i} * \boldsymbol{R_{i,j}} \quad \textbf{(3.1)}$$

D_i: degree of importance of customer requirements i (final step in planning matrix)

$R_{i,j}$: Relationship value between customer requirements i, and technical characteristics j

AW: Absolute weight of technical characteristics

n: number of customer requirements

m: number of technical characteristics

2. **Calculate the relative weight using Equation 3.2**

$$\mathbf{RW} = (\mathbf{AW} / \sum \boldsymbol{AW}) * \mathbf{100} \quad \textbf{(3.2)}$$

3. **Rank the technical requirements according to RW values**
4. **Based upon ranking, identify the most important technical specifications**

3.4 Fuzzy System

Fuzzy set was introduced by *L.A. Zadeh* in1965 in order to deal with the vagueness of human thought [102]. Fuzzy set theory provides a strict mathematical framework (there is nothing fuzzy about fuzzy set theory) in which vague conceptual phenomena can be precisely and rigorously studied. It can also be considered as a modeling language, well suited for situations in which fuzzy relations, criteria, and phenomena exist [119]. The acceptance of

this theory grew slowly in 1960s and 1970s of the last century. In 1992 [119], in three simultaneous conferences in Europe, Japan, and United States, the three areas of fuzzy sets, neural nets, and evolutionary computing (genetic algorithms) joined forces and are henceforth known under *"computational intelligence"*.

Fuzzy sets are an extension of crisp (two-valued) sets to handle the concept of *partial truth*, which enables the modeling of the uncertainties of natural language. The vagueness in natural language is further emphasized by linguistic terms used to describe objects or situations. For example, the phrase *when it is very cloudy, it will most probably rain*, has the linguistic terms *very* and *most probably* – which are understood by human brain. Fuzzy sets, together with fuzzy reasoning systems, give the tools to also write software, which enables computing systems to understand such vague terms, and to reason with these terms [38].

The term "fuzzy logic" emerged as a consequence of the development of the theory of fuzzy sets. What is necessary is a formal logic system that can be used to reason about uncertainties in order to derive at plausible actions. Fuzzy logic is such a system, which together with an inference system form a tool for approximate reasoning. *Zadeh* defines fuzzy logic (FL) as *a logical system, which is an extension of multi valued logic that is intended to serve as logic for approximate reasoning* [38].

The fuzzy logic variables may have a membership value of not only 0 or 1, but a value inclusively between 0 and 1. In fuzzy logic the degree of truth of a statement can range between 0 and1and is not constrained to the two truth values {true (1), false (0)} as in classical propositional logic. Thus the fuzzy logic provides a basis for approximate reasoning, that is, a mode of reasoning which is not exact or very inexact. It offers a more realistic framework for human reasoning than traditional two-valued [57].

3.4.1 Basic Concepts of Fuzzy System

To the knowledge base, fuzzy logic has been and still is, thought to a lesser degree, an object of controversy. A source of confusion is that the label" fuzzy logic" is used in two different senses; narrow sense: fuzzy logic is a logical system, and wide sense: fuzzy logic is coextensive with fuzzy set theory [116]. Today, fuzzy logic is used for the most part in its wide sense. Therefore, in order to deeply understand the fundamentals of fuzzy logic, the main terms and concepts of a combination of fuzzy set and fuzzy logic would be explained in details in the following subsections.

3.4.1.1 Formal Definitions

The elements of a fuzzy set have membership degrees to that set. The degree of membership to a fuzzy set indicates the certainty or uncertainties that the element belongs to the set. Formally defined, suppose X is the domain, or universe of discourse, and $x \in X$ is a specific element of domain X *(universe of discourse)*. Then, the fuzzy set A is characterized by a membership mapping function [38]

$$\boldsymbol{\mu_A : X \rightarrow [0, 1]} \qquad \textbf{(3.3)}$$

Therefore, for all $x \in X$, $\mu_A(x)$ indicates the certainty to which element x belongs to fuzzy set A. If $\mu_A(x) = 0$, then x des not belongs to A, if $\mu_A(x) = 1$, then x completely belongs to A, meanwhile $\mu_A(x)$ ranges between 0 and 1, then x partially belongs to A and its membership to A increases according to the value of $\mu_A(x)$. Fuzzy sets can be defined for discrete (finite) or continuous (infinite) or discrete domains. In the case of a discrete domain X, the fuzzy set is often expressed in the form of sum notation. If $X = \{x_1, x_2 \ldots x_n\}$, then

$$\mathbf{A} = \boldsymbol{\mu_A(x_1)} / \boldsymbol{x_1} + \ldots + \boldsymbol{\mu_A(x_n)} / \boldsymbol{x_n} = \sum_{i=1}^{x_n} \boldsymbol{\mu_A(x_i)} / \boldsymbol{x_i} \qquad \textbf{(3.4)}$$

3.4.1.2 Membership Functions

The membership function is the essence of fuzzy sets. A membership function, also referred to as the characteristic function of the fuzzy set, defines the fuzzy set [38, 116]. The function is used to associate a degree of membership of each of the domain to the corresponding fuzzy set. In another words, it describes the degree of relation of a variable values with its representation by means of fuzzy sets.

Membership functions can be any shape or type as determined by experts in the domain over which the sets are defined [38]. Different examples of membership function are presented in Fig. 3.7. The membership functions examples include, triangular, trapezoidal, logistic, exponential-like, and Gaussian. The designers of fuzzy sets have much freedom in selecting appropriate membership functions; these functions must satisfy the following constraints:

- A membership function must be bounded by 0 and from above by 1.
- The range of membership function must therefore be [0,1]
- For each $x \in X$, $\mu_A(x)$ must be unique, that the same element cannot map to different degrees of membership for the same fuzzy set.

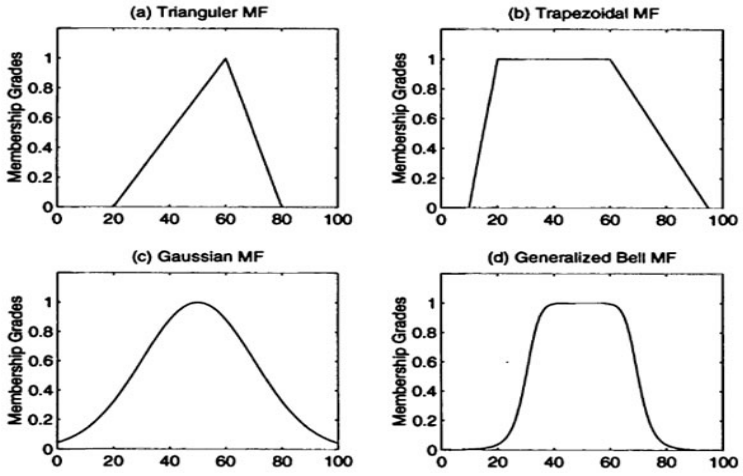


Fig 3.7 Examples of membership functions for fuzzy sets [38]

3.4.1.3 Fuzzy Operators

As for crisp sets, relations and operators are defined for fuzzy sets. Each of these relations and operators are defined below [38]. For this purpose let *X* be the domain, and *A* & *B* are fuzzy sets defined over the domain *X*.

Equality of fuzzy sets: two fuzzy sets *A* and *B* are equal if and only if the sets have the same domain, and $\mu_A(x) = \mu_B(x)$ for all $x \in X$. That is $A = B$.

Containment of fuzzy sets: fuzzy set *A* is a subset of fuzzy set *B* if and only if $\mu_A(x) \leq \mu_B(x)$ for all $x \in X$. That is $A = B$. That is $A \subset B$.

Complement of a fuzzy set (NOT): let $\overline{A}$ denotes the complement of set *A*. then for all $x \in X$, $\mu_{\overline{A}}(x) = 1 - \mu_A(x)$.

Intersection of fuzzy sets (AND): the intersection of two-valued sets is the set of elements occurring in both sets. Operators that implement intersection are referred to *t-norms*. The result of a t-norm is a set that contain all the elements of the two fuzzy sets, but with degree of membership that depends on the specific t-norm. If *A* and *B* are two fuzzy sets, then

- **Min –operator:** $\mu_{A\cap B}(x) = \min\{\mu_A(x), \mu_B(x)\}, \forall x \in X$
- **Product operator:** $\mu_{A\cap B}(x) = \mu_A(x)\,\mu_B(x), \forall x \in X$

Union of fuzzy sets (OR): the union of two-valued contains the elements of all the sets. The same is true for fuzzy sets, but with membership degrees that depend on the specific union operator used. These operators are referred to as *s-norms* of which the max-operator and summation are most frequently used. If *A* and *B* are two fuzzy sets, then

- **Max-operator:** $\mu_{A\cup B}(x) = \max\{\mu_A(x), \mu_B(x)\}, \forall x \in X$
- **Summation operator:** $\mu_{A\cup B}(x) = \mu_A(x) + \mu_B(x) - \mu_A(x)\,\mu_B(x), \forall x \in X$

3.4.1.4 Linguistic Variables

Linguistic variables are variables that are words or sentences from natural language. Sensory inputs are linguistic variable, or nouns in a natural language, for example, temperature, pressure, displacement, etc. Linguistic variables allow the translation of natural language into logical or numerical statements, which provide the tools for approximate reasoning. Many examples for linguistic variables are provided like, *all, most, none; sometimes, always; possible, likely, certain; very, almost no, etc.*

3.4.1.5 Fuzzy Rules

In general, the dynamic behavior of fuzzy systems is characterized by a set of linguistic fuzzy rules [38]. These rules are based on the knowledge and experience of a human expert within the domain. Fuzzy rules are of the general form

IF antecedent (s) THEN consequent (s)

The antecedent and consequent of a fuzzy rule are prepositions containing linguistic variables; For example, if *temperature* is *high* then *weather* is *hot*. Usually, the antecedents of a rule form a combination of the logic operators (i.e. complement, intersection, union), whereas the consequent is often a single fuzzy set, with a corresponding membership function.

3.4.2 Fuzzy Logic System

Together, the fuzzy sets and fuzzy rules form the knowledge base of a fuzzy rule-based reasoning system. By implementation, a fuzzy reasoning system consists of three components [38], each performing a specific task in the reasoning process, *fuzzification*, *inference*, and *defuzzification*. Figure 3.8 portrays a schematic representation of general fuzzy logic system. Fuzzification process denotes the process of transforming crisp values into grades of membership, while the defuzzification is the reverse process. The input space is

defined by a combination of input fuzzy sets, while the output space is defined by the combination of output sets.

The most common way that is describing fuzzy logic system is summarized in the following steps [57]

1- Define linguistic variables and terms (initialization)
2- Construct the membership functions (initialization)
3- Construct the rule base (initialization)
4- Convert crisp input data to fuzzy values using the membership functions (fuzzifcation)
5- Evaluate the rules in the rule base (inference)
6- Combine the results of each rule (inference)
7- Convert the output data to non-fuzzy values (deffuzification)

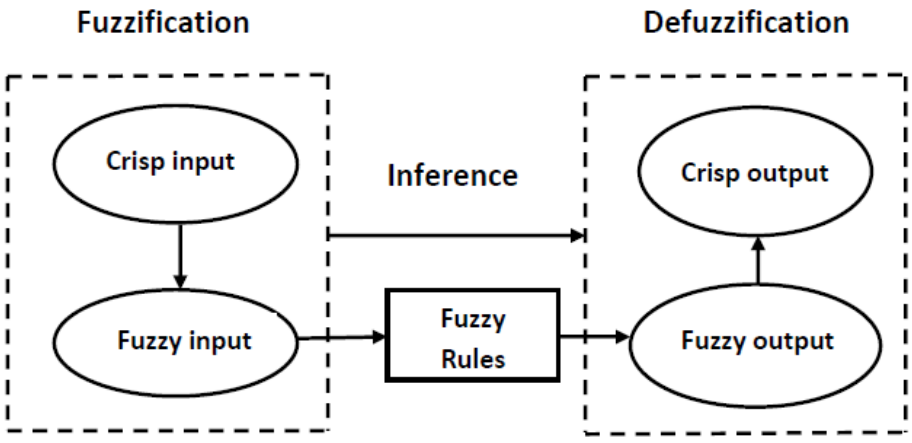


Fig 3.8 Fuzzy logic system processes

3.4.2.1 Fuzzification Process

The fuzzification process is concerned with finding a fuzzy representation of non-fuzzy input values [38]. This is achieved through application of the membership functions associated with each fuzzy set in the rule input space. For illustration purposes, assume the fuzzy sets *A* and *B*, and assume the

corresponding membership functions have been defined already. Let X denotes the domain for both fuzzy sets. The Fuzzification process receives the elements a, b ∈ X, and produces the membership degrees $\mu_A(a)$, $\mu_A(b)$, $\mu_B(a)$, and $\mu_B(b)$.

3.4.2.2 Inference

The task of the inference process is to map the fuzzified inputs (as received from the fuzzification process) to the rule base, and to produce a fuzzified output for each rule [38]. That is, for the consequents in the rule output space, a degree of membership to the output sets is determined based on the degrees of memberships between input sets. The relationships between input sets are defined by the logic operators that combine the sets in the antecedents. The output fuzzy sets in the consequent are then combined to form one overall membership function for the output of the rule. In other words, it is a combination of the output of fuzzy rules in order to formulate the output membership function as shown in Fig. 3.9. In general, there are two common ways for fuzzy inference systems or rule-based fuzzy models; Mamdani and Takagi-Sugeno [37, 57, 76].

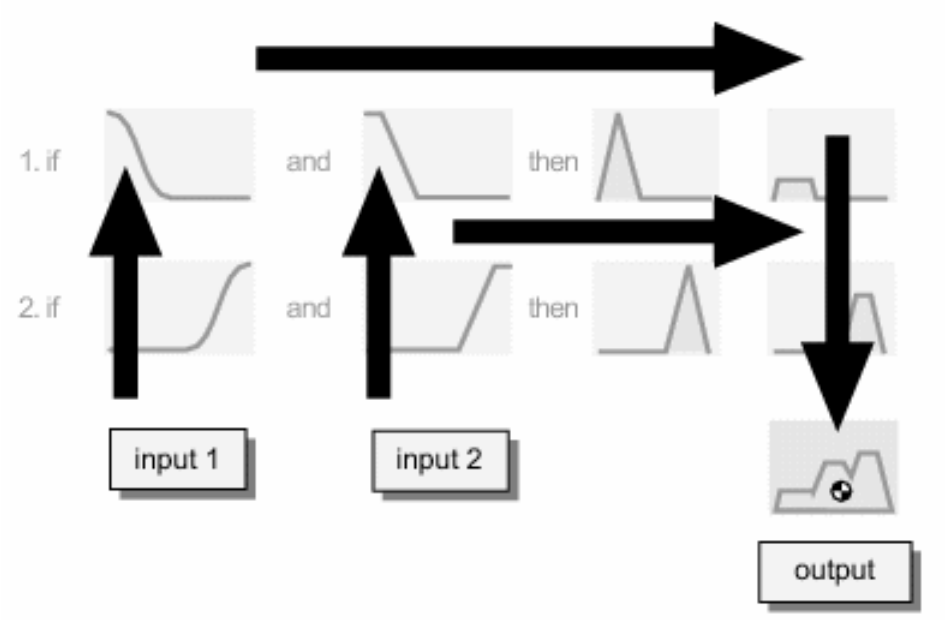


Fig 3.9 Fuzzy inference diagram [76]

Mamdani method: the method also is known as max-min method. The method reveals how rule-based fuzzy output is mapped. The goal of the technique was to control a steam engine and boiler combination by a set of linguistic control rules obtained from experienced human operators [64]. The basic idea of this method is depicted in Fig. 3.10, starting through the rule with the largest firing strength (threshold) is being selected, and consequently it is determined which consequent membership function is activated. The centroid is taken of the area under that function is calculated and the horizontal coordinate of that centroid is taken as the output of the controller [38].

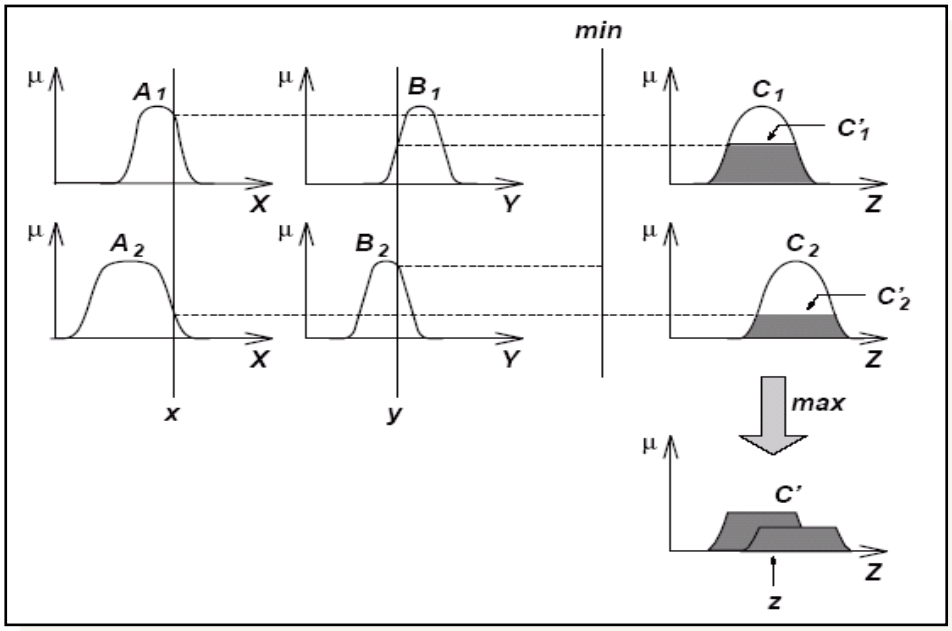


Fig 3.10 A schematic representation of Mamdani (max-min) inference [47]

Takagi-Sugeno (T-S) method: in this method, a multidimensional fuzzy reasoning model was suggested [104] in order to generate fuzzy rules from a given input-output data set. In each fuzzy subspace, a linear input-output relation is formed. The output of fuzzy reasoning is given by aggregation of the values inferred by some implications that were applied to an input. Figure 3.11 illustrates the principal configuration of this method.

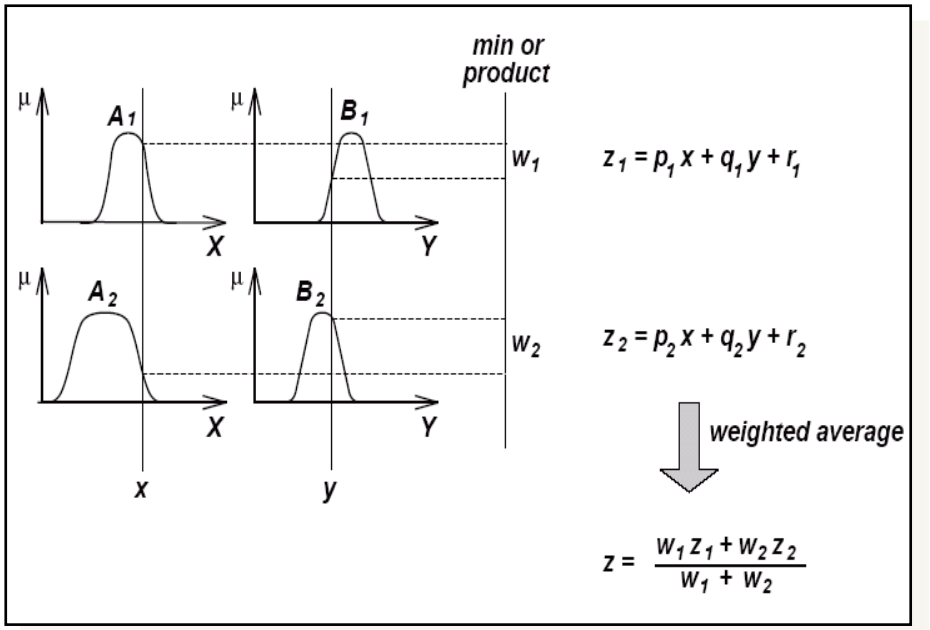


Fig 3.11 A schematic representation of Takagi - Sugeno inference [47]

In summary, we can compare the two fuzzy-rule based models with respect to input-output data set as follow. In Mamdani linguistic fuzzy model, both the antecedent (input) and the consequent (output) are fuzzy prepositions, while in Takagi-Sugeno fuzzy model, the antecedent is a fuzzy preposition; the consequent is a crisp function [57]. In comparison, advantages of Mamdani fuzzy inference system are its intuitive, has wide spread acceptance and well suited to human cognition. The T-S fuzzy inference system works well with linear techniques and guarantees continuity of the output surface. But the T-S fuzzy inference system has difficulties in dealing with the multi-parameter synthetic evaluation, as well as it has difficulties in assigning weight to each input and fuzzy rules [37].

3.4.2.3 Defuzzification Process

The task of the defuzzification process is to convert the output of the fuzzy rules into a scalar, or non-fuzzy value i.e. crisp values [38, 57, 90]; taking into account, defuzzification process is performed according to the membership function of the output variable. There are different algorithms for

defuzzification as well. These are Center of Gravity, Center of Gravity for Singletons, Center of Area, Mean of Maxima, Left Most Maximum, and Right Most Maximum [68]. Among all defuzzification methods, the two common methods for this purpose are Mean of Maxima (MOM) and Center of Gravity (COG) [90].

Mean of Maxima (MOM) applies to the fuzzy output $\mu_A(x)$ by taking the mean of the x values at which $\mu_A(x)$ is maximized [90]. Suppose that $x_1, x_2 \ldots x_n$ are the maximizing points of C (x), then

$$\boldsymbol{MOM\ [\mu_A(x)] = \frac{x1+x2+\cdots+xn}{n}} \qquad \boldsymbol{(3.5)}$$

Center of Gravity (COG) finds the points where a vertical line would slice the aggregate set into two equal masses [57]. It can be expressed in continuous area with boundaries a and b as

$$\boldsymbol{COG\ [\mu_A(x)] = \frac{\int_a^b x\mu_A(x)dx}{\int_a^b \mu_A(x)dx}} \qquad \boldsymbol{(3.6)}$$

The discrete version of this equation [90] is written as

$$\boldsymbol{COG\ [\mu_A(x)] = \frac{\sum_{i=1}^{q} x_i\mu_A(x_i)}{\sum_{i=1}^{q} \mu_A(x_i)}} \qquad \boldsymbol{(3.7)}$$

, where q is the number of sample values of the output, and x_i is the value of the control output at the sample value.

3.5 Ant Colony Optimization

Swarm intelligence is a relatively new approach to problem solving that takes inspiration from the social behaviors of insects and of other animals. In particular, ants have inspired a number of methods and techniques among which the most studied and the most successful is the general purpose optimization technique known as Ant Colony Optimization (ACO). Ant colony has been formalized into a metaheuristics for combinatorial optimization problems. A metaheuristics [31] is a general-purpose algorithmic framework that can be applied to different optimization problems with relatively few modifications. In the following subsections, we highlight the main idea of the algorithm as well as we introduce the main concepts, parameters, and formulas of the algorithm.

3.5.1 ACO Overview

From the early nineties, when the first ant colony optimization algorithm was proposed by the Italian researcher *Marco Dorigo*, ACO attracted the attention of increasing numbers of researchers and many successful applications [31]. Lately, this new born bionic simulated evolutionary algorithm has become a hot issue in the field of artificial intelligence and employed to solve problems in various fields [101]. The algorithm has been widely applied in several fields such as combinatorial optimization, network routing, function optimization, data mining and robot path planning, etc [115].

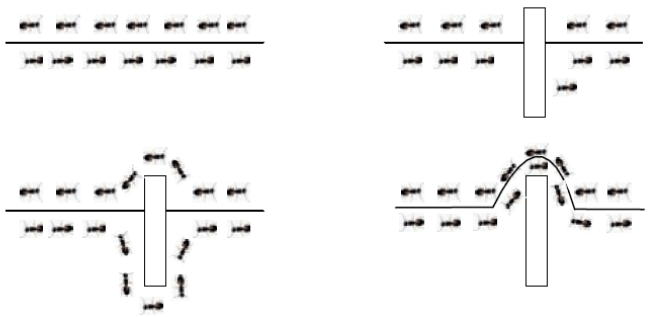


Fig 3.12 Real ants after a while tend to choose the shortest path between nest and food [74]

Ant Colony Optimization (ACO) takes inspiration from the foraging behavior of some ant species. It mimics the natural behavior of real ants in seeking food. During seeking food tour, these ants deposit a chemical substance called *pheromone* on the ground in order to mark some favorable path that should be followed by other members of the colony [32] as shown in Fig 3.12. Other ants perceive the presence of pheromone and tend to follow paths where pheromone concentration is higher.

The ants return to the nest using always the same path, depositing other portions of pheromone in the way back. Imagine then, two ants at the same location choose two different trails at the same time. The pheromone concentration on the shortest way will increase faster than the other; the ant that chooses this way, will deposit more pheromones in a smaller period, because it returns earlier [56]. If a whole colony of thousands of ants follows this behavior, soon the concentration of pheromone in the shortest path will be much higher than the concentration in other paths. Then the probability of choosing any other way will be very small and only very few ants among the colony will fail to follow the shortest path.

There is another pheromone related with pheromone concentration. Since it is a chemical substance, it tends to evaporate in the air, so the concentration of pheromone vanishes along the time. In this way, the concentration of the less used paths will be much lower than on the most used ones, not only because the concentration increases in the other paths, but also because their own concentration decreases [56].

ACO algorithms have been applied to many combinatorial optimization problems, ranging from quadratic assignment to fold protein or routing vehicles and a lot of derived methods have been adapted to dynamic problems in real variables, stochastic problems, multi-target and parallel implementations. It has also been used to produce near-optimal solutions to the travelling salesman problem. They have an advantage over simulated annealing and genetic algorithm approaches for similar problems when the graph may change

dynamically; the ant colony algorithm can be run continuously and adapt to changes in real time. This is of interest in network routing and urban transportation systems [98].

3.5.2 ACO Principals

Ant colony algorithm simulates the cooperation process of a real ant colony. In ACO, a number of artificial ants build solutions to an optimization problem and exchange information on their quality via a communication scheme that is reminiscent of the one adopted by real ants. The artificial ants are used as an optimization tools, hence, the artificial ants have some major differences with real ants [32]. The first one is the artificial ants are assumed to have some memory, secondly, they are not be completely blind, and finally, they live in an environment where time is discrete.

3.5.2.1 Travelling Salesman Problem Optimization

The first ACO algorithm has been formalized into a metaheuristics for combinatorial optimization problems called Ant System (AS). It was introduced by *Dorigo* and his colleagues, and was firstly applied to the traveling salesman problem (TSP) [34]. In TSP, a set of cities is given and the distance between each of them is known. The goal is to find the shortest tour so that each city is visited exactly once and the tour ends in the initial city.

For a set of cities, we consider *dij* to be the distance between any given cities *i* and *j*, such that the path length $dij = [(x_i - x_j)^2 + (y_i - y_j)^2]^{1/2}$, where (x_i,y_i) and (x_j,y_j) are the coordinates of city *i* and *j*. Initially, each of *m* ants is put on some randomly chosen city, and then decides independently which city to go to using a transition rule that is a function of the distance to the city and the amount of pheromone of the present connecting path until the tour is completed. The probability which shows the transition rule of the *k*th ant making the transition from city *i* to city *j*, is given by (3.8) as follow:

$$P_{ij}^{k} = \begin{cases} \frac{\tau_{ij}^{\alpha} . \eta_{ij}^{\beta}}{\sum_{l \in allowed\ k} \tau_{il}^{\alpha} . \eta_{il}^{\beta}}, & if\ j \in allowed\ k \\ \mathbf{0}, & otherwise \end{cases} \quad \textbf{(3.8)}$$

where ηij = 1 / *dij* is a heuristic value , *allowed k* is the list of nodes not yet visited by the *k*th ant, and α is the information heuristic factor, which indicates the importance of path. The larger α is, the more the ant will tend to choose the path that other ants have passed, and the stronger cooperation among ants will be. The coefficient β represents the expectation heuristic factor, which indicates relative importance of visibility and reflects the stressing degree of heuristic information when the ant chooses the path [115]. After all ants have built a tour, ants perform following pheromone update rule given by (3.9) [118]:

$$\tau_{ij}\ (t+1) = (1-\rho).\tau_{ij} + \sum_{k=1}^{m} \Delta\ \tau_{ij}^{k} \quad \textit{(3.9)}$$

where $\rho \in (0,1)$ is the evaporation rate of the pheromone trail , 1- ρ indicates the information remaining factor, and $\Delta\ \tau_{ij}^{k}$ is the amount of pheromone laid on path (*i*, *j*) by the *k*th ant. The amount of pheromone that an ant *k* deposits on an edge (*i*, *j*) is defined by L^{k} (*t*), the length of the tour created by that ant at iteration *t* as follows:

$$\Delta\ \tau_{ij}^{k}(t) = \begin{cases} \frac{Q}{Lk\ (t)}, & if\ (i,j)\ \textbf{is used by ant}\ \ k \\ \mathbf{0}, & otherwise \end{cases} \quad \textit{(3.10)}$$

where Q is constant [118]. In this way, the increase of pheromone for an edge depends on the number of ants that use this edge, and on the amount of

the solutions found by those ants. The solution of TSP as a problem example that was solved by ACO algorithm is presented in Fig. 3.13.

The steps of ACO algorithm in solving TSP are summarized through four shapes of Fig. 3.13 as follows [114].

1- Single ant constructs a solution.
2- Multiple solutions are constructed by all the ants individually.
3- The pheromone trails adaptively adjust their values during the iterations.
4- The optimal solution emerges as the search learns from its experience.

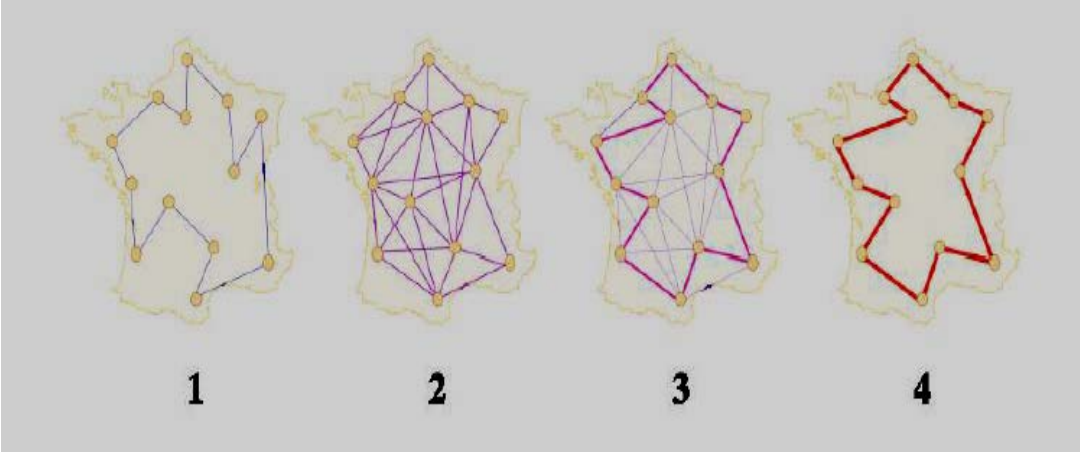


Fig. 3.13 An illustration steps on how ACO-TSP works [114]

3.5.2.2 Advantages and Disadvantages of ACO

Indeed, as any other computational technique, ACO has its advantages and disadvantages [98]. The main advantages of ACO are inherent parallelism, its ability to provide positive feedback accounts for rapid discovery of good solutions; it provides strong robustness in finding solutions of combinatorial problems such as TSP, and its ability to be used in dynamic application. On the other hand, the disadvantages of ACO are summarized as follow

- Theoretical analysis is difficult
- Sequences of random decisions
- Probability distribution changes by iteration
- Research is experimental rather than theoretical
- Time to convergence uncertainty

3.5.3 Main ACO Algorithms

The first ant colony optimization algorithm is known as Ant System and was proposed in the early nineties. Since then, several other ACO algorithms have been proposed [31]. The previous optimization technique to solve TSP is considered the original algorithm and called Ant System. The two other most successful variants are Max-Min ant system and ant colony system. The following subsections describe the differences between these three algorithms.

3.5.1.1 Ant System

Ant system (AS) is the first ACO algorithm proposed in the literature [31, 32, 34]. Its main characteristics for each iteration, the pheromone values are updated by *all the ants* that have built a solution in the iteration itself. The best ant (that which traversed the shortest path) deposits a large quantity of pheromone, with a view to increase the probability of the other ants of exploring the most promising solution [31, 34]. The previous solution steps of TSP explain the main steps of AS algorithm with its fundamental equations.

3.5.1.2 Max-Min Ant System

This algorithm is an improvement over the original AS; some notable differences are presented [31, 34]. Its main characteristics are *only the best ant* updates the pheromone trails and that the value pheromone is bound. The main differences of algorithm are listed down [34]. The pheromone update is implemented as follows:

$$\tau_{ij}\,(t+1) = [(1-\rho).\tau_{ij}+\sum_{k=1}^{m}\Delta\,\tau_{ij}^{k}]_{\tau_{min}}^{\tau_{max}}, \qquad (3.11)$$

1- Only the best ant updates a trail of pheromone.
2- The values of the trails are limited by $\boldsymbol{\tau_{min}}$ and $\boldsymbol{\tau_{max}}$
3- The trails are initialized with the maximum value $\boldsymbol{\tau_{max}}$
4- The updating of the trails is made in a proportional manner, the strongest trails being less reinforcement than the weakest.
5- A re-initialization of trails can be carried out.

3.5.1.3 Ant Colony System

The ant colony systems (ACS) algorithm was introduced to improve the first algorithm for problems of higher dimensions [34]. The most interesting contribution of ACS is the introduction of *a local pheromone update* in addition to the pheromone update performed at the end of the construction process (called offline pheromone update) [31]. The local pheromone update is performed by all ants after each construction step. Each ant applies it only to the last edge traversed:

$$\boldsymbol{\tau_{ij} = (1-\varphi).\tau_{ij} + \varphi.\ \tau_0} \qquad \textbf{(3.12)}$$

Where $\varphi \in (0, 1]$ is the pheromone decay coefficient, and τ_0 is the initial value of the pheromone. The main goal of the local update is to verify the search performed by subsequent ants during iteration by decreasing the pheromone concentration on the traversed edges, ants encourage subsequent ants to choose other edges and, hence to produce different solutions. This makes it less likely that several ants produce identical solutions during one iteration [31].

3.6 Genetic Algorithms

Many human inventions were inspired by nature. Artificial neural network is an example. Another example is Genetic Algorithms (GAs). Genetic algorithms

are generally attributed to Holland and his students in 1970s, although evolutionary computation dates back further [5]. GAs are stochastic metaheuristics that mimic some features of natural evolution. GAs represent an intelligent exploitation of a random search used to solve optimization problems [71].

3.6.1 GAs Overview

In the world of the evolutionary algorithms, the *individuals* or *chromosomes* subjected to evolution are the solutions, more or less efficient, for a given problem. These solutions belong to the search space of the optimization problem. The set of the individuals treated simultaneously by evolutionary algorithm constitutes *a population*. It evolves during a succession of iterations called *generations* until a termination criterion, which takes into account a priori the quality of the solutions obtained, is satisfied [34].

During each generation, a succession of operators is applied to the individuals of a population to generate the new population for the next generation. When one or more individuals are used by an operator, they are called the *parents*. The individuals originating from the application of the operators are called *offspring*. Thus, when two operators are applied successively, the offspring generated by one can become parents for the other [34].

In nature, the individual that has better survival traits will survive for a longer period of time acts to the principle of Darwin, *"The survival of the fittest*" [66, 71]. GA simulates the survival of the fittest among the individuals over consecutive generations in order to find the best solutions of the problem. In order to well-understand the working principles of GAs, a biological background should be given.

Every organism has a set of rules, describing how that organism is built. All living organism consisting of *cells*, in every cell there is a same set of

chromosomes. Chromosomes are strings of DNA (deoxyribonucleic acid) and serves as a model for whole organism. A chromosome consists of *genes*, blocks of DNA. Each gene encodes a particular protein that represents a *trait* (feature) e.g. color of eyes. Possible settings for a trait (e.g. blue, brown, green) are called *alleles*. Each gene has its own position in the chromosome called its *locus*. Complete set of genetic materials (all chromosomes) is called a *genome*. Particular set of genes in a genome is called *genotype* [71]. The physical expression of the genotype is called *phenotype* that represents the physical and mental characteristics of an organism.

When two organisms mate they share their genes; the resultant offspring may end up having half the genes from one parent and half from the other. This process is called *crossover* or recombination. The new created offspring can be mutated; *mutation* means that the elements of DNA are a bit changed. These changes are mainly caused by errors in copying genes from parents. On the other hand, the *fitness* of an organism is measured by success of the organism in its life i.e. survival [71]. A schematic diagram for general evolutionary process is illustrated in Fig.3.14.

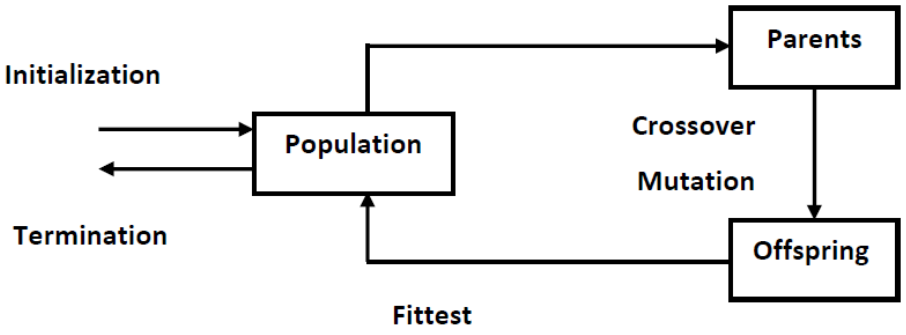


Fig. 3.14 General scheme of evolutionary process

3.6.2 Canonical GA

Genetic algorithms are search algorithms that are based on concepts of natural selection and natural genetics. The genetic algorithm differs from other search

methods in that it searches among population of points and works with a coding of parameter set, rather than the parameters values themselves. It also uses objective function information without any gradient information. The transition scheme of genetic algorithm is probabilistic, whereas the traditional methods use gradient information [66]. Because of these features of genetic algorithm, they are used as general purpose optimization algorithm. They also provide means to search irregular space and hence applied to a variety of function optimization, parameter estimation, and machine learning applications.

The canonical GA (CGA) as proposed by Holland follows the general algorithm as given in Fig. 3.15 with following implementation specifics [38].

```
                                        /*Algorithm GA */
formulate initial population
randomly initialize population
repeat
      evaluate objective function
      find fitness function
      apply genetic operators
            reproduction
            crossover
            mutation
until stopping criteria
```

Fig. 3.15 A simple canonical genetic algorithm [38]

- A bit string representation was used
- Proportional selection was used to select parents for recombination
- One – point crossover was used to select as the primary method to produce offspring
- Uniform mutation was proposed as a background operator of little importance.

Since the CGA, several variations of the GA have been developed that differ in representation scheme, selection operator, crossover operator, and mutation operator. Some implementations introduce other concepts from nature such as mass extinction, culling, population islands, amongst others [38].

3.6.3 GA Working Principals

Genetic algorithm starts working on a randomly generated set of solutions, known as initial population [54]. The flow chart illustrated in Fig.3.16 depicts GA procedures. Every step in this chart includes its own procedure that is described in details in the following items.

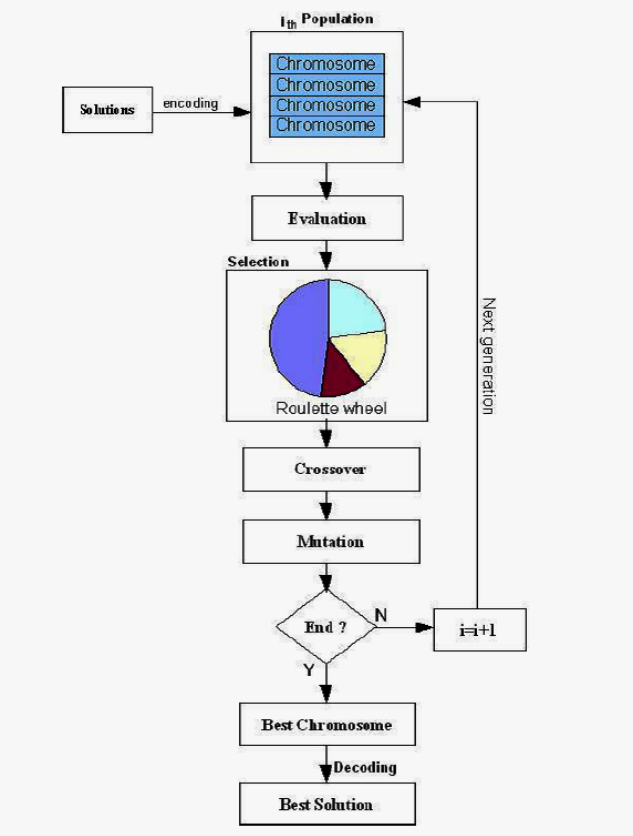


Fig. 3.16 Genetic algorithm flowchart [42]

3.6.3.1 Encoding

When we start to solve a problem with GA, encoding the solutions or chromosomes in the initial population is the first decision to be made [54]. The encoding of the chromosomes is the problem dependent. There are various

encoding schemes like binary encoding, permutation encoding, integer encoding, value encoding, and tree encoding [34, 54]. Among these types, binary encoding having 1's and 0's is mostly used [38, 42, 54, 66].

In order to illustrate the binary encoding method [66, 71], let us consider the simple function $f(x) = x^2$ to be optimized for the maximum value of x in the integer interval [0, 12], i.e. x = 0... 12. Because the maximum value of x is 12, and by using the binary coding, 4-bit strip is used to represent the integers, i.e. the chromosome length is 4. As 4-bit string can represent integers from 0 to 15, the strings (0000) and (1111) would represent the minimum and maximum values respectively.

Any other bit string can be found to represent a point in the search space according to a fixed mapping rule. Usually, the following linear mapping rule is used [54, 66, 71]

$$\boldsymbol{x_i = x_{min} + \frac{xmax - xmin}{2^n - 1} \sum_{j=0}^{n} \gamma_j 2^j} \qquad \textbf{(3.13)}$$

Where n is the length of string. In the above equation, the term $\sum_{j=0}^{n} \gamma_j 2^j$ is presented the decoded value of the string. For example, a four bit string (0111) has a decoded value equal to $((1)2^0 + (1)2^1 + (1)2^2 + (0)2^3)$ or 7 [66]. It is worthwhile to mention here that with four bits to code a variable, there are only 2^4 or 16 distinct or sub-strings possible because each bit-position can take a value either 0 or 1. The accuracy that can be obtained with a four bit coding is only approximately $1/16^{th}$ of the search space. The length of the sub-string varies with the desired precision of the results, the longer the string length, the more the accuracy.

3.6.3.2 Fitness Function

As mentioned earlier, GAs mimic the survival-of-the-fittest principle of nature to make a search process. Fitness in biological sense is a quality value which is a measure of reproduction efficiency of chromosomes [71]. In genetic algorithm, fitness is used to allocate reproductive traits to the individuals in the population and thus acts as some measure of goodness to be maximized. This means that individuals with higher fitness value will have higher probability of being selected as candidates for further examination.

For maximization problem, the fitness function can be considered to be the same as the objective function [54, 66]. For minimization problem, to generate non negative values in all the cases and to reflect the relative fitness of individual string, it is necessary to map the underlying natural objective function to fitness function form. The most common mapping function is adopted by

$$F(x) = \frac{1}{1+f(x)} \qquad (3.14)$$

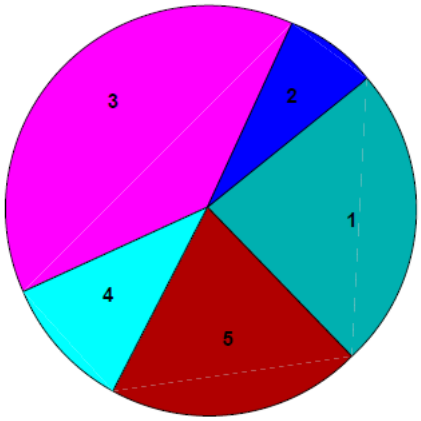
Where $f(x)$ is the objective function and $F(x)$ is the fitness function [66]. This transformation does not alter the location of the minimum, but converts a minimum problem to an equivalent maximization problem.

3.6.3.3 Reproduction and Selection

Reproduction or selection is an operator that makes more copies of better strings in a new population. Reproduction selects good strings in a population and forming a mating pool. Thus, in reproduction operation the process of natural selection causes those individuals that encode successful structures to produce copies more frequently [71]. There are a number of reproduction operators in GA literature, but the essential idea in all of them is that the above

average strings are picked from the current population and their multiple copies are inserted in the mating pool in probabilistic manner.

Roulette wheel selection is the commonly-used reproduction operator [38, 54, 66, 71]. Here; all chromosomes put in an imaginary roulette wheel where each chromosome in the population gets a place big on the wheel proportional to its fitness [34, 54]. Figure 3.17 shows a roulette wheel for five individuals having different fitness values. Since the third individual has higher fitness value than others, it is expected to be selected rather than others.



Population	Fitness
1	25.0
2	5.0
3	40.0
4	10.0
5	20.0

Fig. 3.17 A roulette wheel marked for five individuals according to their fitness values [66]

The typical procedures of roulette wheel are summarized in the following steps [54]

- Calculate the fitness for each input and put it and then represent it on the wheel in terms of percentages ($F_i / \sum Fi$)
- In search space *"n"*, spin the roulette wheel *"n"* times.
- Chromosomes with high fitness, will be selected

3.6.3.4 Crossover

A crossover operator is used to recombine two strings (parents) in order to produce new offspring (child). In crossover operation, recombination process

creates different individuals in the successive generations by combining two materials from individuals of previous generation [34, 54, 66, 71]. In order to preserve some of the good strings those are already present in the mating pool, not all strings in the mating pool are used for crossover. When a population probability is defined for any problem, only this probability, *pc*, is used for crossover and (1-p_c) will remain in the pool [38].

Crossover can be divided into three main categories based on the arity (i.e. number of used parents), *asexual*, *sexual*, and *multi-recombination* [38]. Asexual refer to only one parent is used; sexual means two parents are used, meanwhile multi-recombination means more than two. Indeed, most of the crossover operators for binary representations are sexual, being applied to two selected parents. Literature provides us with several crossover operators as shown in Fig. 3.18.

- **Uniform crossover:** uniform crossover operator decides with some probability (known as mixing ratio) which bits would contribute in swapping. For example if P = 0.5, then each bit has an equal chance to be swapped. Uniform crossover is illustrated in Fig. 3.18 (a) [38, 71].
- **One – point crossover:** A one point crossover operator is developed that randomly selects a crossover point and the strings after that point are swapped between the two parents. One – point crossover is illustrated in Fig.3.18 (b) [38]

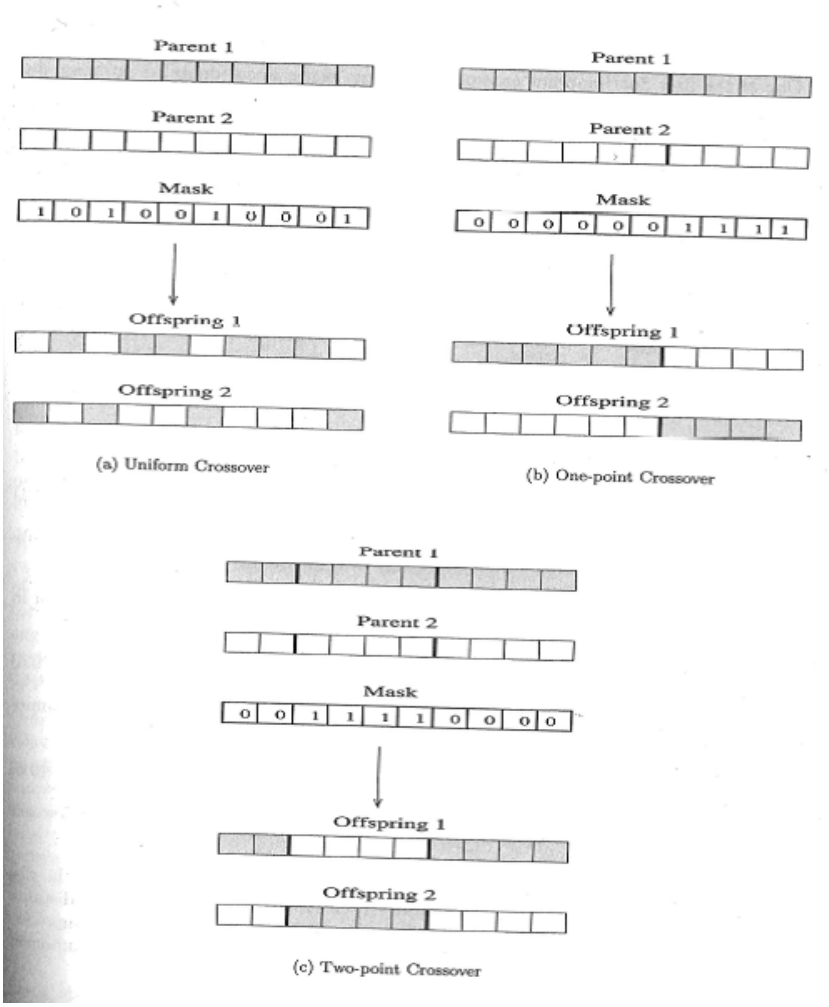


Fig. 3.18 Crossover operators for binary representations [38]

- **Two – point crossover:** In this case, two bit positions are randomly selected, and the strings between these points are swapped as illustrated in Fig. 3.18 (c) [38].

3.6.3.5 Mutation

The aim of mutation is to introduce new genetic material into an existing individual to add diversity to the genetic characteristics of the population [38]. Mutation is used in support of crossover to ensure that the full range of allele is accessible for each gene [34, 38, 66]. Figure 3.19 illustrates an example; we notice that underline bit in the right part is mutated from 1 to 0.

Fig. 3.19 Mutation operator example [54]

Mutation is applied at a certain probability, p_m, to each gene of the offspring, to produce the mutated offspring. The mutation probability, also referred to as the mutation rate, is usually a small value, $p_m \in [0, 1]$, to ensure that good solutions are not distorted too much [38, 54, 66, 71]. Given that each gene is mutated at probability p_m, the probability that an individual will be mutated is given by 3.15, where the individual contains n_x genes.

$$\textit{Prob } (x_i(t) \textit{ is mutated}) = 1 - (1 - p_m)^{nx} \qquad (3.15)$$

In summary, these three operators; reproduction, crossover, and mutation are simple and straightforward. The reproduction operator selects good strings and crossover operator recombines good sub-strings from good strings together, hopefully, to create a better sub-string. The mutation operator alters a string locally expecting a better string [66]. Figure 3.20 summarizes the application of the three operators in GA. Further insight into these operators, different ways of implementations some mathematical foundations of genetic algorithms can be obtained from GA literature.

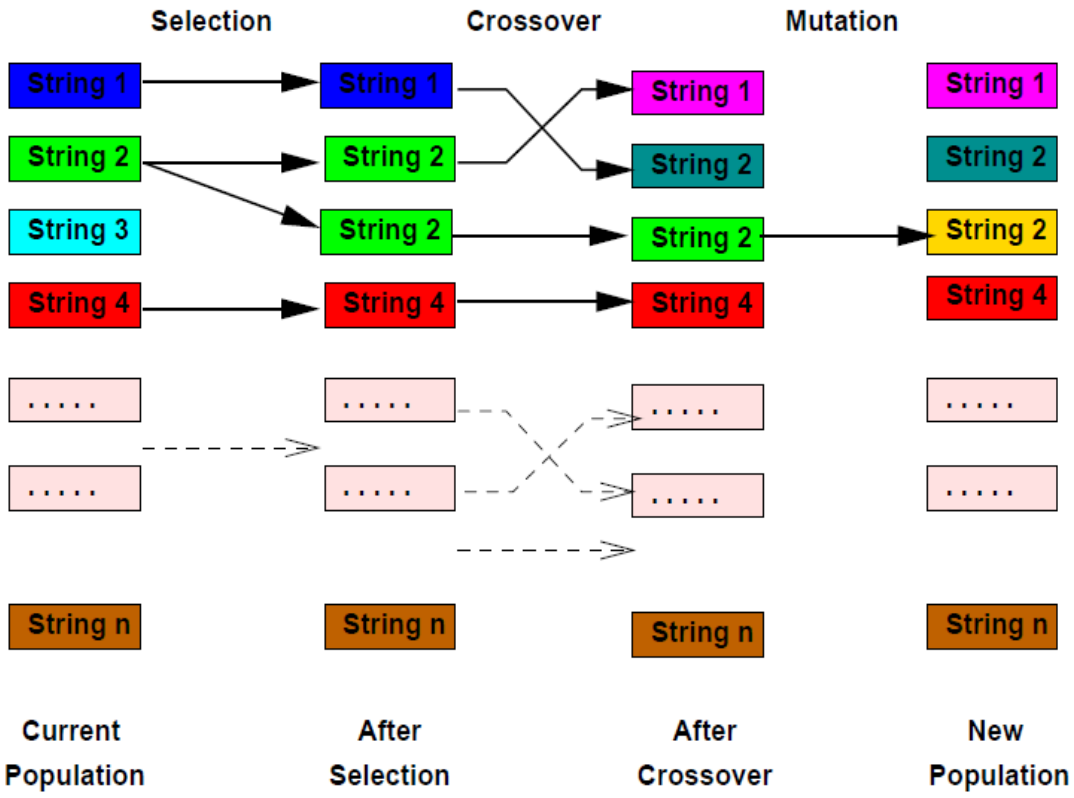


Fig. 3.20 Basic GA operators including selection, crossover, and mutation for generation of new population [71]

3.7 Process Modeling

Information systems have become a critical part of the infrastructure of most, if not all, business, government organizations, and even individual households. To be useful, an information system must integrate and align with the way the business conducts its operation. Be necessity this means that information systems construction requires an understanding of the organization's procedures, operations, and processes [95].

A process model is a visual representation of the sequential flow and control logic of a set of related activities or actions [95]. Process modeling is used to obtain a graphical representation of a current or future process within an organization. A model may be used as its highest level to obtain a general

understanding of a process or at a lower level as a basis for simulation so that the process can be made as efficient as possible.

Although standard notations are required for process modeling, there is no specific notation for graphical representation [95]. In essence, two main modeling languages are utilized, Unified Modeling Language (UML) and Business Process Modeling Notation (BPMN). BPMN emerged as an alternative standard at about the same time as UML. However, BPMN is purely for process modeling, it does not offer any support for modeling data, deliverables, roles, organizations, lifecycle states, or system. Classic flowchart is considered an alternative for both, although is somewhat outdated and does not provide the richness of either UML or BPMN. For more details on UML, refer to [9].

3.7.1 Process Modeling Elements

A process model is a collection of several interrelated models, diagrams, and narratives. Overall, a process model consists of a process synopsis, context model, work breakdown model, participant model, system model, deliverable model, domain data model, workflow model, business rule catalog, and a process narrative, see Fig. 3.21. It is worthwhile to mention that; process model minimally consists of a process synopsis, a participant model, and a workflow model. Any of the process model components represent either the current state *("as-is")* or the future state *("to-be")* [95]. Table 3.1 below provides a summary of the process model components, their intent, and need.

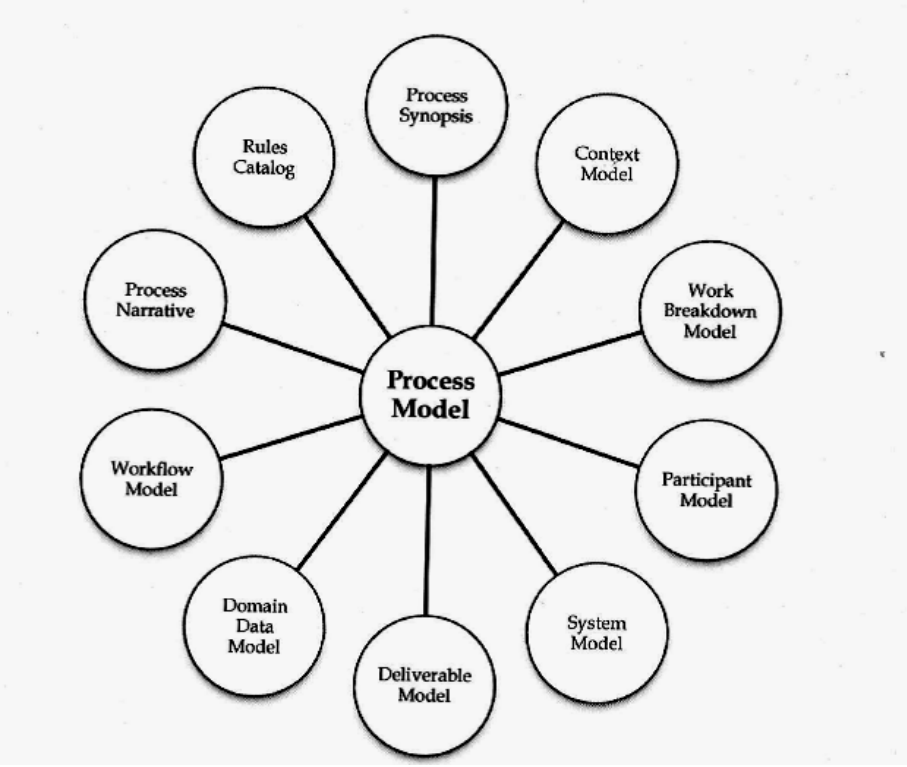


Fig. 3.21 Process model components [95]

Table 3.1 Process model components description [95]

Component	Type	Intent	Need
Process Synopsis	Diagram	Summarize participants, inputs, outputs, triggering event, and results for a process	Required
Context Model	Diagram	Summarizes participants ant their information inflows and outflows for a process	Optional
Work Breakdown	Diagram	Shows the hierarchical decomposition of the process into activities and sub-activities	Suggested
Participant Model	Diagram + Matrix	Describes the profile of all process participants and show their relations	Required
System Model	Diagram + Matrix	Describes the profile of all systems and shows their relationships	Suggested
Deliverable Model	Matrix	Describes the results produced by the processes	Suggested
Domain Data Model	Diagram + Matrix	Describes the information produced or consumed by a process and shows the relationships	Suggested
Workflow Model	Diagram	Describes the sequence of activities that make up a process	Required
Process Narrative	Narrative	Describe the process and its results in text	Suggested
Rules Catalog	Narrative	List of business rules and regulations that influence the process	Suggested

3.7.1.1 Process Synopsis

The overall process structure is illustrated in a high-level summary diagram called the process synopsis. The synopsis is exactly what is says: a summary of the process elements. It shows the event that starts the process, all of the inputs (data and materials), any outputs that it generates or transforms, all of the participants (people and systems), and the final result of the process. The result must be some product or service [95]. A schematic diagram for process synopsis is shown in Fig. 3.22.

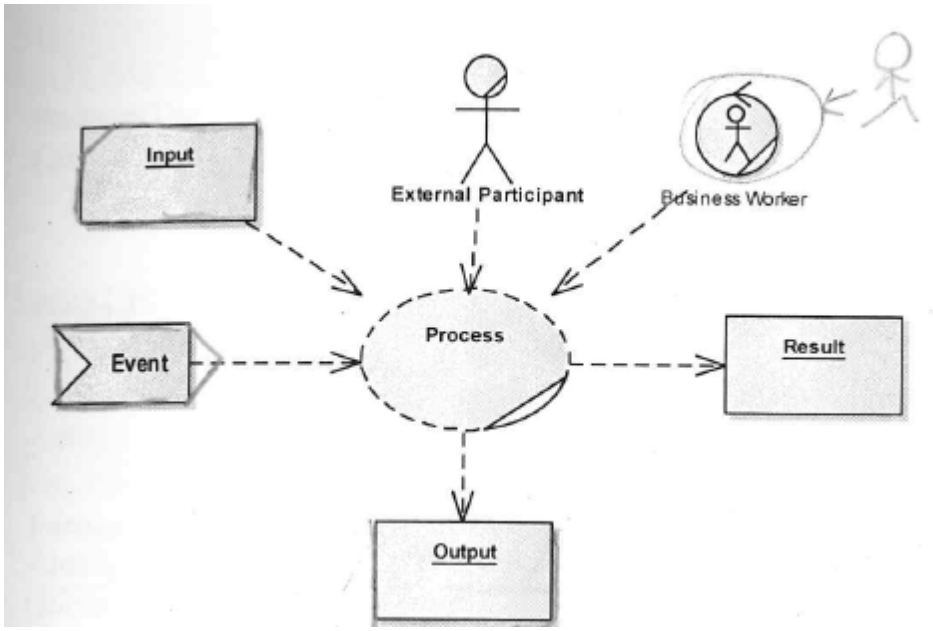


Fig. 3.22 Process synopsis with external and internal participants in UML [95]

The inputs, outputs, and the results are all modeled as objects with rectangle symbol, while the triggering event is an event element. Participants as modeled as business actors and the process itself are modeled as a collaboration with dashed circle. In fact, you can use any collection of symbols as long as you are consistent and the stakeholders clearly understand their semantics. Be sure to provide a legend or a guide to the notation you are using. We can use

business actors and business workers to visually differentiate between external and internal process participants as shown in Fig. 3.22 [95].

3.7.1.2 Process Workflow

A workflow is an essential technique in representing the activities of a process to be modeled. A workflow model is a visual representation of the flow of the work [95]. Indeed, each step in the process is described as an activity, if an activity cannot be further decomposed it is actually termed an action. In general, to be able to draw a workflow model, four important configurations should be presented in the model.

- **Representing activities:** usually each activity is described with a verb-phrase, e.g. "print request form". An activity representing a task to be carried out by one workflow participant is graphically presented as a round corner rectangle as shown in Fig. 3.23. Sequencing of activities is indicated with control flows (edges). You should only have one input and output flow per activity; use merges and join when combining multiple control flows [95].

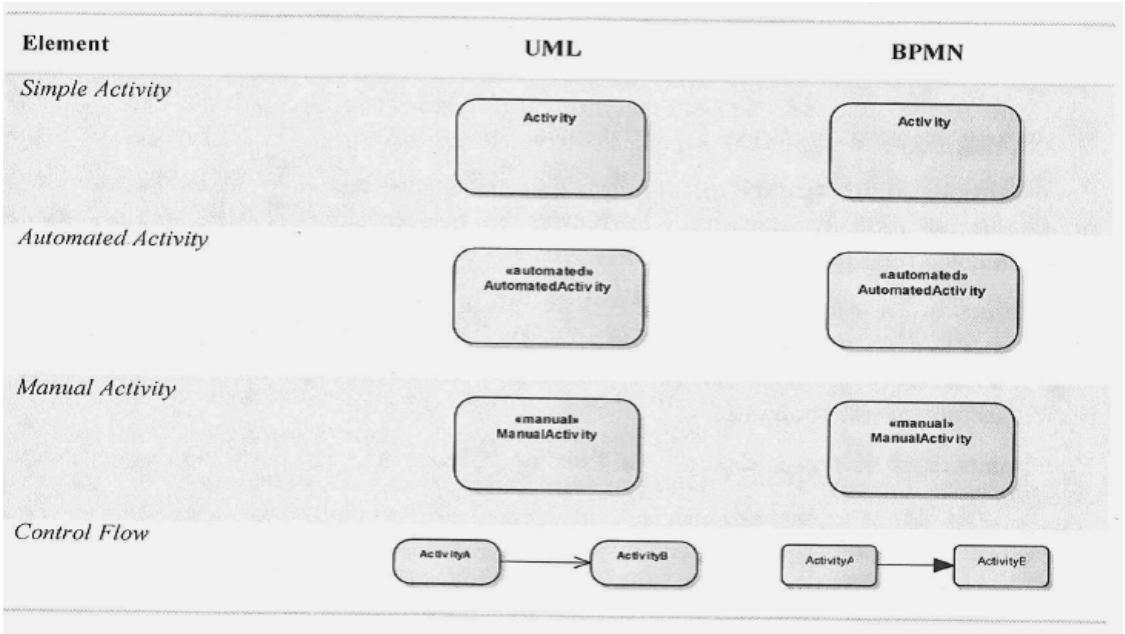


Fig. 3.23 Activity presentation and control symbols in workflow model [95]

- **Indication process start and end:** The start (source) of a process and the ends (sinks) of a process must be clearly indicated. There can only be one start for each process, but there may be multiple ends. The symbols of starting and ending activities are illustrated in Fig. 3.24.

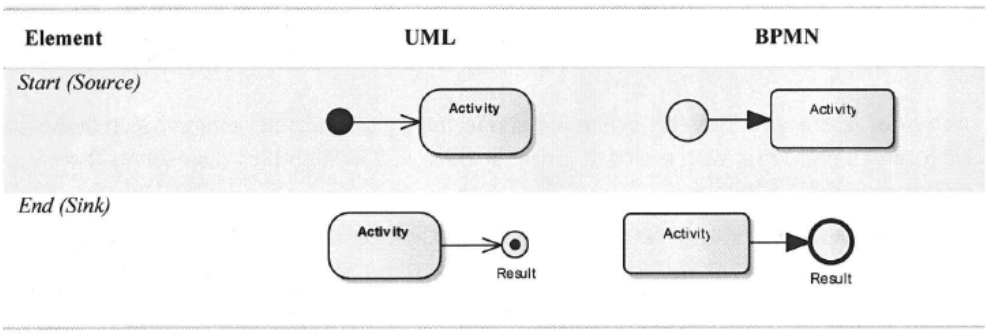


Fig. 3.24 Process terminal in workflow model [95]

- **Showing pre- and post-conditions:** pre-conditions summarize the assumptions that the process designer makes. Furthermore, pre-conditions indicate constraints that must be true in order for the process to be completed successfully. The representation of these conditions is shown in Fig. 3.25.

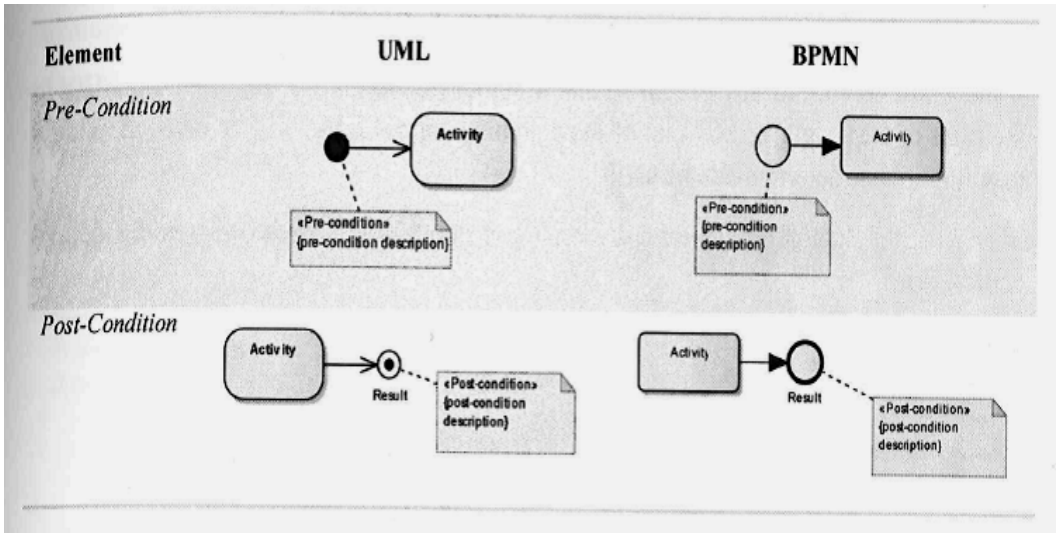


Fig. 3.25 Pre- and post- conditions representation in workflow modeling [95]

- **Workflow divergence**: Many times during a workflow, some condition may occur that causes the flow to branch and different activities are carried out in response to the outcome of the condition. A decision is shown graphically with a diamond shaped icon from which at least two control flows emanate. The approach differs from classical flowchart where the decision is followed either with *"yes"* or *"no"*. The approach makes it possible to have more than two outgoing control flows from a decision. Workflow divergence is presented in Fig. 3.26. The labels on the outgoing control flows are called guard conditions and are placed into a pair of square brackets (' […]') in UML language only. There is no prescriptive format for the writing of the guard conditions. Also, for this kind of implementation, [2] could be helpful to develop such models based on Petri Nets as it is used in our thesis.

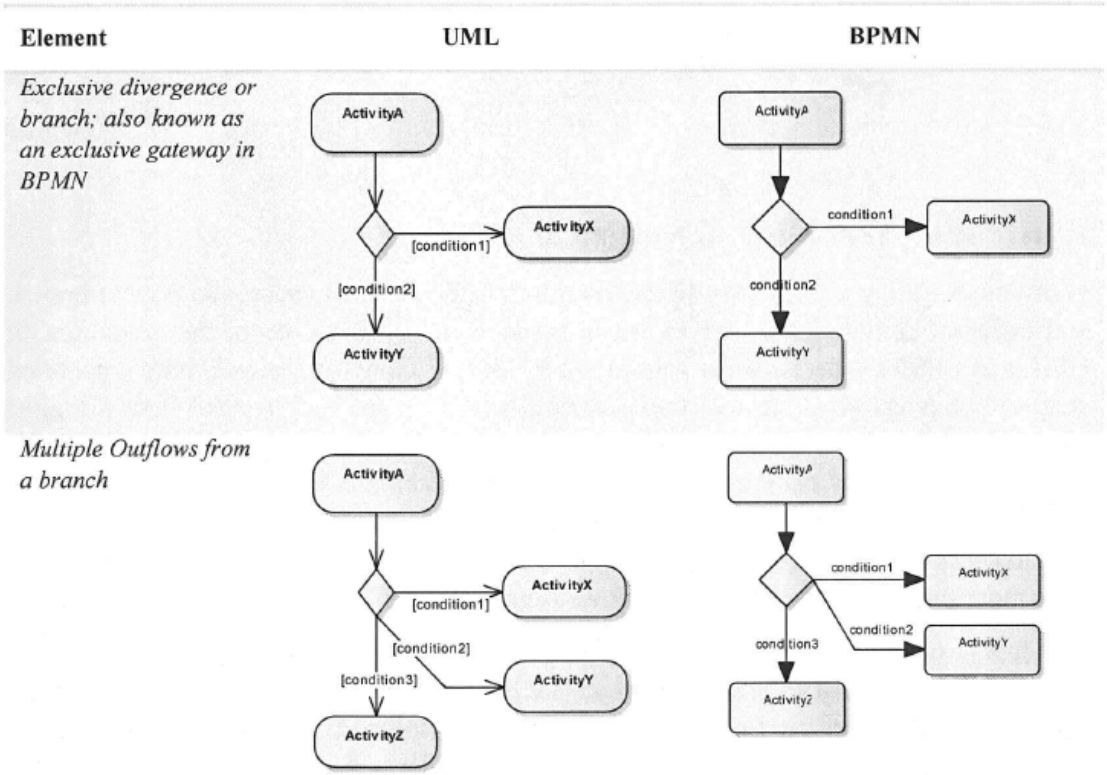


Fig. 3.26 Divergence symbols of activities in workflow model [95]

Chapter 4

Prioritization of Purchasing Requests of Medical Equipment

4.1Chapter Outlines

This chapter aims to solve the problem of how to give a reasonable priority for a purchasing request of new medical equipment among a range of purchasing requests in public hospital. The problem definition and motivations are given in section 4.2. In section 4.3, a survey of literature review belonging to purchasing medical equipment is provided. The proposed methodology that combines the quality function deployment with fuzzy logic in one framework is presented in section 4.4, revealing the important criteria that are considered in every model and how every model is constructed as well as the integration between the two proposed models. The model verification through application of data set in a public hospital and results of implementation are given in section 4.5. Finally, the chapter conclusions are presented in section 4.6.

4.2 Problem Definition

Despite the fast medical technology development worldwide, today's hard economical conditions have imposed restrictions on the procurement of medical equipment; consequently, the resources should be allocated carefully. Public hospitals are the foundations that are directly affected from these circumstances, usually work with limited resources. In management stages, the acquisition process including purchasing medical equipment is considered one of most important decisions that more attention should be given in resource allocation.

Considering the acquisition process, it is clear that if equipment purchase is realized without making an evaluation of requirements and getting cooperation of the hospital management, then the purchasing items could be so far from meeting the hospitals real need [57]. Moreover, traditionally, the decision to use a new technology is based on the desires of the physicians and the added benefit to patient care, with its financial impact often a secondary consideration [79].

Improper purchasing activities in hospitals can lead to serious consequences which include lack of inventory control, missed contract compliance, excess inventory levels, frequent stock-outs, workflow interruptions and expensive rework, and increased health system labor requirements [57]. Therefore to prevent such problems, it is essential to have a systematic and a comprehensive acquisition program to improve the purchasing process.

It is worthwhile to mention that to avoid such problems in purchasing medical equipment; a reasonable priority should be given to purchasing requests considering a range of criteria that influence purchasing process. Typically, the purchasing process in public hospitals is a series of actions and activities that should be precisely implemented. Regarding our prospective for purchasing process of medical equipment, the synopsis diagram of this process

is shown in Fig. 4.1 in terms of the participants, input, trigger event, output, and result. In addition, the workflow diagram that describes the common major activities of purchasing process is illustrated in Fig. 4.2. According to our task in this thesis, we handle only the activities shown in red color.

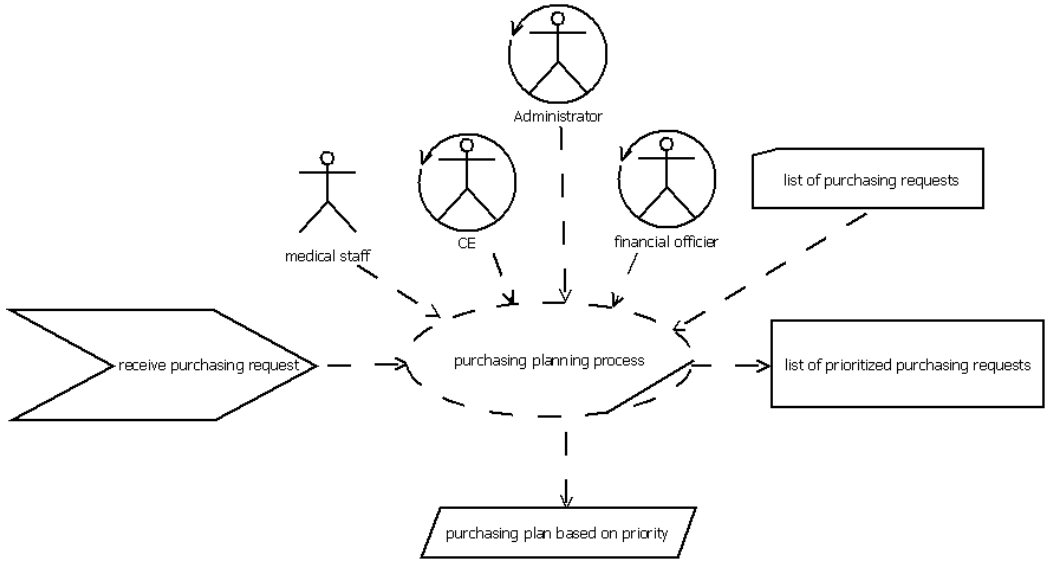


Fig. 4.1 Synopsis diagram of purchasing process of medical equipment

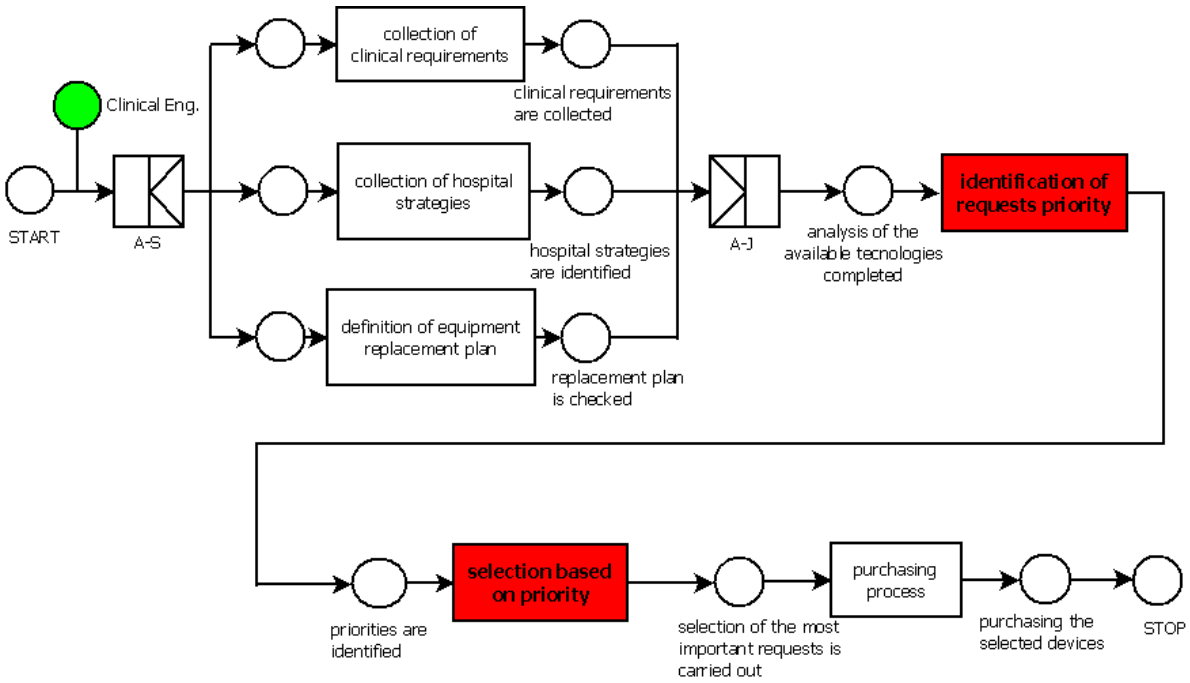


Fig. 4.2 Workflow diagram of purchasing process describing the major activities.

4.3 Literature Review

Healthcare industry is known for its continued innovation and production of new devices and techniques intended to improve the delivery and outcome of patient care. As new technologies enter the market, hospitals and physicians must determine which of these new devices they should incorporate into practice [79]. Funding constraint is considered the master key to evaluate incorporation of new technology to healthcare service. Thus, more attention should be given to purchasing process regarding both of healthcare delivery outcomes and funding availability.

In general, purchasing process of medical equipment is not widely covered in literature. Few studies were conducted regarding this issue. One study revealed that the necessity of developing a five year equipment replacement and procurement model to predict required funding levels [13]. In procurement process, the researchers suggested that no single centralized purchasing option would suit the wide range of medical equipment items that need to be purchased annually according to the five year equipment acquisition and replacement plan. Hence, the research proposed five possible options that can be considered in relation to the various types of equipment. The proposed purchasing options are *status quo position*, *ad hoc purchasing groups*, *centrally negotiated contracts, preferred suppliers*, and *centralized purchasing body*.

Another study was implemented to derive a value - based model for purchasing medical equipment [79]. The authors proposed a physician-driven committee that standardized and utilized evidence-based and financially responsible methods for introducing new devices and technology for patient care. The authors handled four challenges that could impact purchasing process with respect to the perspectives of physicians. The challenges include lack of alignment of incentives, physician industry relationships, lack of price transparency, and new technologies that do not result in clinical improvement.

Human factors engineering was conducted by *Ginsburg* to inform hospital procurement decision-making in selecting a general- purpose infusion pump [40]. Two phases of the human factors evaluation of the infusion pumps were conducted. The first phase involved a heuristic evaluation of each pump according to four sets of criteria. The second phase of the human factors evaluation consisted of user testing in which the Human Factors Engineer visited different clinical areas with the pumps and observed users as they performed realistic clinical scenarios with each infusion pump. For model validation, a comparison between three vendors was performed based on the two stages to select the best vendor.

Another approach was developed to improve purchasing process in public hospitals by integrating Fuzzy logic with Failure Modes and Effect Analysis (FMEA) [57]. In this research, the authors identified the purchasing process of medical equipment through five stages; planning, assessment, acquisition, contract preparation, and contract award. These stages were identified in terms of 17 actions that should be carried out. FMEA was used to calculate the risk priority number (RPN) to each action to determine failure prioritization. Then, RPN was recalculated by fuzzy logic to reproduce a new prioritization list in order to enhance the whole purchasing process.

On the other hand, another research tries to indicate a policy that give priorities for patients and services including public purchasing in public health sector in New Zealand [44] especially after implementing it in private sector. In order to set service priorities, a methodology was proposed centered around five principles: effectiveness, cost, equity f outcome, Maori health and acceptability. It utilizes a framework known as Program Budgeting Marginal Analysis (PBMA) which examines whether a marginal change in expenditure on one service would be effective, equitable, and acceptable relative to its opportunity cost. The framework proposed that, where possible, the effectiveness of services should be assessed in terms of the common currency quality-adjusted life years.

By regarding such literature, we can easily reveal that developing a priority index that could prioritize purchasing requests of medical equipment considering the beneficial impact on healthcare delivery as well as the limited resources is relatively absent. Therefore, our goal is to generate a priority index for all purchasing requests of medical equipment in different departments at the hospital in a consistent way.

4.4 Methodology

Our task in purchasing stage is to develop a realistic prioritization model that provide the purchasing requests a suitable priority regarding a set of technical, financial, and administrative criteria, which guarantee the cooperation between the decision makers in order to enhance the overall purchasing process. The methodology adopted in this issue combines the quality function deployment and fuzzy logic in one framework as shown in Fig. 4.3.

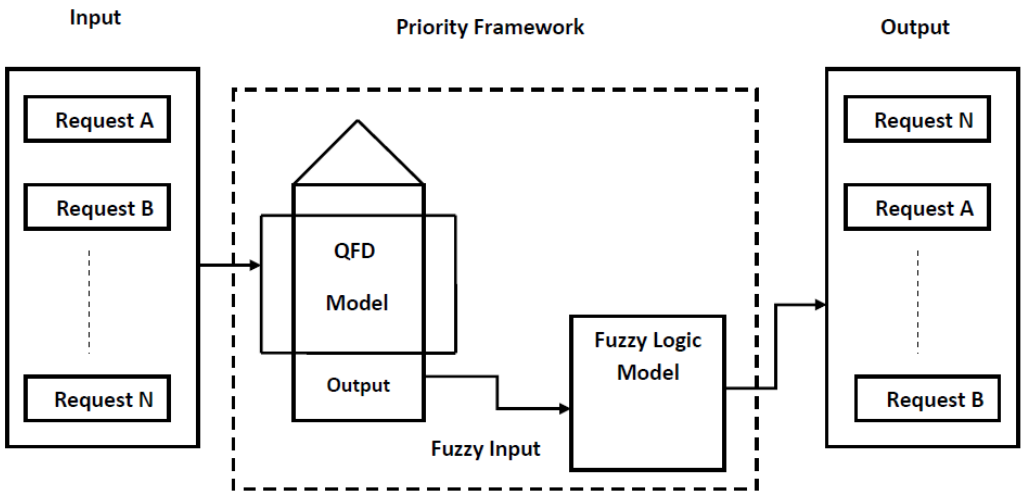


Fig. 4.3 Proposed framework of QFD-Fuzzy logic model for prioritization of purchasing requests of medical equipment

Quality function deployment has proven its validity in prioritization process [92, 93]; moreover it is considered a planning technique for assuring quality in any process. In addition, fuzzy logic offers a realistic framework for

human reasoning by adopting human way of thinking. Accordingly, we decided to integrate both of them in one framework in order to generate a prioritization index for purchasing requests of medical equipment. As shown in Fig. 4.3, the input of the proposed model is a list of purchasing requests, and the output of the model is the same list of those requests but with a prioritized ranking. The target of QFD model is to select the important criteria for prioritization process; whereas the purpose of fuzzy logic model is to classify the requests priority taking into account the selected criteria.

4.4.1 Quality Function Deployment Model

Quality function deployment is a methodology that links any organization with its customers in order to recognize their requirements and at the same time tries to satisfy them by developing technical specifications that meet these requirements [117]. Recent attempts to apply quality function deployment principles to the healthcare sector concentrated upon gaining deeper understanding and analysis of customer needs. The quality function deployment methodology has few applications in medical equipment management field.

In our case, we need to identify a priority index for purchasing requests in public hospitals based on a set of criteria. The house of quality is employed to build the base of priority index by selecting the most important criteria. Firstly, we need to identify in this case, the voice of customers (WHATs), and the voice of technicians (HOWs). The customers here are considered the clinical staff that is responsible to ask purchasing new equipment. On the other hand, the technical specifications are the required criteria meeting customer needs in order to rank requests by reaffirming clinical needs and the intended applications. Often, three entities could develop those criteria; clinical engineering department, financial department, and the general administration of the hospital [43].

4.4.1.1 Customer Requirements

Typically, the requests for purchasing medical equipment could be addressed in terms of needs and benefits [16]. Usually needs identification starts from the users of technology such as medical staff including physicians and nurses. The next task is to outline the benefits of clinical requirements based on the identified needs. To recognize the needs and benefits of customer requirements, several scenarios are put forward, either by elicitation through questionnaire and/or literature or experience. In our case, the experience and literature are the source of knowledge.

The needs of customer requirements may be one or a combination of the following; *required services, new service, improve service efficiency, improve clinical outcomes, improve research outcomes, and meet minimum standards*. On the other hands, the benefits of customer requirements may include *reduce operating costs, increase cost benefits, reduce patient stay length, reduce risk, reduce patient waiting list, standardization, quality assurance, and finally facilitate replacement procedures.*

4.4.1.2 Technical Requirements

To satisfy the customer requirements in purchasing process, cooperation should be existed between clinical engineering department and financial department from one side and general administration of the hospital from the other side. Hence, the requirements could be categorized into three sub-categories depending on the department as technical, financial, and administrative. The proposed technical characteristics are listed in Table 4.1 with a brief description for every criterion. In particular, six criteria are related to the technical criteria, other four criteria are referred to financial criteria, and seven criteria belonging to administrative criteria, thus, we have a total of seventeen criteria that should be selected among the most important criteria.

Table 4.1 Technical characteristics of the proposed QFD for prioritization purchasing process.

Class	Criterion	Description
Technical	Technology assessment.	Evaluation of technology baseline in terms of survey and benefits [36]
	Installation requirements.	All required utilities, e.g. electricity, ventilation, etc.
	Risk evaluation	The associated risk in case of none purchasing.
	Life expectancy	The expected life for the new device.
	Replacement list.	Checking the replacement list to evaluate the actual need.
	Equipment inventory.	Referring to information that already exists for similar devices.
Financial	Available budget	Checking funding for purchasing.
	Acquisition method	Type of procurement; purchasing; loan, lease.
	Life cycle cost analysis	Analysis of all expenditures including operation and service costs.
	Gain new revenue	Checking availability of gaining revenue in case of purchasing.
Administrative	Service assessment	The impact of service on healthcare delivery and outcomes.
	Qualified users	Availability of qualified users.
	Area expansion	The impact of expansion of utilization area on outcomes.
	Service sharing	Checking the availability of sharing the intended service with other departments.
	Area criticality	Assessment of area criticality for patients.
	Utilization level	Evaluation of working load.
	Regularly compliance	Checking whether a specific standard needed to be met or no.

4.4.1.3 Planning Matrix

The planning matrix is a tool used to help the management team to systematically re-prioritize customer needs. In this matrix, in order to reprioritize the customer requirements, a comparison between two requests should be performed. We assumed that we have request A versus request B to determine the important benchmarking points with respect to B. The planning matrix is presented in far right of HOQ using a 5 point scale for evaluation and the steps mentioned in section 3.3.3.3.

For instance, considering the first customer requirements *"needed service"*, the improvement ratio is calculated by dividing the goal score to request B i.e. 5/3 = 1.7, and the absolute weight is calculated by multiplying improvement ratio by importance factor i.e. 1.7 x 5= 8.3. The relative weight percentage for each requirement is calculated by normalizing the absolute weight, i.e. (8.3 / 95.7) *100 = 8.71 as shown in Fig. 4.4. By analysis, we found that the top priorities came to *providing new service*, and then some criteria like *provide needed service* and *reduce risk* came with the same priority level. In sense, customer requirements ranking is suited to the reality.

4.4.1.4 Relationship Matrix

The relationship matrix portrays the link between customer requirements and technical requirements in terms of scores that impact the degree of correlation between both of them. Usually *Cohen* scale is used for presenting the relationship scores between WHATs and HOWs [26] as 9 for strongly linked, 3 for moderately linked, 1 for low link, and blank cell for no relationship.

4.4.1.5 Technical Target Matrix

The goal of target matrix is to prioritize the technical characteristics considering the resultant prioritized customer requirements of the planning matrix. In fact, this matrix is considered the design matrix since it distinguishes important criteria that the designer should consider in designing phase.

Comparing this concept with our case, we can easily realize the role of this matrix in our problem. The results of this matrix are absolute weight and relative weight that conclude the influencing criteria in determining the priority of purchasing requests.

The absolute weight is the total summation of multiplication of the relative weight of planning matrix by each technical characteristic relationship score. For example, if we consider the first technical characteristic "technology assessment", the absolute weight equals 9 x 8.71 + 9 x 12.5 + 3 x 8.71 + 1 x 7.02 + 3 x 6.2 + 1 x 4.18 + 9 x 8.71 + 1 x 6.97 + 9 x 8.71 + 3 x 6.27 + 9 x 8.71= 508. The relative weight percentage is calculated by normalizing the absolute weight i.e. the relative weight of physical risk is (508/ 5333) *100 = 9.5. The proposed HOQ model is shown in Fig. 4.4 presenting overall matrix including all the previous matrices as explained above.

According to the resultant characteristics (output of HOQ), we suggested all criteria that are greater than 6.5 % are considered the most important criteria. This implies that the top criteria based on this threshold yields only five criteria among seventeen criteria to be included for the second stage of the proposed framework. The criteria are *service assessment*, *technology assessment*, *risk evaluation*, *available budget*, and *life cycle costs*. Thus, these five outputs of HOQ are the input of the cascaded model, fuzzy logic in the second stage.

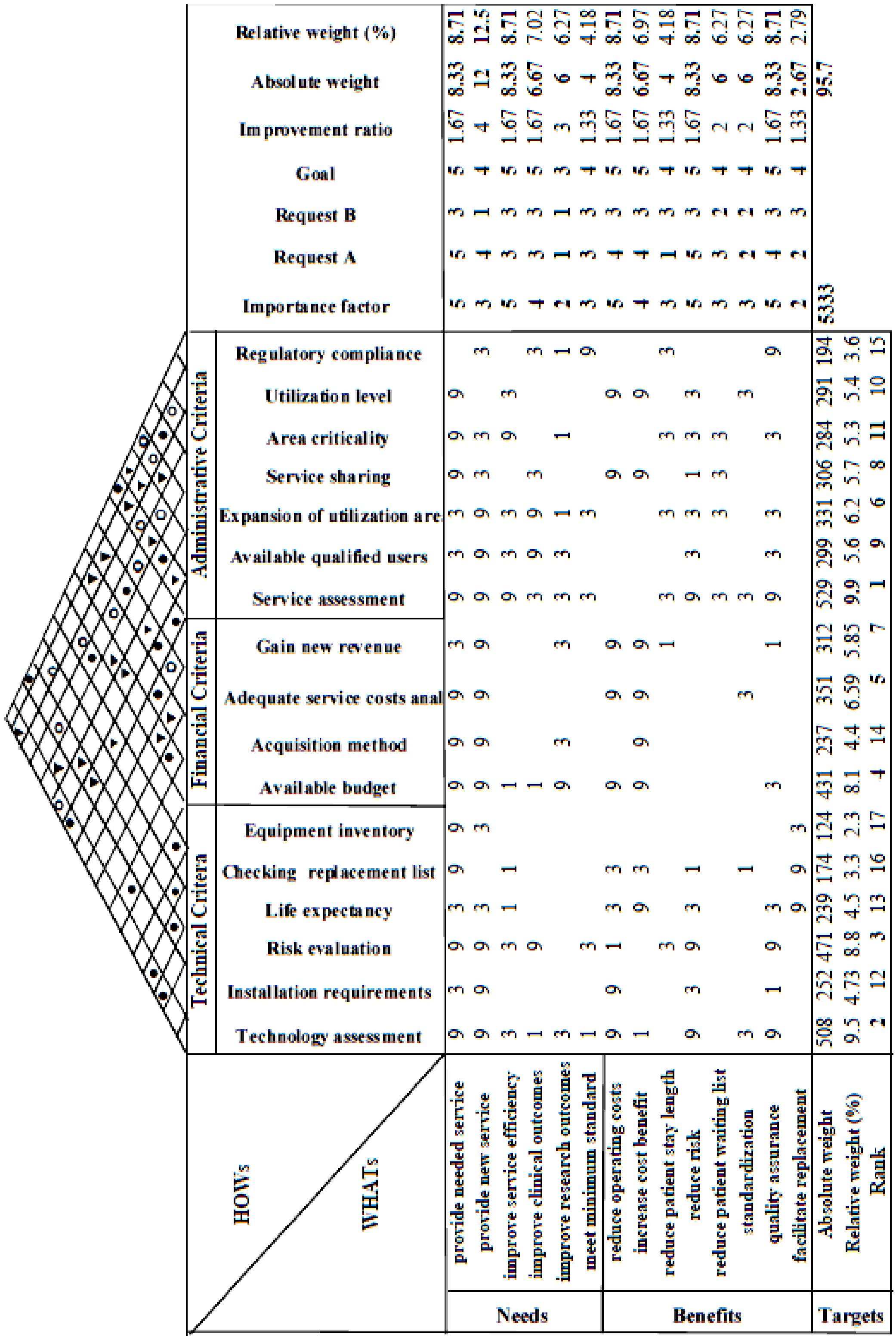


Fig. 4.4 Proposed HOQ matrix for identifying important criteria for prioritization of medical equipment purchasing requests

4.4.2 Fuzzy Logic Model

Fuzzy logic (FL) was successfully applied in a wide range of fields such as automatic control, expert systems, system identification, and time-series prediction [107]. In this study, the task of fuzzy logic is to prioritize the purchasing requests considering the five most important criteria of QFD model. Therefore, the proposed FL model has five inputs; service assessment, technology assessment, risk evaluation, available budget, and life cycle cost analysis.

A MATLAB Fuzzy Logic Toolbox graphical user interface (GUI) tools was used to build a software module for a classification of purchasing requests of medical equipment. Five primary GUI tools are available for building, editing, and observing fuzzy inference systems in the aforementioned toolbox [107]:

- Fuzzy inference system editor
- Membership function editor
- Rule editor
- Rule viewer
- Surface viewer

4.4.2.1 Fuzzy Inference System

Fuzzy inference system (FIS) displays information about the system; also it is used to handle high level issues of the system with no limit for inputs [1]. In this case, FIS displays five inputs and one output as shown in Fig. 4.5. The five inputs of FIS are called service, technology, risk, budget, costs analysis respectively; meanwhile, the name of the output is called priority. The type of inference method used in this fuzzy analysis is Mamdani. The MATLAB toolbox provides the flexibility to add, to modify, and to delete the inputs and the outputs of any system.

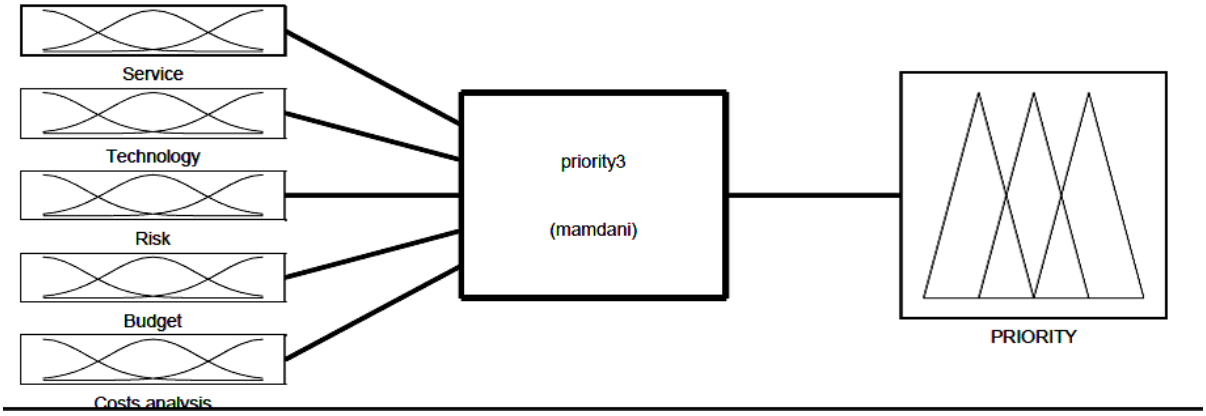


Fig. 4.5 Proposed FIS model with five inputs and one output for priority index of purchasing requests of medical equipment

4.4.2.2 Membership Function

The membership function editor is a tool that lets the user displays and edits all of the membership functions associated with all of the input and output variables for the entire fuzzy interference system [1]. The membership function associated with each input or output should be set up according to the proposed linguistic terms for every variable. In our case, we have five inputs and one output, so every variable has its own membership function. *Trapezoidal* membership function is selected for all inputs, whereas *triangular* membership function is selected for output. The membership functions for input parameter, namely, "*Risk*" and the output variable "*PRIORITY*" are shown in Fig. 4.6 and Fig. 4.7 respectively. Table 4.2 summarizes the proposed linguistic terms for the inputs and the output of the proposed FL model.

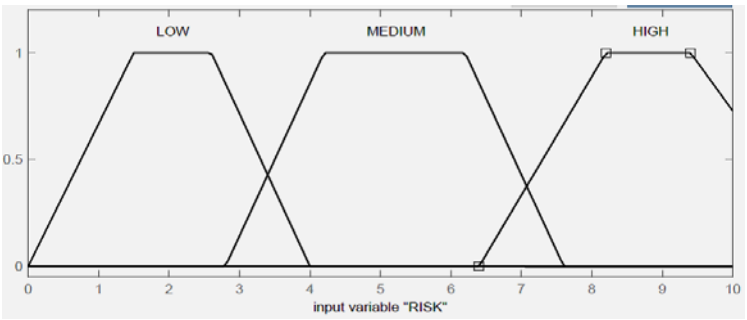


Fig. 4.6 Membership function of FL input parameter, namely, "risk"

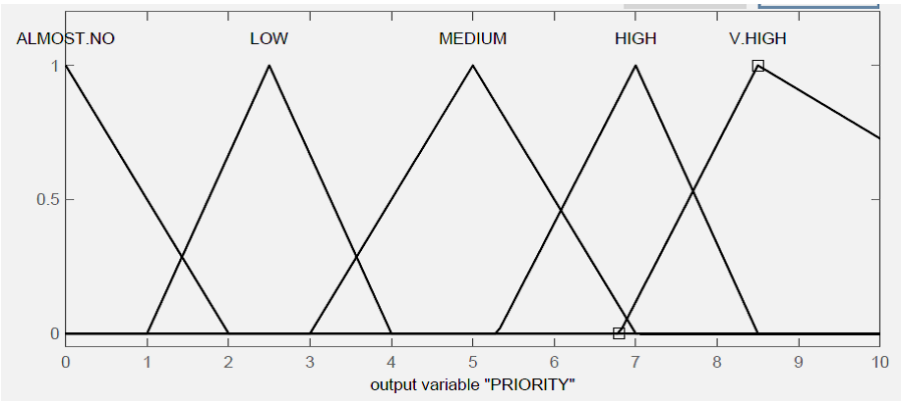


Fig. 4.7 Membership function of the output variable "priority" of FL model

Table 4.2 Linguistic terms summary of proposed FL model inputs and output

No	Parameter	Type	Linguistic terms
1	**Service**	Input	Low
			Medium
			High
2	**Technology**	Input	Poor
			Good
			Very good
3	**Risk**	Input	Low
			Medium
			High
4	**Budget**	Input	Not available
			Donation
			Available
5	**Cost analysis**	Input	Low
			Medium
			High
6	**Priority**	Output	Almost No
			Low
			Medium
			High
			Very high

4.4.2.3 Rule Editor

Based on the description of the input and output variables defined with FIS editor, the rule editor allows to construct the rule statement automatically [1] using the rule IF-THEN, implementing AND-OR operators. Considering the

input and output parameters of our FL model, we proposed 30 IF-THEN rules depending on our experience to classify the purchasing requests priority into *five* classes; *very high*, *high*, *medium*, *low*, and *almost no*. For example, IF service is *high*, AND technology is *very good*, AND risk is *high*, AND budget is *available*, AND life cycle costs are *low* THEN priority is *very high*. For more details of the proposed rules refer to *Appendix A*.

4.4.2.4 Rule Viewer

The rule viewer displays a roadmap of the whole fuzzy inference process and thus allows for the interpretation of the entire FIS [1]. It is based on the previous sections of FL. Figure 4.8 depicts the rule viewer of the proposed FL model. Each row in the figure presents a rule, while each column presents a variable including inputs and output.

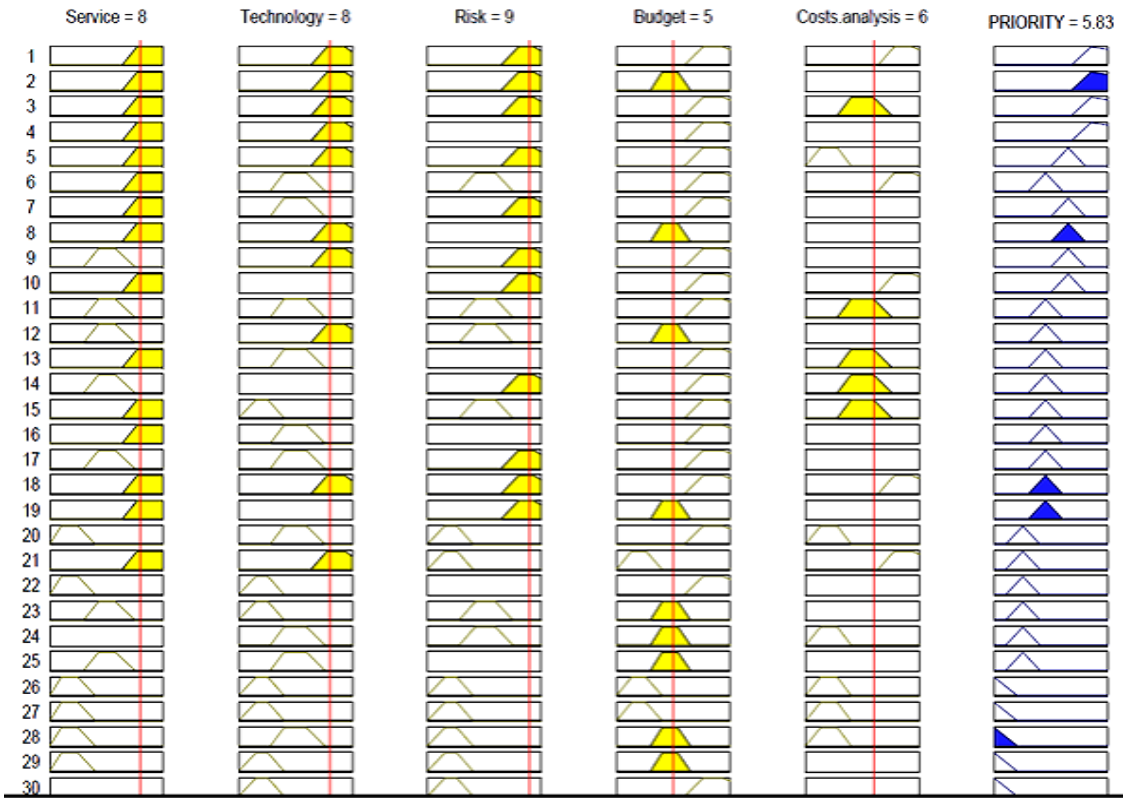


Fig. 4.8 Rule viewer display of the proposed FL model, illustrating five plots of inputs and one plot of the output in terms of proposed rules.

4.4.2.5 Surface Viewer

Surface viewer is a 3 dimensional curve that maps the relationship between inputs and outputs and allows for the comparison between the selected rules and the discussed human's opinion [107]. In our case, we have five inputs and one output, therefore, the graph presents different pairs of input against the output. When a pair of inputs is presented on a curve, the others assumed to be constant [1]. The surface viewer curve shown in Fig. 4.9 shows the relationship between priory and two inputs of the proposed model, namely, service and technology.

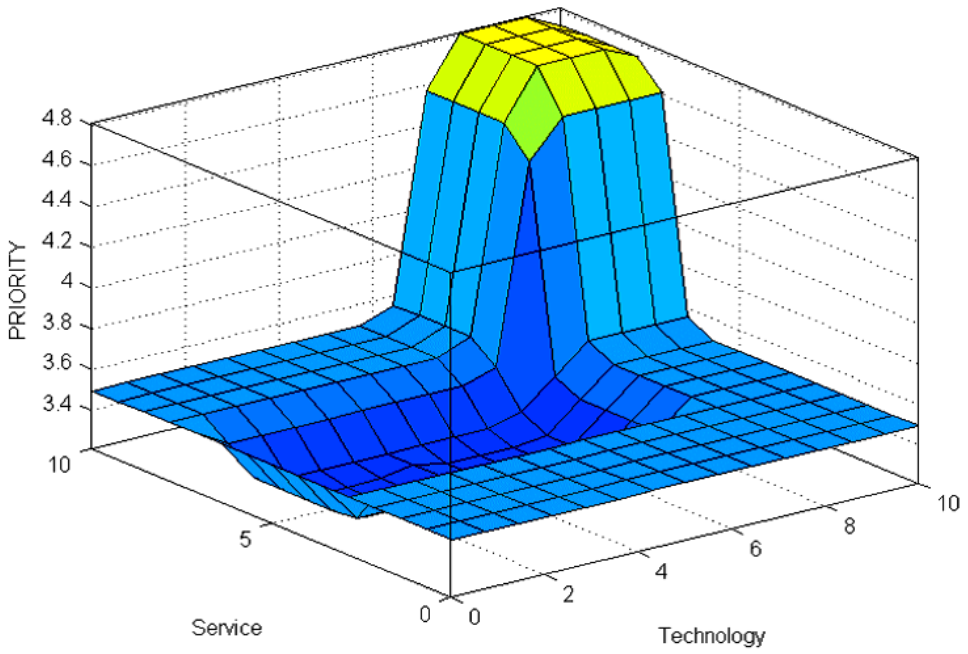


Fig. 4.9 Surface view curve portrays the relationship between priority and two inputs of the model, namely, service and technology.

4.5 Results

The framework containing both of QFD and FL models is proposed to derive a priority index for purchasing requests of medical equipment in public hospitals to improve the procurement process. The model was tested on a list of *twenty* requests of purchasing medical equipment in a public hospital in Egypt. The

requests were collected from different departments in the hospital considering one or a combination of needs and benefits indicated in QFD model. The list of purchasing requests contained a wide range of medical equipment varied between sophisticated devices such as echocardiography and simple devices such as sphygmomanometer. In order to facilitate the output ranking, we coded the requests alphabetically from A to T.

By utilizing the proposed model with its two stages; QFD and FL models, the list of twenty purchasing requests is prioritized. Table 4.3 shows the purchasing requests with its resultant priority index supported by expert's opinion in evaluating the five inputs of FL model.

Table 4.3 Output priority of purchasing requests of medical equipment

Department	Equipment (request)	Fuzzy score	Priority	Rank
Radiology	Echocardiography (K)	7.08	V. High	1
Operations	Anesthesia machine (M)	6.99	V. High	2
Emergency	Defibrillator (U)	5.83	High	3
NICU	Infant incubator (A)	5.10	High	4
ICU	Ventilator (T)	5.04	High	5
ICU	Advanced monitor (L)	4.80	Medium	6
Labs	Spectrophotometer (R)	4.44	Medium	7
NICU	Portable infant incubator (B)	4.23	Medium	8
CCU	Mobile X-ray unit (S)	3.61	Medium	9
Labs	Refrigerated centrifuge (D)	3.50	Medium	10
NICU	Basic monitor (C)	3.34	Low	11
ICU	Electrical bed (P)	3.31	Low	12
Inpatients	ECG (G)	3.23	Low	13
Labs	Plasma deep freezer (E)	3.19	Low	14
Inpatients	Syringe pump (I)	3.10	Low	15
Labs	Lab incubator (F)	3.05	Low	16
Inpatients	Infusion pump (J)	2.89	Low	17
Inpatients	Pulse oximeter (H)	2.77	Low	18
Operations	Stretcher (N)	0.881	Almost No	19
Urology	Sphygmomanometer (O)	0.633	Almost No	20

By analyzing the data set of purchasing requests as the results yielded in Table 4.3, we found that 10% of requests come as very high priority , which means should be purchased immediately, 15 % is included as high priority meaning that their purchasing procedures should be started as soon as possible, whereas 25% should be considered as medium priority, which implies their purchasing depending on urgent need and funding availability, 40% is estimated as low priority, i.e. only considering the essential devices that have a direct impact on healthcare delivery, and finally 10 % comes as almost No in case of no need for purchasing. Figure 4.10 illustrates the priorities ranking orders of purchasing requests by utilizing the proposed framework.

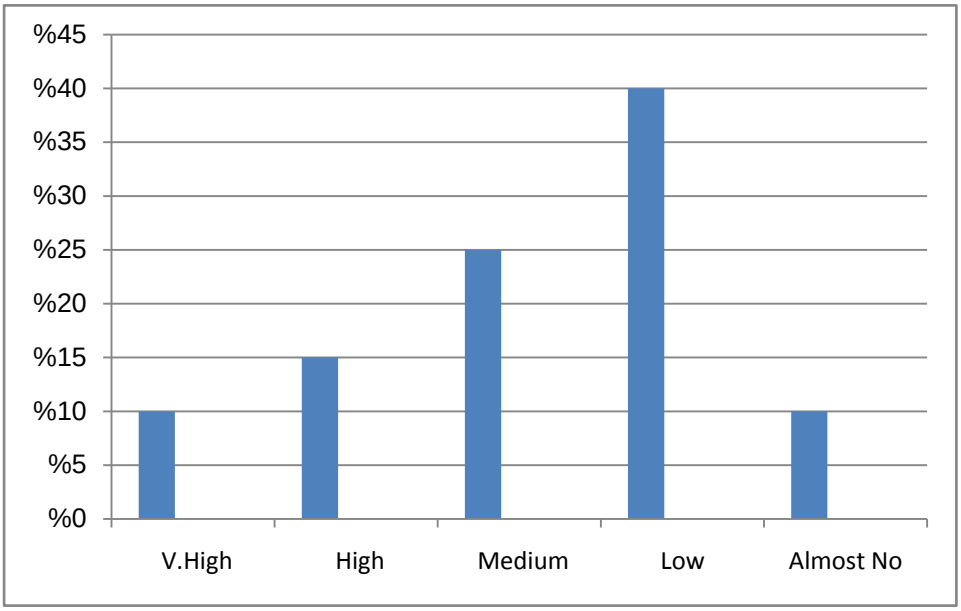


Fig. 4.10 Priority index of purchasing requests of medical equipment according to proposed framework for prioritization

The proposed QFD-FL model was developed to solve the problem of giving a reasonable priority to purchasing requests of medical equipment. The results revealed that all devices that are required either for new service or an urgent need with a very good technology assessment in addition to existence of risk probability in case of none purchasing as well as availability of budget regardless the life cycle costs analysis came as very high priority.

High priority subcategory includes all requests of equipment with high impact on healthcare delivery and/or very good survey for technology assessment. Also, high risk in case of none purchasing as well as the availability of funding and a significant life cycle costs. Medium priority takes place when the service assessment is moderate and/or the technology assessment is very good or good, the risk is medium, and the budget is either available or to be donated in addition to a reasonable life cycle costs analysis.

In contrast, in case of low impact on healthcare and/or good or poor technology assessment as well as low risk existence and/or insignificant lifecycle costs analysis, the priority comes in low class. In addition, when all criteria are met except budget availability, priority gets low. Consequently, in case of none fulfillment of all criteria or most of them, the purchasing priority comes almost no.

4.6 Chapter Conclusions

In this chapter, a QFD-FL model was developed to solve the prioritization problem of purchasing requests of medical equipment in public hospitals. The proposed model has proven its validity by classifying the requests into *five* classes; *very high*, *high*, *medium*, *low*, and *almost No*.

The output of QFD, evaluation criteria, is based on the actual needs and benefits of purchasing requests. In fact, this output should guide the decision makers to pay more attention for the most important criteria that should be considered in evaluation process. Moreover, the evaluation criteria have proven that the important role of technology assessment either related to the equipment or to the service as well as risk evaluation and financial resources availability in prioritization process.

The main advantages of the proposed model is its ability to match between the customer requirements priority and the requests priority, for example "Echocardiography" priority ranking result comes first since it is requested as a new service, which also comes first in customer requirements ranking.

The research identifies the stakeholders working on the process of purchasing medical equipment and highlights their roles taking into account also the vision of the hospital in providing new services as well as other requirements.

It is important to notice that the proposed model for prioritization of purchasing requests of medical equipment can be used as an assessment tool that could impact equipment management decision making within the clinical engineering department.

Chapter 5

Prioritization and Scheduling of Preventive Maintenance of Medical Equipment

5.1 Chapter Outlines

This chapter aims to solve the major problems associated with preventive maintenance of medical equipment; prioritization and scheduling. Problems definitions are explained in section 5.2. In section 5.3, a literature review with a wide survey is provided considering the prioritization problem and the scheduling problem of preventive maintenance. The first framework proposed for preventive maintenance prioritization of medical equipment including the structure and model validation is presented in section 5.4. The second proposed model for identifying an optimal scheduling of preventive maintenance is introduced in section 5.5 as well as the results of the proposed model. Finally, the conclusions that elicited from this chapter are illustrated in section 5.6.

5.2 Problems Definition

Preventive maintenance (PM) is a core function of clinical engineering and it is essential to guarantee the correct functioning of medical equipment. PM is being applied to keep equipment in a specified condition, taking into account both consequences of equipment failures and the cost of undertaking maintenance activities. The choice of a PM policy is an important step in the planning of maintenance activities.

Maintenance prioritization is a crucial task in healthcare systems, especially when there are more maintenance work orders than available people or resources that can handle those [78]. Maintenance executed in a random sequence or in an ad hoc sequence could potentially not only waste the labor and resources, but also could increase risk level of some devices. Unnecessary and excessive preventive maintenance could be loss-making likewise inadequate level of maintenance. Consequently, PM prioritization, in sense, is a significant decision in maintenance management.

However, optimizing PM interval and activities is an old problem that is discussed extensively in the literature. Several models were developed for this purpose considering both costs and reliability. Despite the clear role of PM optimization, the majority of literature focuses on optimal PM interval or frequency of medical equipment regardless the optimal schedule of equipment itself for PM. In other words, suppose that we have a list of medical equipment waiting PM activities to be executed, what is the optimal schedule that we have to follow to perform PM considering the priority of equipment, is it better to start with equipment 1 followed by 2 followed by 3 or starting with equipment 2 followed by 3 followed by 1?.

Hence, our target in this chapter is to present a new framework that gives a reasonable priority index for PM of medical equipment considering a range of criteria, and then use this index to identify an optimum PM scheduling of medical equipment. In essence, to generate a PM priority index, QFD model

is proposed in cascaded framework for this purpose. On the other hand, ant colony optimization methodology is complied with QFD model to develop new algorithms for identification of optimum PM scheduling relied on the resultant prioritized list of medical equipment.

PM includes a set of activities that should be carried out in order to keep medical equipment in safe and reliable conditions. The question that should be arisen is what are the common PM activities that should be performed in PM? To answer this question, first, a schematic diagram describes synopsis of PM prioritization and PM scheduling are illustrated in Fig. 5.1 and Fig. 5.2 respectively. Then, based on these synopsis diagrams, the workflow diagram is summarizing the associated PM activities as shown in Fig. 5.3. According to the previous mentioned problems and our target, we handle only the activities in red color. Beginning with a list of devices requires to be prioritized, and then optimizing that list for scheduling.

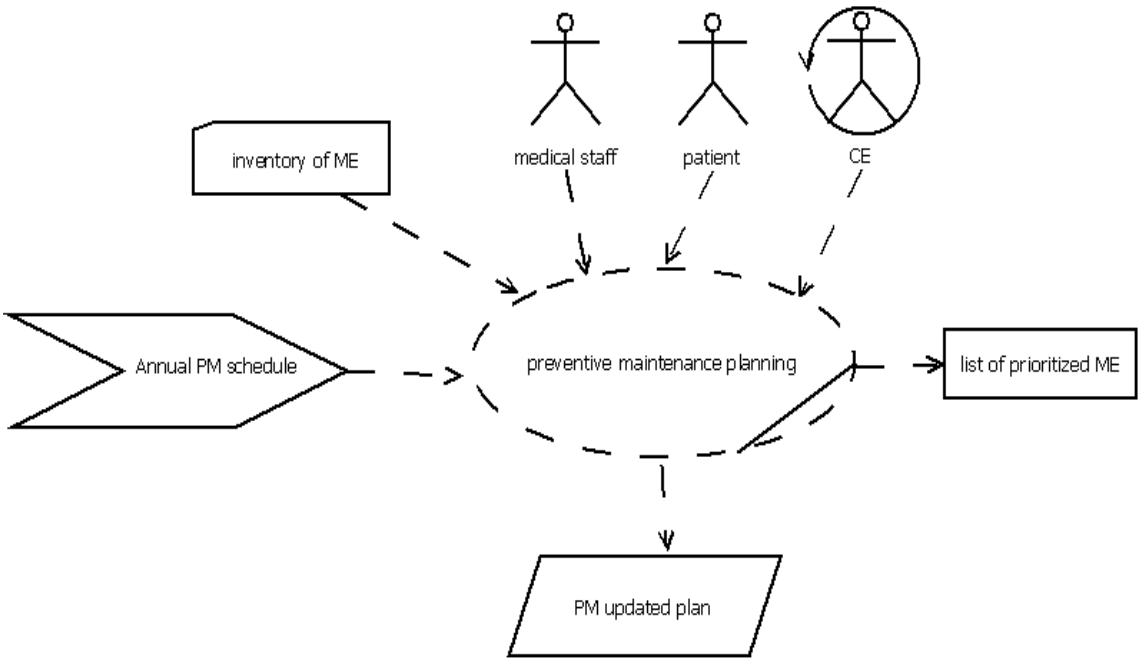


Fig. 5.1 Synopsis diagram of PM prioritization of medical equipment

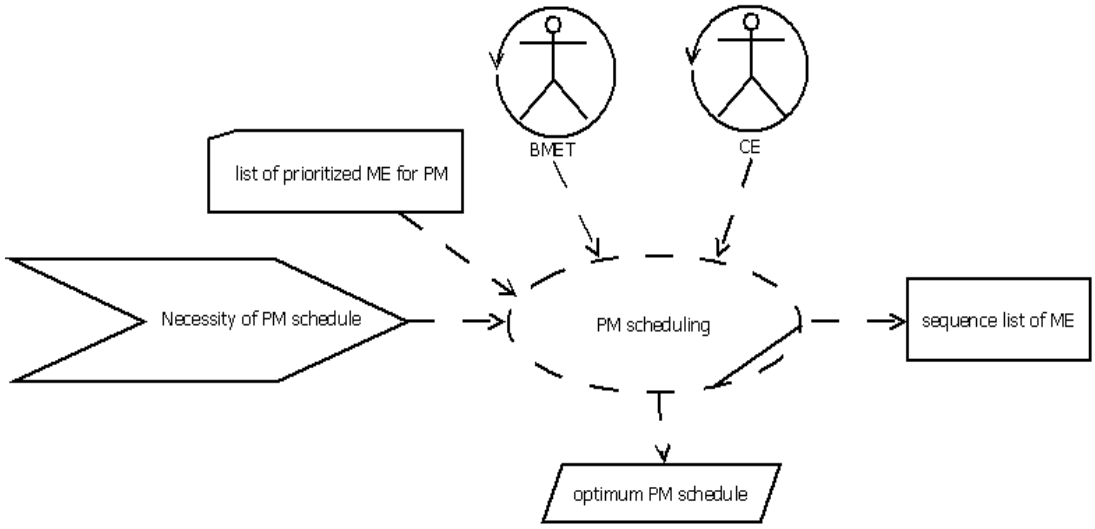


Fig. 5.2 Synopsis diagram of PM scheduling of medical equipment

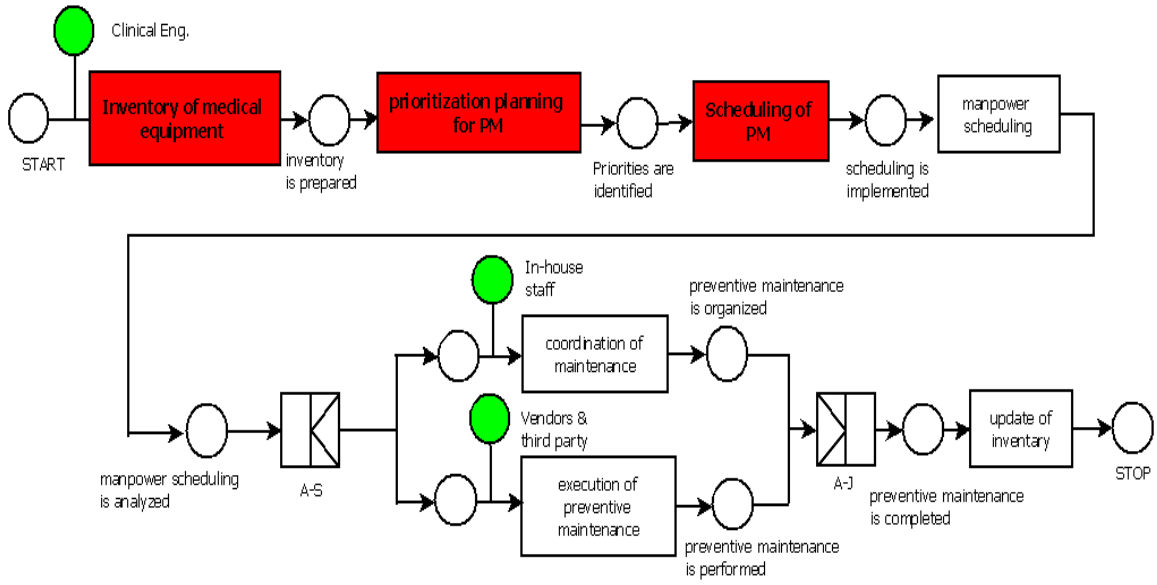


Fig. 5.3 A schematic workflow diagram of medical equipment PM

5.3 Literature Review

Like other health technologies, medical equipment is an essential tool for physicians and other healthcare professionals to deliver care. Unfortunately, medical equipment can also cause harm to both patients and users if it used improperly or it failed to perform safely and according to the specifications.

According to The Joint Commission (TJC), there were a total of 176 sentinel events related to medical equipment in the period of 2004-2011 and 39 in 2011 alone [113]. It is important, therefore, to have a well planned and managed maintenance program that is able to keep the medical equipment reliable, safe, and available for use when it is needed.

Indeed, the medical equipment maintenance can be divided into two major categories; inspection and preventive maintenance (IPM), and corrective maintenance (CM) [109]. Performance inspections ensure that equipment is operating correctly, safety inspections ensure the equipment is safe for both patients and operators, and preventive maintenance (PM) aims to extend the life of equipment and reduce the failure rate. Additionally, some hidden problems may be discovered during a scheduled inspection. CM restores the function of a failed device and allows it to be put back into service.

Preventive maintenance (PM) or planned maintenance is a core function of clinical engineering, having as its objective the assurance of ongoing safety and performance of medical devices, and the preservation of the investment in the equipment through improved longevity. Despite its core role, the design and management of an effective PM program is not a simple matter [45]. Adequate administrative support is a requirement for an effective PM program.

The two key issues for PM are the procedures or performance checks and frequencies [7, 45, 83, 89]. The procedures indicate the necessary steps that are required to assure the performance of the device either that are general or specific [45, 70]. In general, the procedures or activities of PM could be identified in terms of *inspection*, *servicing*, *calibration*, *testing*, *alignment*, and *installation* [28]. The second key of PM is the frequency at which a set of procedures should be done. The two major models for frequency are *fixed interval* and *evidence-based interval* [45]. The fixed interval selects the external recommendations such as accreditation standards for deployment, meanwhile evidence-based method is based upon make adjustment for PM

intervals considering a set of criteria (e.g. failure rates), that could impact the reliability of the medical device.

5.3.1 Preventive Maintenance Prioritization

Maintenance prioritization is a crucial task in management systems, especially when there are more maintenance work orders than available people or resources that can handle those [78]. No longer content to merely follow manufacturers' recommendations, hospital clinical engineering departments all around the world including Canada, Australia, and United States have begun to employ more efficient and cost-effective maintenance strategies [104].

However, current standards of CMS obligate the healthcare organizations to adopt the manufacturer's recommendations for PM to all critical equipment. To reveal the literature survey on how to optimize the PM priority for MEMP, we propose to classify based on the literature the PM scheduling techniques into three major methods; risk-based technique, mission-based technique, and multi criteria-based technique. For every category, we will present different examples explaining various models and principles for PM prioritization tasks.

5.3.1.1 PM Risk-Based Techniques

The so-called risk-based characterization has been in widespread use as an indicator of a device's PM needs since the Joint Commission on Accreditation of Healthcare Organizations implicitly endorsed the *Fennigkoh-Smith* risk rating methodology in 1989 and eventually in 2004 approved it as the standard (EC 6.10) (JCAHO, 2004) [88 , 104]. Many risk based Medical Equipment Management Programs (MEMPs), including the seminal Fennigkoh-Smith method and its variations, have been proposed and are currently in use. A common theme in these methods is that a single measure of a number of different risks is defined and used to guide safety and performance inspection and preventive maintenance activities [87, 107].

Ridgway [89] try to answer the question what would be the impact of eliminating or increasing the intervals for some or all of the PM on PM-related safety, amount of downtime, and expensive PM-related repairs?, by developing a new approach for PM scheduling. The new approach is based on determining the failure mode's RCM (Reliability Centered Maintenance) risk score for all the equipment included in the maintenance program. According to the final score the PM preference will be considered. Table 5.1 shows the RCM risk scores. The scores is the result of multiplication LOS (Level of Severity) scores by LOF (Likelihood of Occurrence) scores. The PM prioritization decision is classified into 3 classes based upon risk score.

Table 5.1 RCM risk score matrix [89]

LOS = 4 Catastrophic	4	8	12 "must-do PM"	16 "must-do PM "
LOS = 3 Major	3	6	9	12 "must-do PM"
LOS = 2 Moderate	2 "do no PM"	4	6	8
LOS = 1 Minor	1 "do no PM"	2 "do no PM"	3	4
	LOF = 1 Remote	LOF = 2 Uncommon	LOF = 3 Occasional	LOF = 4 Frequent

The same author also has presented in 2003 [88], developed a method that allows to reduce the test results to a simple single measure (the risk score) that can be used to characterize the effectiveness and levels of safety of PM. The first step of the method is to collect information on any failures discovered during PM inspection. This number of PM failures is cited as percentage and called PM yield. By following FMEA, any type of problem found during PM inspection allocated into 1of 4 PM problem severity classes; *catastrophic, major, moderate,* and *minor*. The proposed analogous PM problem severity classes are divided into 4 levels according to failure hidden level. Also by using the FMEA probability rating is classified into 4 levels; *frequent, occasional, uncommon,* and *remote*.

The seriousness of each potential adverse event is given a hazard score as it is shown in Table 5.2. The author then translates the traditional hazard matrix into analogous PM-related hazard score matrix as shown in Table 5.3 to judge the PM interval. If the risk score is less than 8 the PM program for the device can be considered effective, the lower score the greater margin of safety. If the risk score is much lower than 6, consideration should be given to extending PM interval.

Table 5.2 Traditional Risk Score Matrix Using FMEA [88]

Probability		Severity of Effect			
		Catastrophic (wt = 4)	Major (wt = 3)	Moderate (wt = 2)	Minor (wt = 1)
	Frequent (wt = 4)	16	12	8	4
	Occasional (wt = 3)	12	9	6	3
	Uncommon (wt = 2)	8	6	4	2
	Remote (wt = 1)	4	3	2	1

Table 5.3 New Risk Score Matrix using traditional Risk Score Matrix [88]

% PM Failure Rate Found	PM Problem Severity Rating			
	Level 1 (wt = 4)	Level 2 (wt = 3)	Level 3 (wt = 2)	Level 4 (wt = 1)
High >25% (wt = 4)	16	12	8	4
Moderate 10%–25% (wt = 3)	12	9	6	3
Low 0.1%–9.9% (wt = 2)	8	6	4	2
Very Low <0.1% (wt = 1)	4	3	2	1

*wt indicates weighting factor applied.

Fault Tree Analysis (FTA) can provide valuable risk comparison even when crisp numeric probabilities and severities for risks are not available [87]. Based upon this fact, *Rice* has been developed a partial fault tree analysis for an IV pump to explain how we can use FTA as an approach to determine the composite risk score. He presented new formula for risk score calculation by

multiplication of the severity by probability instead of fixed scaling factor. The probability of a given event is different for each type of device and use and can vary with time. For traditional MEMP, the top event is defined to be function, or physical risk, or maintenance requirements and others. Risk is assigned using arbitrary and somewhat subjective measures.

Another model to classify risks of medical equipment was argued in [107]. The authors developed a fuzzy logic model to classify the risk associated with every device using four criteria; *mission criticality, equipment function, maintenance requirements,* and *physical risks*. The study demonstrated that the same equipment type may have different risk scores depending on the operating conditions within the hospital.

There are other endeavors to develop preventive maintenance index for medical equipment inventory to assign PM interval for every piece of equipment. *Josegh, J. et al* have been developed a model for preventive maintenance index considering Risk Level Coefficient (RLC) of the instrument [49]. Risk level coefficient was calculated by calculating five different classified factors related with the medical equipment electrical risk. The five classifications are *the static risk, the degree and quality of safety arrangements, insulations, physical risk,* and *equipment contact with patient*. By calculating and weighting these terms the PM interval is resolved for each instrument.

Another example also considers preventive maintenance interval for every piece of equipment is illustrated in [7]. In this research, a soft ware tool is developed to implement a risk oriented prioritization of equipment for preventive maintenance inspections. The main term of the system is Risk Level (RL). The risk level is a function of *function of the device*, *consequence rating, maintenance rating, protection rating, lethality rating*, and *finally usage rating*. The PM frequency term is calculated for this approach by dividing RL score to 15, and consequently PM interval is identified by dividing inverted PM frequency to 12.

5.3.1.2 PM Mission-Based Techniques

Mission criticality or operational impact describes the extent to which a device is crucial to the care delivery process of a hospital. For example Electrocardiograph (ECG) device is critical and essential device for cardiology department, but for other departments such as outpatients is necessary. Wang suggests classification of devices in three groups; critical, important, and necessary according to their mission criticality as shown in Table 5.4 [52].

Table 5.4 Examples of equipment classification based on mission criticality [52]

		Patient Risk		
		High	Medium	Low
Mission Criticality	Critical	anesthesia equip, ventilator, radiotherapy	MRI, CT scanner, cath lab, auto chem. analyzer	electron microscope
	Important	PCA pump, infant incubator, defibrillator, telemetry system	infusion pump, hypo/hyperthermia, physiological monitor, ESU, blood gas analyzer, ultrasound scanner	special procedure table, lab microplate reader, cine projector, flat-panel detector
	Necessary	bariatric patient lift, laminar airflow	enteral feeding pump, ECG, pulse oximeter	patient scale, examination light, treadmill

The first example which considers the mission criticality in preventive maintenance is presented by *Roberto et al*. the authors develop a methodology to assist decision makers in constructing preventive maintenance plan [70]. They developed System of Information Technology and Support System for Maintenance Actions (SISMA) which considers two aspects for evaluation; technical and economic needs. The technical criteria, consists of two levels, 1 and 2. Level 1 is developed to identify preventive maintenance priority index based on complexity of technology, and activity area as critical index, in addition to is the device for life support or not. Level 2 considers the output of level 1 and other two cases; contractual coverage and purchased devices to assess PM plan for equipment as shown in Fig 5.4.

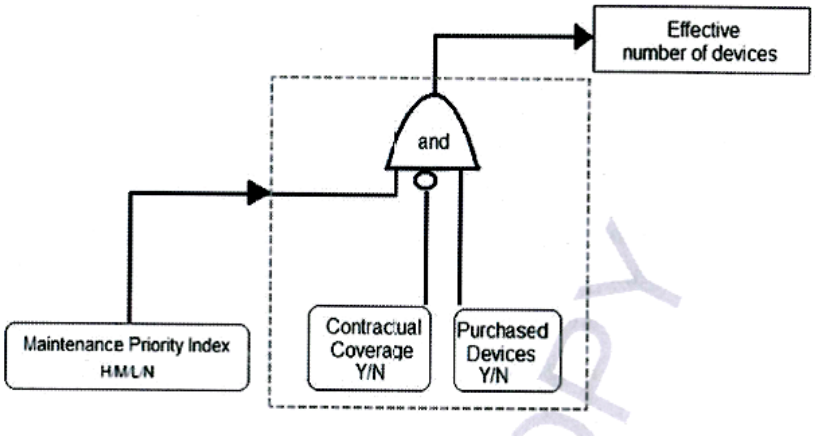


Fig 5.4 Boolean operator for assessing the devices needing PM planning [70]

Another approach considers the equipment criticality for preventive maintenance scheduling activities is a mathematical evidence-based model. The strategy is composed of a combination of user actions (user checks and operational maintenance), scheduled maintenance, repairs, replacement, etc. the mission criticality is used to decide the minimum available units for service delivery and will be used for the initial classification of inventory to determine the initial maintenance strategy [52]. A mixed integer approach is proposed for equipment maintenance scheduling optimization.

5.3.1.3 PM Multi Criteria-Based Techniques

Different models have been developed for appropriate maintenance strategy for medical equipment utilizing multi criteria approach [23]. Multi-Criteria Decision Making (MCDM) can be used to prioritize medical equipment for different maintenance strategies. MCDM is a well-known branch of decision making, divided into multi-objective and multi-attribute decision making [105]. Analytical Hierarchy Process (AHP) is an example of MCDM methodology.

In [105] PM prioritization was decomposed into 3 levels hierarchy. The first level is the goal, prioritization of medical devices, the second level is the criteria and sub-criteria, and the third level is the alternatives. The steps of the proposed model are to identify criteria and sub criteria, determine their

weights, determine intensities for each criterion, evaluate alternatives with respect to criterion, calculate device criticality score, and finally order devices according to their criticality scores. The criteria for maintenance prioritization are illustrated in Fig 5.5.

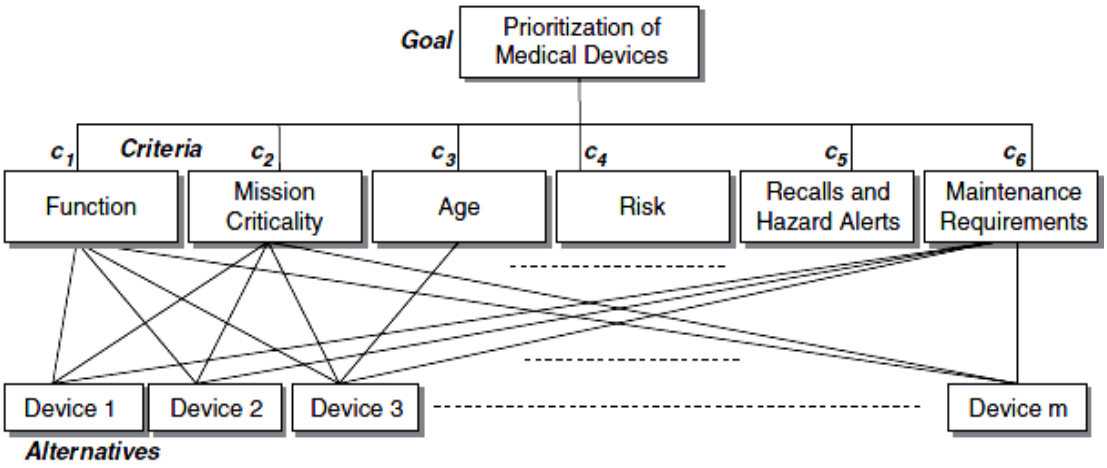


Fig 5.5 Decision hierarchy for maintenance prioritization of medical devices using AHP [105]

Another study describes a framework to support the choice of the maintenance in universal hospital of Brazil is carried out. The decision support approach combining Activity Based Costing (ABC) and the Analytical Hierarchy Process (AHP) in one model. Based on weighting of the technical criteria by AHP method, a comparison between in-house staff and third party contract is performed for a CT device as a case study [25]

A different and new technique for evaluation of medical devices maintenance system was developed by Jordanian group in Prince Hamzah hospital [6]. The quality function deployment (QFD) is utilized as an improving method in maintenance management system and as a guideline in highlighting the weak points in the performance and finding the suitable procedures to achieve the customer satisfaction. Quality function deployment is a system to identify, communicate, and prioritize customer's requirements so

that an organization can optimize its products and services to exceed customer's expectations.

5.3.2 Preventive Maintenance Scheduling

Once a medical device is added to the equipment inventory, an appropriate maintenance schedule has to be selected. The aim of PM scheduling is to be able to schedule the preventive maintenance activities with optimal time duration and minimum overall maintenance costs but at the same time to provide the best quality of reliability and availability of the system [100]. As PM is expensive, it is important to decide when it should be performed. Accordingly, PM interventions should be optimized in order to keep the resources.

However, PM scheduling can be categorized into two main concepts; periodical and sequential [96, 97]. Periodical PM specifies the interventions to be done at equal time [36, 91, 97]. The alternative approach is sequential PM, it is characterizing by search of the optimal number of maintenance actions to be carried out during a given period, i.e. the optimal PM frequencies [96]. Although the first concept is more convenient, sequential PM results more realistic because it usually complies better with budget constraints [91].

In general, the literature is rich with different techniques for PM scheduling either for single unit or multi-unit systems. Examples presented in [10, 48, 53, 58, 61] demonstrate different techniques and implementations for optimum single-unit PM interval, meanwhile other articles [60, 62, 65, 77, 85] present different scenarios for multi-unit systems.

Considering scheduling techniques, one study calculated PM schedule taking into account the failure distribution of a component as *Weibull* to minimize the maintenance costs. The presentation of *Weibull* parameters α and β were estimated by a given PM costs and corrective maintenance (CM) costs. The study proved an important relationship between PM frequency and the

costs of CM [22]. The study indicates that if the cost difference between PM and CM are marginal the frequency of the PM schedule will be minimum for a minimum costs.

Another study was conducted based on the use of a Monte Carlo simulation to evaluate the expected cost of maintenance as well as the expected economic loss, an economic indicator for maintenance performance. Genetic algorithm was used to optimize PM frequency considering three practical issues; different failure modes of equipment, ranking of equipment according to consequences of failure, labor resource constraints and material resource constraints. The proposed model was tested using Tennessee Eastman plant [77].

The risk management group at the South Texas Project Electric Generating Station (STPEGS) has successfully developed PM optimization application based on a new mathematical model. Robust statistical analysis, coupled with an efficient algorithm generates an optimal PM schedule, based on a Non-Homogenous Poisson Process (NHPP) with a power law failure rate function. In addition, the risk associated with significant plant events triggered by a component failure is appropriately captured in CM costs estimation. The probabilities of such events are modeled via fault tree analysis, and consequences re-expressed in monetary values. The net cost of CM is then modified by a weighted sum of the probability of each event multiplied its monetary cost. The ratio of risk adjusted CM costs to PM costs is used with the failure rate parameters to calculate the optimum PM frequency that minimizes combined PM and CM costs [110].

Although, there are extensively literature review handle the preventive maintenance optimization in terms of policies, frequencies, intervals, and scheduling, the survey proves that there is no empirical approach has been presented for medical equipment to find the optimum sequential list of devices to perform PM. In other words, if we have a set of medical equipment that should undergo PM, what is the best sequence of devices that minimizes time,

labor, and consequently costs? In this study, starting with a list of medical equipment with prioritized ranking for PM purpose, we try to solve the problem of finding the optimal scheduling for medical equipment PM over a finite planning horizon.

5.4 Proposed Model of PM Prioritization of Medical Equipment

Recent attempts to apply quality function deployment principles to the healthcare sector concentrated upon gaining deeper understanding and analysis of customer needs. The quality function deployment methodology has few applications in medical equipment management field. Our research is considered a new contribution to apply QFD in medical equipment maintenance management. It is the first time to use quality function deployment in preventive maintenance prioritization of medical equipment.

A 3 domains framework for preventive maintenance is proposed for preventive maintenance prioritization. The proposed model as illustrated in Fig 5.6 consists of 3 phases or stages; *requirements domain*, *function domain*, and *concept domain*. The first domain is the requirements domain which considers the voice of customers and the technical characteristics that meet it. In other words this stage is the House of Quality (HOQ) of the proposed model.

The second domain is the function domain or design matrix. In this stage the top technical characteristics that resulted in first domain will be measured through new criteria to identify the critical criteria for preventive maintenance prioritization, i.e. top HOWs of the first domain becomes the new WHATs of the second domain. The priority score index of the prioritization is determined in the last stage, the concept domain. In this domain, a priority index is generated considering the weights of critical criteria based on the critical criteria of the second domain.

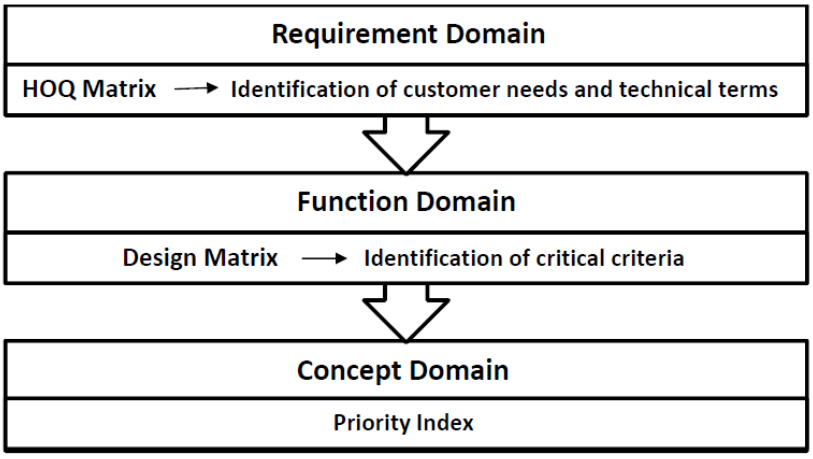


Fig 5.6 A 3 domain framework model for preventive maintenance prioritization of medical equipment

5.4.1 Requirement Domain of the Proposed Model

The requirements domain is the house of quality (HOQ) of the proposed model. According to HOQ construction, the customers should be identified. In general, the customers of medical equipment in hospitals include all customers that have a direct interface with medical equipment and who expecting a range of services with this equipment. Therefore, the patients and the clinical staff including the physicians and nurses are considered the customers of this HOQ.

On the other hand, the clinical engineering department including the Clinical Engineers (CE) and the Biomedical Engineering Technicians (BMET) who are responsible of medical equipment management are considered the voice of technicians who are responsible to satisfy the customer's requirements or needs through technical characteristics development. In summary, the patients and clinical staff present WHATs of HOQ; meanwhile the clinical engineering department presents HOWs of HOQ [93]. For simplicity, we build this HOQ without the correlation matrix (roof).

5.4.1.1 Customer Requirements

No doubt that the safety and availability of medical equipment in the hospitals are essential requirements for all patients. We can imagine the dissatisfaction of patients if one of these basic requirements is absent or not considered. To consider the requirements of the clinical staff, several scenarios are existed. One of these scenarios is to make a survey through questionnaires for different categories of clinical staff. Another method is to use a literature for this purpose, in case of availability. Also, if there is a reasonable contact and experience to estimate the complaints and aspirations of clinical staff, it could be used as source of knowledge to identify their needs.

In our case, the clinical staff requirements for preventive maintenance scheduling are considered based on the literature [6] and our experience in clinical engineering management. Regarding both of patient's requirements and clinical staff requirements, the customer needs (WHATs) for medical equipment preventive maintenance scheduling are listed below. Alphabetic symbols are given for both of customer requirements and technical requirements for simplicity.

- Safety of the medical device (W1)
- Efficiency (W2)
- Durability (W3)
- Quick response of technical team (technicians) (W4)
- Back up availability (W5)
- Check the device after maintenance (W6)
- Regular monitoring of the devices (W7)
- Importance (W8)
- Obvious operating instructions (W9)
- Knowledge of maintained devices (W10)
- Existence of a contact person 24 h (W11)
- Avoiding suspension of services (W12)

5.4.1.2 Technical Requirements

To satisfy all customers' requirements for preventive maintenance prioritization, the clinical department should address these requirements and develop the technical characteristics or measures to meet these needs. By regarding the customer requirements, the technical requirements are classified into five main criteria and twenty sub-criteria. Table 5.5 shows the technical measures of HOQ including the main criteria and sub criteria with given symbols for the sub criteria

Table 5.5 Technical measurements of proposed HOQ

No	Main criteria	Sub criteria
1	Risk	Physical Risk (H1)
		Function (H2)
		Maintenance Requirements (H3)
2	Performance Assurance	Mission Criticality (H4)
		Functional Verification (H5)
		Age (H6)
		Labeling (H7)
		Electrical Safety Testing (H8)
		Replacement of the Parts (H9)
		Regular Inspection (H10)
3	User Competence	Qualifications of Technicians (H11)
		Complexity of Devices (H12)
		Equipped workshop (H13)
		Test Equipment Availability (H14)
		Service Manual Availability (H15)
		Activities recording (H16)
4	The costs	Updating or loan (H17)
		Spare Parts Availability (H18)
		Type of Service Provider (H19)
5	Standard Compliance	Meet Specific Standards (H20)

The main criteria are the risk, performance assurance, user competence, the costs, and standard competence. The risk sub criteria are considered based on literature [52, 105, 107, 109]. The other criteria are regarded based on both the literature and experience of clinical engineers in Egypt and Italy to meet the customers' requirements.

5.4.1.3 Planning Matrix

The matrix determines how important the requirements are for the customers. According to the principles of QFD to evaluate the customer satisfactions, a comparison between Italian hospital in Piedmont province and Jordanian hospital as in [6] is performed to develop the planning matrix of HOQ. Hence, this step classifies how the Italian hospital is perceived compared to its competitor, the Jordanian hospital. Our target is to develop a prioritization index for preventive maintenance of Italian hospital by utilizing this comparison in HOQ.

The planning matrix is presented in Table 5.6 using a 5 point scale for evaluation. For example, considering the first customer requirements "safety", the improvement ratio is calculated by dividing the goal score to Italian satisfaction i.e. 5/3=1.67, and the absolute weight is calculated by multiplying improvement ratio by importance factor i.e. 1.7 x 5= 8.35. The relative weight percentage for each need is calculated by normalizing the absolute weight, for example, (8.35 / 91.5) *100= 9.12

Table 5.6 Planning matrix of proposed HOQ

No	Customer requirements	Importance factor	Italian hospital satisfaction	Jordanian hospital satisfaction	The Goal	Improvement Ratio	Absolute Weight	Relative Weight	Rank
1	W1	5	3	5	5	1.67	8.35	9.12	4
2	W2	5	3	1	5	1.67	8.35	9.12	4
3	W3	4	3	3	5	1.67	6.68	7.30	6
4	W4	4	3	5	5	1.67	6.68	7.30	6
5	W5	3	1	2	3	3	9	9.83	3
6	W6	4	4	3	4	1	4	4.37	9
7	W7	4	2	3	4	2	8	8.74	5
8	W8	3	2	1	3	1.5	4.5	4.91	8
9	W9	4	2	1	5	2.5	10	11.04	2
10	W10	3	1	1	4	4	12	13.11	1
11	W11	4	2	2	4	2	8	8.74	5
12	W12	2	1	1	3	3	6	6.55	7

Ranking the customer's needs in this matrix, we find the knowledge of maintained devices, obvious operating instructions and back up availability are the top requirements for the clinical staff, while the safety and efficiency are the top requirements for the patients. The next requirements ranking are regular monitoring of the devices, durability, quick response of technical staff, avoiding suspension of services, importance, and finally checking the device after maintenance.

5.4.1.4 Relationship Matrix

The relationship matrix is the core matrix of HOQ. Its purpose is to prioritize the technical characteristic's contributions to achieving customer satisfaction, i.e. it maps technical features and customer needs in which each cell represents a judgment (made by the implementation team) of the strength of the relation linking each [26]. We use Cohen scale for relationships indication as, 9, 3, and1 for strong, medium, and weak respectively. The blank cells indicate that no relations.

5.4.1.5 Technical Target Matrix

At this stage, the target matrix is established to prioritize the technical characteristics based upon the prioritized customer's requirements. To determine the top critical technical characteristics, the absolute weight and the relative weight are calculated. The absolute weight is total summation of multiplication of the relative weight of planning matrix by each technical characteristic relationship scores. For example, if we consider the first technical characteristic "physical risk", the absolute weight equals 9 x 9.1 + 9 x 7.3 + 9 x 4.4 + 3 x 8.7 = 213.3. The relative weight percentage is calculated by normalizing the absolute weight as shown in Fig 5.7, i.e. the relative weight of physical risk is (213/ 4238) *100 = 5. For better representation of five addressing criteria, we propose all sub criteria with relative weight greater than 4.5 % to be selected as *top criteria* ranging from risk criteria with its clear

impact in PM to a regular inspection since it is not regularly followed by a lot of hospitals especially in developing countries [93].

HOWs	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	H 9	H 10	H 11	H 12	H 13	H 14	H 15	H 16	H 17	H 18	H 19	H 20
Absolute Wight	213	487	315	406	258	269	117	183	114	191	223	223	72	144	48	67	105	115	362	326
Relative Weight	5	11.5	7.4	9.6	6	6.3	2.8	4.3	2.6	4.5	5.3	5.2	1.7	3.4	1.1	1.6	2.5	2.7	8.5	7.7
Rank	10	1	5	2	7	6	14	12	16	11	8	9	18	13	20	19	17	15	3	4

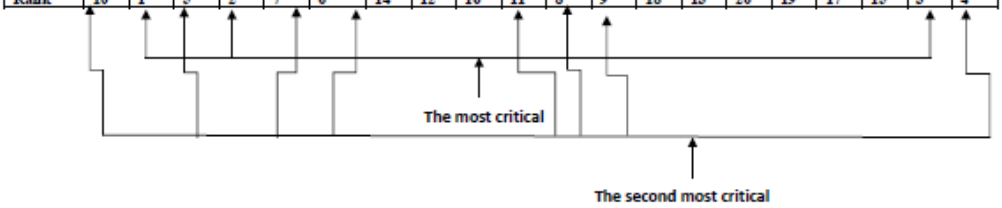


Fig 5.7 Technical target with most critical factor of proposed HOQ

By analyzing the technical target matrix, we find the highest relative weight is given to "Function" or H2, followed by "Mission criticality" or H4. The second critical technical characteristics that can impact on the preventive maintenance prioritization decision are "Type of service provider" or H3," meet specific standard" or H4, "maintenance requirements" or H5, "age" or H6, "functional verification" or H7, "qualification of technicians" or H8, "complexity of devices" or H9, "physical risk" or H10, and "regular inspection" or H11. Accordingly, we considered only these technical characteristics as critical factors for prioritization process based upon the experience of the authors.

The proposed overall HOQ matrix is depicted in Fig 5.8 which all previous matrices are mapped together to formulate the first domain of our proposed model, the requirements domain. It also includes the most important customer needs and the most critical technical factors for decision making. For simplicity purpose, the roof matrix of the first domain is neglected. The most critical technical factors (HOWs) of requirement domain become input of the second domain, “Function domain”. As a result, only *eleven* technical factors are considered as input for function domain based on their relative weights.

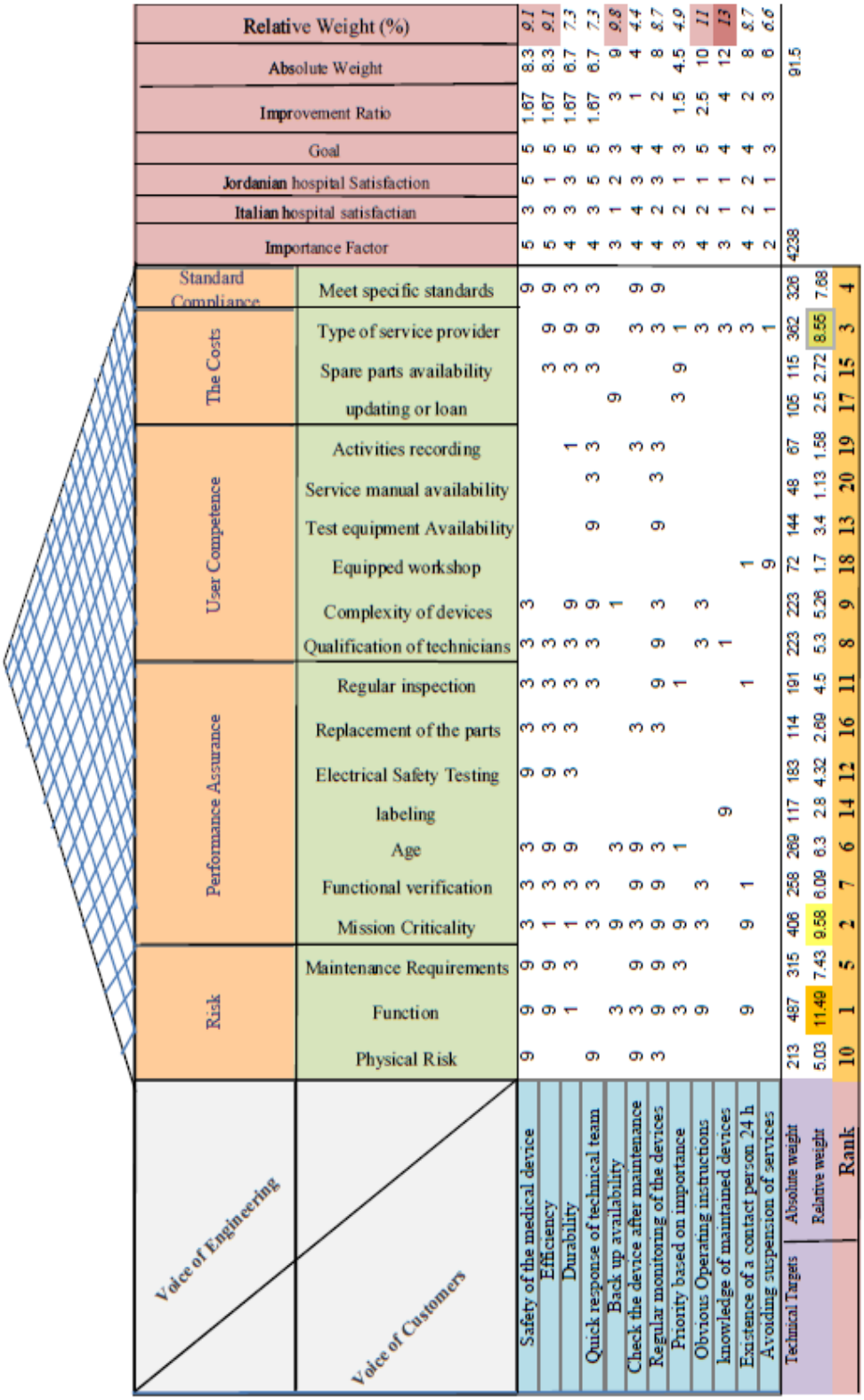


Fig 5.8 Proposed HOQ matrix for PM prioritization of medical equipment

5.4.2Function Domain of the Proposed Model

The second phase of our proposed model is the function domain model. In this stage the technical criteria for preventive maintenance prioritization are identified using the results of the first HOQ matrix. In this stage, we identify the critical criteria by using the second matrix of QFD process for preventive maintenance priority purpose. We selected the top eleven technical criteria regarding their weights and importance to become the inputs (WHATs) of the second matrix.

5.4.2.1 WHATs and HOWs of Design Matrix

The input requirements (WHATs) of the design matrix are the top selected criteria of the requirement domain; *function*, *mission criticality, service provider type, standards meet, maintenance requirements, age, functional verifications, team qualifications, device complexity, physical risk,* and *regular inspection*. To address these requirements, the authors develop 3 main categories for prioritization process referring to [109]. The three main categories are *risk-based*, *mission-based*, and *maintenance-based*. Every category has its own sub criteria [92] as shown in Table 5.7 with its symbol.

Table 5.7 Technical Criteria (HOWs) of the Design Matrix

No	Main criteria	Sub criteria
1	Risk-based criteria	Function (H'1)
		Physical Risk (H'2)
		Maintenance Requirements (H'3)
2	Mission-based criteria	Utilization Level (H'4)
		Area Criticality (H'5)
		Device Criticality (H'6)
3	Maintenance-based criteria	Failure Rate (H'7)
		Useful Life Ratio (H'8)
		Device Complexity (H'9)
		Number of Missed Maintenance (H'10)
		Downtime Ratio (H'11)

5.4.2.2 Structure of Design Matrix

The design matrix is considered the second phase of QFD process, so the same procedures that are followed in the first stage is adopted in this matrix. The output of the first matrix i.e. the top critical characteristics with their importance weight are utilized as inputs for the design matrix with their weights in planning part of the matrix. Also the relationship matrix is developed using the same scale 9-3-1 to indicate the strength or weakness level between WHATs and HOWs.

In the design matrix, we developed the correlation matrix between the technical criteria (HOWs) because of the low number of technical characteristics and also it is important in this stage to know if there is a trade-off between the criteria or not. Fig 5.9 presents the correlation matrix or the roof of the design matrix.

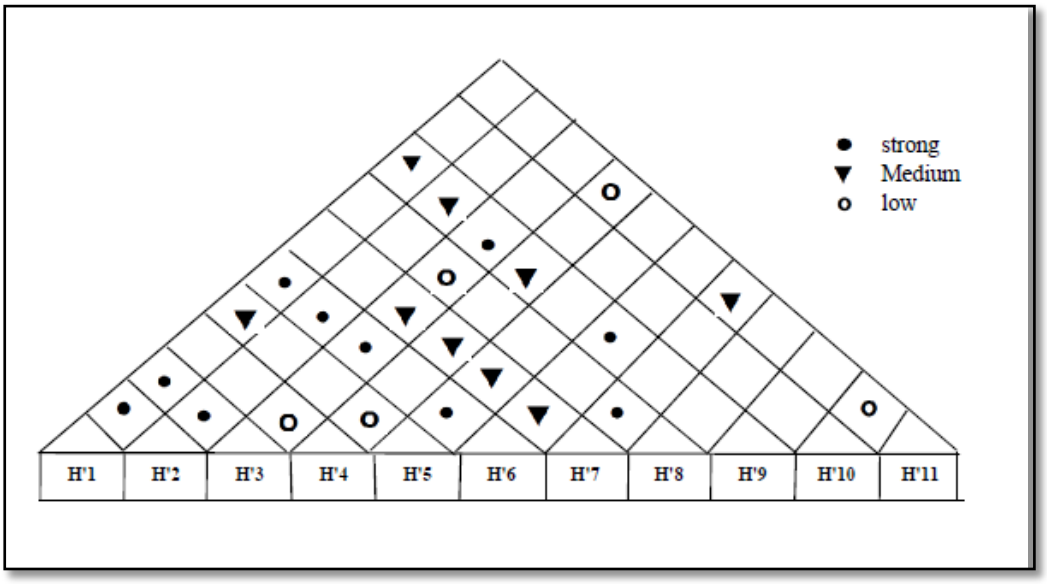


Fig 5.9 Correlation matrix (roof) of the proposed design matrix

The overall design matrix as shown in Fig 5.10 is considered the guide matrix for decision of medical equipment PM prioritization. In part of technical target, we proposed the critical values of the technical criteria to compare these

criteria against. The thresholds of these values are discussed in detail in next domain. The relative weights of technical criteria referred to risk – based criteria have a great impact on the decision of preventive maintenance schedule priority. Mission – based criteria also affecting this decision followed by maintenance – based criteria.

HOWS / WHATS	Risk- Based			Mission - Based			Maintenance - Based					Importance Weights
	Function	Physical Risk	Maintenance Req	Utilization Level	Area criticality	Device Criticality	Failure Rate	Useful life Ratio	Device Complexity	# of missed maintena	Downtime Ratio	
Function	9	9	3		3	3						11.5
Mission criticality	3		9	9	9	9						9.6
Tpe of service provider									3		1	8.5
Meet standards			9									7.7
Maintenance requirements	3	9	9	9		3	9	3	3	3		7.4
Age				3			9	9			3	6.3
Functional verifications	3	3	3	3		9	3	1	1			6.1
Qualification of the team									3			5.3
Complexity of the device			9					1	9		3	5.3
Physical risk	9	9	3									5
Regular inspection		1	9	3		3	3	1		9	3	4.5
Critical targets	life support	Death	Extensive	> 4 days a week	Urgent	Critical	High	≥ 80 %	High tech	≥ 2	≥ 20%	
Absolute Weight	217.8	237.9	378.3	203.7	121	211.5	155	94.8	117	62.7	56.8	1857
Relative Weight %	11.73	12.81	20.373	10.97	6.51	11.39	8.35	5.11	6.32	3.38	3.06	100
RANK	**3**	**2**	**1**	**5**	**7**	**4**	**6**	**9**	**8**	**10**	**11**	
Criteria Weight	44.91%			28.87%			26.22%					

Fig 5.10 Proposed design matrix for PM prioritization of medical equipment

5.4.3 Concept Domain of the Proposed Model

The concept domain is the priority index proposed for preventive maintenance prioritization of medical equipment. In this last stage of our proposed model, a priority index is a result score given to the device. The output of the design matrix is a prioritization equation which considers the eleven critical criteria with weights as shown in equation 5.1

$$PS = 11.7(FN) + 12.8(PR) + 20.4(MR) + 11(UL) + 6.5(AC) + 11.4(DC) + 8.3(FR) + 5.1(LR) + 6.3(CM) + 3.4(MM) + 3.1(DR) \quad (5.1)$$

PS: priority score

FN: function of equipment

PR: physical risk

MR: maintenance requirements

UL: utilization level

AC: area criticality

DC: device criticality

FR: failure rate

LR: useful life ratio

CM device complexity

MM: missed maintenance

DR: downtime ratio

5.4.3.1 Function of Medical Equipment

The function of medical equipment is the purpose for which it is to be used. The function has different classifications, but common classification considers five classes [36, 49, 105, 109]; life support, therapeutic, diagnostic or

monitoring, analytical, and miscellaneous. For parameter evaluation, we used 5 point scale as shown in Table 5.8.

5.4.3.2 Physical Risk

Risk can also play an important role in determining preventive maintenance schedule. Physical risk means that all probable harms caused by equipment failure [36]. Physical risk severity ranges from death to no risk [109] depending on the degree of potential harm. Table 5.8 illustrates 5 scores for this factor.

5.4.3.3 Maintenance Requirements

Maintenance Requirements describes the level and frequency of maintenance required as noted by the manufacturer or through experience [109]. According *to Fennigkoh* and *Smith* (1989), equipment that is predominantly mechanical, pneumatic, or fluidic often requires the most extensive maintenance. A device is considered to have an average maintenance requirement if it requires only performance verification and safety testing. Equipment that receives only visual inspection, a basic performance check, and safety testing is classified as having minimal maintenance requirements [105]. Maintenance requirements are classified to five categories [109] with 5 scores as reported in Table 5.8.

5.4.3.4 Utilization Level

Utilization level indicates the total hours a device is used on average in a hospital [105] (hours per day or days per week or weeks per month). In this model, we consider the average days a device is used per week. We proposed 4 days a week is a threshold for high utilization level and less than 3 days for low utilization. Table 5.8 shows the proposed three level of utilization.

5.4.3.5 Area Criticality

It is important to evaluate each device according to its area criticality. Area criticality shows the importance level of clinical area in healthcare delivery. Based on [70], we proposed to classify the hospital areas into five places as shown in Table 5.8. Regarding the criticality factor, we proposed urgent area such as operating rooms, intensity care units, diagnostic units, low intensity units such as labs, and non clinical area such as sterilization unit.

5.4.3.6 Failure Rate

Failure rate is an important indicator for preventive maintenance process. It refers to the number of failures per specific time duration [36]. For our proposed model, we identified failure rate per one year. According to the experience, we propose a range of scores based on criticality level of the device. As literature provides us with three levels of device criticality, thus, we propose three levels of failure rate as described in Table 5.8.

5.4.3.7 Device Criticality

Device criticality deals with availability of equipment for patient care. It describes the extent to which a device is crucial to the care delivery process of a hospital [105]. Based on literature see Table 5.4, the device criticality is classified into three levels; critical, important, and necessary [52] as described in Table 5.8.

5.4.3.8 Useful Life Ratio

Several studies were conducted to indicate the criticality of device age in management of medical equipment. Life ratio is a threshold that indicates the age of a device to its expected life time in hours or years [16, 36, 81]. In this study, the scores of life ratio are given for 3 levels depending on this ratio. Table 5.8 presents the proposed levels of ratio with the scores.

Table 5.8 A brief description of critical criteria and their scores [92, 93]

Parameter	Description	Thresholds	Scores
Function	Device function	Life support	5
		Therapeutic	4
		Diagnostic / monitoring	3
		Analytical	2
		Miscellaneous	1
Physical risk	Probable harms caused by equipment failure	Death	5
		Injury	4
		Misdiagnosis	3
		Equipment damage	2
		No risk	1
Maintenance requirements	Maintenance activities depending on equipment type	Extensive	5
		A above average	4
		Average	3
		Below average	2
		Minimal	1
Utilization level	Number of working days a week	>4 days	3
		3-4 days	2
		<3 days	1
Area criticality	Assessment of area criticality for patients	Urgent	5
		Intensity care units	4
		Diagnostic area	3
		Law intensity area	2
		Non clinical area	1
Device criticality	The importance level of equipment in serviced area	Critical	3
		Important	2
		Necessary	1
Failure Rate	Number of failures a year based on device criticality level	≥2 for critical, ≥4 for important, ≥5 for necessary	3
		1 for critical, 2-3 for important, 3-4 for necessary	2
		0 for critical, ≤1 for important, ≤2 for necessary	1
Useful life ratio	Ratio between age to expected life time of a device	Ratio > 80 %	3
		50% < Ratio ≤80%	2
		Ratio ≤ 50 %	1
Device complexity	Technical complexity based on a model	Score 6 – 8	3
		Score 3 – 5	2
		Score 0 – 2	1
Missed maintenance	Number of missed maintenance a year	≥ 2	3
		1	2
		0	1
Downtime ratio	Ratio between the duration of downtime in days to days a year	Ratio ≥ 20 %	3
		10% ≤ Ratio<20%	2
		Ratio < 10 %	1

5.4.3.9 Device Complexity

Medical device complexity is concerned mainly with the measurement of some factors that affect the required levels of maintenance, training programs, and risk analysis associated with the medical equipment [75]. The technical complexity model as in [75] is used for complexity measurement. We proposed to give complexity score depending on the scores of the complexity model as shown in Table 5.8. The technical complexity model was developed based on four criteria as shown in Table 5.9; maintainability, installation, repair, and connectivity.

Table 5.9 Technical complexity score index for medical equipment [75]

Table 1. Technical complexity and score descriptions		
Equipment Maintainability		
Scores	0	Equipment easily maintainable, with easy access to the different parts of the device.
	2	Equipment is very difficult to maintain because of complete or partial parts' inaccessibility.
Equipment Installation		
Scores	0	Equipment installation requires general technical knowledge. No special utilities or services required
	2	Equipment installation requires highly specialized technical expertise. Special utilities, frequency adjustment, and information technology intervention required
Equipment Repair		
Scores	0	Equipment easily repairable, with easy access to replacement parts
	2	Equipment repair requires specialized knowledge. Vendor support required for replacement parts' accessibility. Full service contract highly recommended
Equipment Connectivity		
Scores	0	Device is stand-alone with independent operation.
	2	Device requires to be connected to other systems through the Web or local distributed wireless monitor systems. Regular software upgrade and high risk of incompatibility with connected environment

5.4.3.10 Missed Maintenance

Missed maintenance is the number of missed preventive maintenance per one year. To develop score index for this factor, we suggested that equal or more than 2 times of missed PM is considered a high level for missed preventive maintenance of medical equipment. The proposed score index is shown in Table 5.8.

5.4.3.11 Downtime Ratio

The Downtime for medical equipment means that the duration in which the equipment is out of service due to failures [81]. Accordingly, the downtime ratio is a ratio between downtime and certain duration in years, or months, or weeks, or days. In our proposed model, the downtime ratio is considered in days. Based on our experience, we propose 20% as a maximum acceptable level for this ratio as illustrated in Table 5.8, in addition to the classification into 3 levels of assessment.

5.4.4 Results of Proposed Model

For model verification, we tested the proposed model on a data set for only one year of two Italian hospitals in Piedmont province. The two hospitals are general hospitals that incorporate several clinical departments. The medical equipment information is extracted for two hundreds devices. Seventy different types of equipment belonging to 32 departments for both of hospitals were analyzed.

5.4.4.1 Data Acquisition

The data of investigated equipment is obtained from Computerized Maintenance Management System (CMMS) for every hospital for only one year 2012. The data set is classified into three types of data; raw data, linguistic data, and score data. The raw data uses the required standard data of equipment such as acquisition date; the linguistic data uses the raw data that is required for identification of critical criteria of medical equipment, and the final score data, which translates the linguistic data to scores based on the index listed in Table 5.8. We attached all utilized data in Appendix B.

The raw data for each device includes; the equipment name, brand, model, serial number, purchasing date, department name, failure rate, downtime interval, the expected life time, and last preventive maintenance date as shown in Table 5.10. The linguistic data includes, function, physical risk,

maintenance requirements, utilization level, area criticality, device criticality, failure rate category, life ratio, complexity degree, number of missed maintenance, and downtime ratio. Table 5.11 demonstrates an example of the extracted data of equipment utilizing the raw data, whereas a sample of the final data incorporating the scores of parameters and the resultant priority scores is given in Table 5.12.

Table 5.10 Examples of raw data set of the investigated medical equipment for PM prioritization

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age[59]	Failure rate	Downtime (days)	Last PM
1	Anesthesia unit	1	Datex ohmeda	Astiva 3000	Operating room	01/01/1998	14	10	2	2	22/08/2012
2	Ventilator	2	Siemens	Servo i	Resuscitation	09/08/2004	8	10	0	0	31/12/2011
3	Defibrillator	2	Nihon Kohden	Cardiolife tec7731R	First aid	04/01/2005	7	8	5	180	18/01/2012
4	Mammography	1	GE	Senographe 800T	Radiology	01/01/2000	12	10	1	3	31/12/2011
5	Infant incubator	1	Datex ohmeda	Giraffe omnibed	Pediatrics	05/01/2005	7	10	2	8	28/06/2012
6	Ultra sound	2	Esaote	Technos	Radiology	02/03/2001	11	12	2	2	31/12/2011
7	Syringe pump	1	B.Braun	Perfusor compact	Resuscitation	01/03/2004	8	10	2	45	04/09/2012
8	Monitor	1	Philips	MP 90	I.C.U	12/12/2005	7	10	9	9	05/09/2012
9	Light source	2	Wolf	4.251.001	Endoscopy	01/01/1996	16	8	11	64	10/10/2012
10	Phototherapy	1	Datex ohmeda	Biliblanket+	Pediatrics	07/07/2004	8	10	1	1	26/06/2012
11	Pulse oximeter	1	Mindray	PM 50	Inpatients	15/02/2008	4	5	1	1	31/05/2012

Table 5.11 Examples of linguistic data set of the investigated medical equipment for PM Prioritiztion

No	Function	Physical Risk	Maintenance Requirements	Utilization Level	Area Criticality	Device Criticality	Failure Rate category	Life Ratio	Complexity Degree	# Missed Maintenance	Downtime Ratio (%)
1	Life support	Death	Extensive	High	Urgent	Critical	High	1.4	High	0	0.548
2	Life support	Death	Extensive	High	High	Critical	Low	0.8	High	2	0
3	Life support	Death	Above average	Medium	Urgent	Critical	High	0.875	Medium	1	49.315
4	Diagnostic	Misdiagnosis	Extensive	High	Medium	Critical	Medium	1.2	High	2	0.822
5	Life support	Injury	Above average	Medium	High	Important	Medium	0.7	Medium	1	2.191
6	Diagnostic	Misdiagnosis	Above average	High	Medium	Important	Medium	0.917	Medium	2	0.548
7	Therapeutic	Inappropriate therapy	Average	High	High	Important	Medium	0.8	Low	1	12.328
8	Monitoring	Misdiagnosis	Average	High	High	Important	High	0.7	Medium	0	2.466
9	Diagnosis	Misdiagnosis	Average	High	Medium	Important	High	2	Low	0	17.534
10	Therapeutic	Injury	Below average	Medium	High	Important	Medium	0.8	Low	0	0.274
11	Monitoring	Misdiagnosis	Below average	Medium	Low	Necessary	Low	0.8	Low	1	0.274

Table 5.12 Examples of final scores of the investigated medical equipment for PM prioritization

No	FN	PR	MR	UL	AC	DC	FR	LR	CM	MM	DR	PS (%)
1	5	5	5	3	5	3	3	3	3	1	1	96.74
2	5	5	5	3	4	3	1	3	3	3	1	92.66
3	5	5	4	2	5	3	3	3	2	2	3	89.75
4	3	3	5	3	3	3	2	3	3	3	1	80.94
5	5	4	4	2	4	2	2	2	2	2	1	77.28
6	3	3	4	3	3	2	2	3	2	3	1	71.49
7	4	3	3	3	4	2	2	2	1	2	2	68.05
8	3	3	3	3	4	2	3	2	2	1	1	67.18
9	3	3	3	3	3	2	3	3	1	1	2	66.02
10	4	4	2	2	4	2	2	2	1	1	1	61.85
11	3	3	2	2	2	1	1	2	1	2	1	48.48

5.4.4.2 Results Analysis

By applying the data set as demonstrated in Tables 5.10 – 5.12 to the proposed QFD model, we can quantify the proposed model according to the final priority scores result. The output priority index gives the priority level for every device based on model implementation. By utilizing the result priority scores percentages, we proposed to classify preventive maintenance priority into *five* groups according to priority score percentage (PS) value as

1- Group I, very high priority class
2- Group II, high priority class
3- Group III, medium priority class
4- Group IV, low priority class
5- Group V, minimal priority class

The first class is very high priority class and includes equipment that should be go under PM within two weeks in case of priority score percentage equal or greater than 80. In second class, PM should be performed within one month if priority percentage in range 70 to 80. Group 3 is medium priority, contains all equipment that should be considered for PM within 2 months in case of priority percentage in range 60 to 70. Class 4 is low priority, includes all equipment with priority percentage of 50 to 60, and in this case PM should be performed within 3 months. Finally, all equipment with priority percentage less than 50 could be visually inspected and considered for next PM as minimal preventive maintenance. Figure 5.11 shows the resultant priority index of medical equipment preventive maintenance based on the resultant priority score of the proposed QFD model.

In application, according to data set of investigated equipment and the suggested QFD priority index output, 15% of equipment needs very high priority preventive maintenance, 19 % should be included as high priority, 30 % should be considered as for medium priority, 27% for low priority, and finally 9 % should be with minimal priority and considered for preventive

maintenance next time. Figure 5.12 shows the priority index for investigated medical equipment.

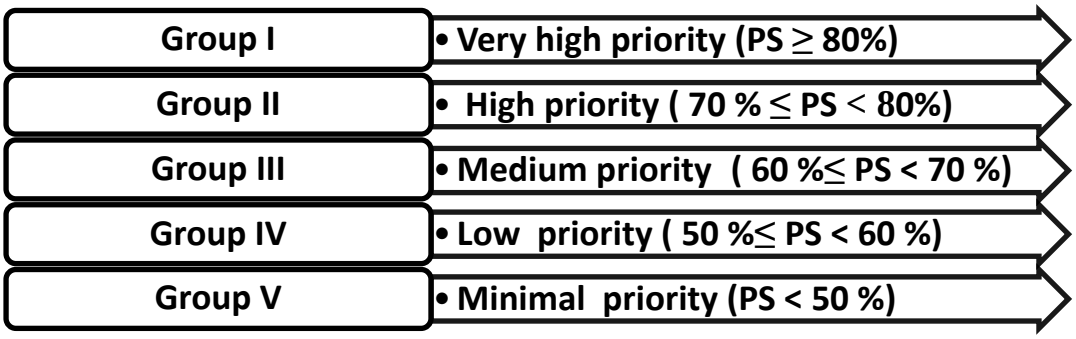


Fig. 5.11 PM priority index groups according to priority score values (PS) of the proposed QFD model.

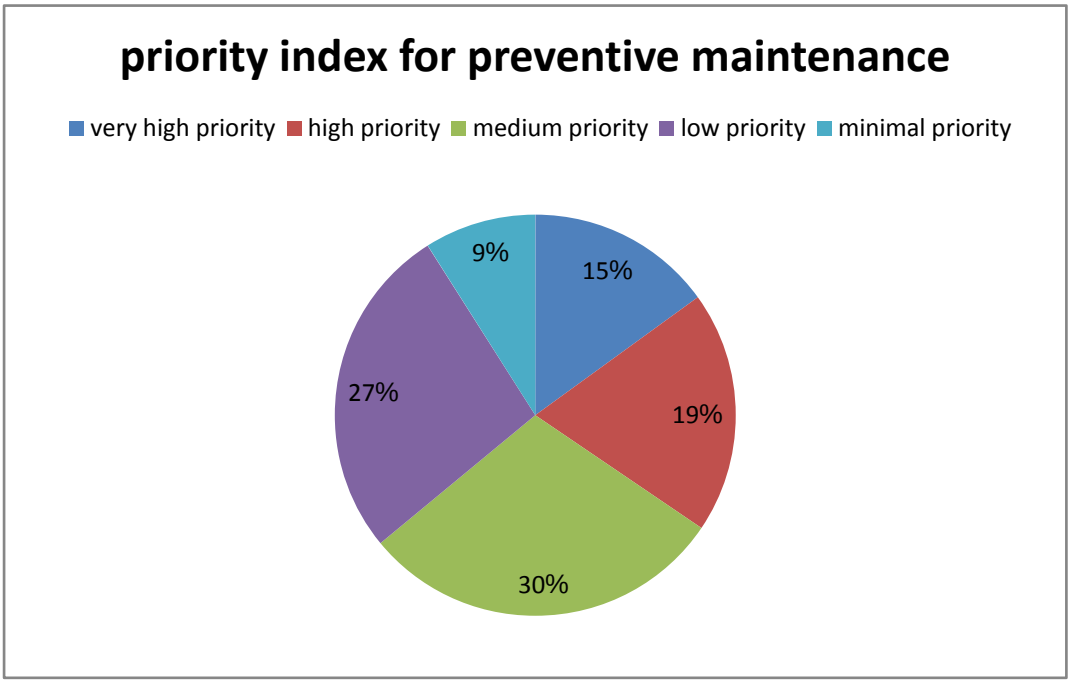


Fig. 5.12 Results of PM priority index for investigated equipment.

By analyzing the result, very high priority class incorporates all equipment with high risk criteria, relatively high mission based criteria, in addition to complex equipment. Anesthesia units and ventilators are examples of this class. High priority group contains relatively high risk criteria and

mission based criteria in addition to high missed maintenance. Ultrasound devices and defibrillators are examples of those devices. Medium priority class is considered for equipment with relatively high utilization level, area criticality, and old equipment such as monitors. Low priority class contains old equipment not risky devices such as pulse oximeters. Relatively stable equipment doesn't need preventive maintenance. The results are consistent with the classifications given by an experienced clinical engineer.

5.5 Proposed Model of PM Scheduling of Medical Equipment

The model is proposed to solve the problem of seeking the optimal schedule of PM for medical equipment at public hospital using ACO algorithm. The idea of ACO solution is representing the problem as graph made by nodes and edges among nodes. A solution is built by adding to the current partial path a new node, moving along the link connecting the nodes. The main steps [91] of ACO algorithm are described as follows.

1. *Pheromone initialization* with a small random value for each link.
2. *Solution construction for each ant*. The construction starts with an empty partial solution and proceeds iteratively by adding to the current path a new node, until the destination (complete solution) is reached. In order to choose the new edge to travel, each ant takes a decision based on a transition probability. This parameter takes into account the pheromone trails, memorizing the solutions already have been visited, and the heuristic probability of edges, that is a measure of the improvements due to the choice of certain node.
3. *Pheromone update*. The evaporation phenomenon allows ants to explore a wider solution region, avoiding the achievement of the same solution too fast.
4. *Reinforcement of pheromone amount* according to the solution quality.

5. *Stopping criteria verification*. The algorithm restarts from step 2 (all ants returned to the starting nodes) until the stopping criterion is verified. Generally, the evaluation stops when a fixed number of iterations are reached or when a satisfactory solution is found.

Based upon the previous algorithm steps, the proposed algorithms for intended application will be developed. The authors decided to implement two algorithms in order to increase the complexity of the model step by step, in addition, to be noticeable if any improvements are occurred for the second one. In summary, the two algorithms are proposed to provide an optimal sequence for PM accumulatively. At the beginning of development, we have to know further information about suggestions and notations, which are described in the following subsection.

5.5.1 Algorithms Formulation

The purpose of the algorithms is to find the optimal scheduling sequence of PM for medical equipment regarding their priority index over planned durations of PM in order to reduce mobility time, and consequently the labor and the maintenance costs. We shouldn't forget that, we have already a list of medical equipment with priority weights for PM generated from the previous QFD model. In addition, the planned horizon for PM is supposed to be three months for all devices. Thus, we consider the priority index for every device in the proposed algorithms. In reality, PM deals with places, individuals, time, and equipment; therefore, some assumptions are made for both algorithms as following

1- There is only one technician for preventive maintenance
2- The working days are 5 days a week with average hours 6 hours a day
3- The required maintenance durations for medical equipment are proposed based on the complexity level of equipment.
4- The planning horizon is a finite time and calculated in weeks (12 weeks)
5- Delay times are calculated in hours.

The notations for problem formulation are

N number of equipment

i index of equipment

W_i priority weight of equipment i

D_i delay time of equipment i

T total PM duration

S_i distance score index of equipment i

F heuristic function

5.5.2 Proposed Algorithms

In order to solve the problem of optimal sequential PM sequence, we proposed two algorithms both based on ACO and differing for the heuristic function. The first algorithm is the simplest one and is considered the basic of the second one. The first algorithm generates the best Sequential Preventive Maintenance Schedule (SPMS) taking into account only the medical equipment priorities. The second algorithm is designed starting from the first one, giving the solution in terms of priority index of medical equipment and the location of equipment (departments) to identify the best SPMS. The algorithms are developed considering the previous procedure of ACO. Both versions of algorithm have common parameters such as the planned PM duration, calculation of the delay time, calculation of estimated maintenance duration, and considering the priority weight for every device. The general proposed SPMS algorithm is demonstrated in Fig. 5.13.

5.5.2.1 First SPMS Algorithm

The proposed first SPMS algorithm was developed in order to find the best sequence of PM for the prioritized list of medical equipment, which was developed in the previous chapter. In addition, it was developed to identify the optimal parameters for ACO implementation. In that list, five categories of medical equipment were identified according to their need of PM. Specifically

in this case, we consider only the equipment in first four classes (182 from 200 pieces of equipment), because the last category includes only the devices that not require PM.

1- Initialization of all parameters α, β, ρ, m, e;
<< m == ants , e == equipment >>
2- **while** ending condition is not met **do**;
3- Initialize pheromone trail $\tau_{ijk} \leftarrow \tau_0$ for each e_{ijk};
4- Compute complexity level of each e_{ijk};
5- Compute maintenance duration based on complexity level of each e_{ijk} ;
6- **for** $1 \leq k \leq m$;
7- Calculate the heuristic function;
8- Calculate the transition probability using (3.8)
9- **until** the path is completed;
10- Update the pheromone trail using (3.9)
11-Select the best path;
12-**end while**;

Fig. 5.13 Proposed ACO algorithm for optimum PM schedule.

The initialization process of SPMS algorithm requires identifying at beginning to determine the number of ants. In fact, the number of ants is set equal to the number of equipment in the first class, since this class requires immediate PM. In our application, 30 devices are the total number of the first class; hence, 30 ants will be used for the algorithm with an ant starting from each of those devices. The heuristic function of first SPMS is formulated as shown in (5.2) in order to maximize the total number of medical equipment to carry out PM, considering the priority weight factor W_i for every device. The priority weight associated for every device ranges from 0 to 1.

$$F\ (max) = \sum_{i=1}^{N} Wi\ \left(1 - \frac{Di}{T}\right) \qquad (5.2)$$

The total PM duration (T) in (5.2) is considered the three months, i.e. 12 weeks as it is discussed. In particular, we assumed that the average total working hours per week is 30 hours (5x6), accordingly, we have 360 maximum working hours in PM duration. The delay time D_i *is the time difference between the recommended maintenance duration (RMD) and the actual maintenance duration (AMD) for each device.*

AMD is estimated according to the complexity level of equipment. In the previous section, we supposed three levels of complexity based upon [75]; *high*, *medium*, and *low*. In particular, we used higher values of AMD for high complexity level devices. Moreover, we implemented different durations for different trails in order to understand the impact of AMD on the best solution. At the end, we decided to use 2 hours for high complexity level equipment, 1.5 hours for medium complex equipment, and finally 0.5 hour for low complex equipment.

On the other hand, RMD represents the time limit for doing PM on each specific category of devices. Since we have four subcategories for PM priority, we suggested four PM durations for every class. Specifically, we set a limit of 60 hours for the first class, because we previously suggested two weeks for this category. The limit setting of the second category is 120 hours, i.e. four weeks, whereas, 240 hours (8 weeks) is the limit time of the third category. The final category limit is set as 360 hours i.e. 12 weeks for the fourth class.

The procedure of SPMS algorithm as shown in Fig.5.13 requires initialization of α, β, and ρ based on the intended application. Therefore, for algorithm implementation, we supposed that the evaporation rate ρ is a constant value equals 0.3 for both algorithms. In addition, we need to determine the optimal values for α, and β, in order to set up transition probability and pheromone update, keeping in mind that all these parameters ranging from 0 to 1. Figure 5.14 depicts a flowchart of the proposed SPMS algorithm regarding the initialization process, the procedure of the algorithm, and the stopping condition. Appendix C is a copy of the first SPMS algorithm.

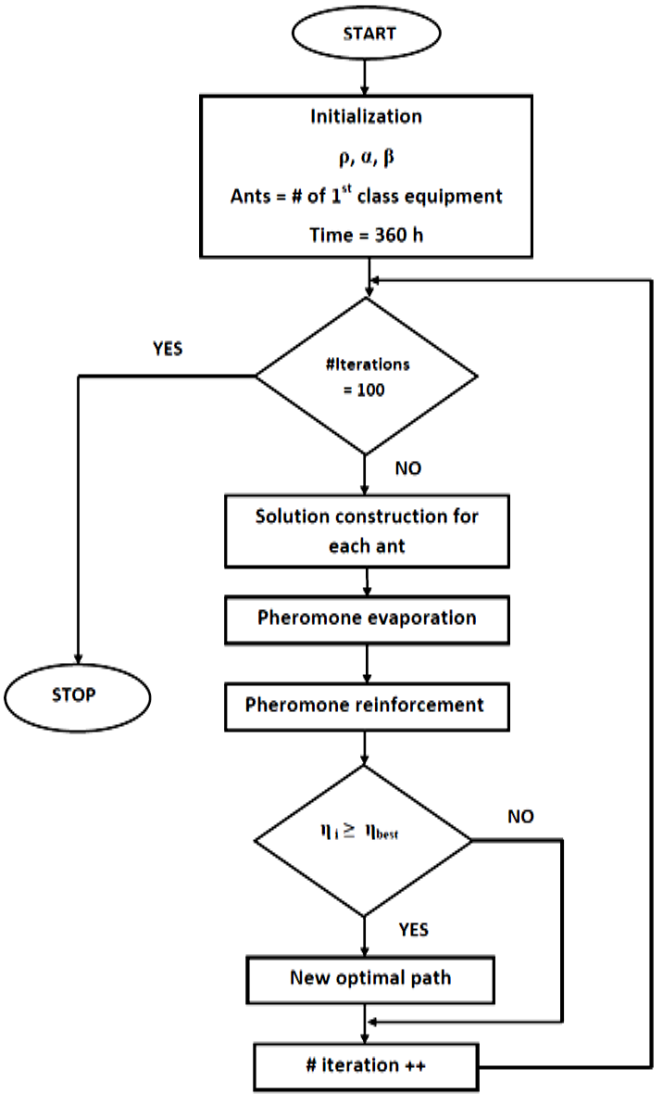


Fig. 5.14 Flowchart of the proposed SPMS algorithm.

5.5.2.2 Second SPMS Algorithm

The second SPMS algorithm is built based upon the first one. In the second algorithm, another parameter is added to the heuristic function, in order to take into account also the location of the medical equipment. As we know, a wide variety of medical equipment distributes in different departments to comply with its intended applications. If we consider the department location as well as the hospital location in case of existence of more than one hospital, could this

consideration reflect on PM sequence positively or negatively? This question is put forward through Fig. 5.15.

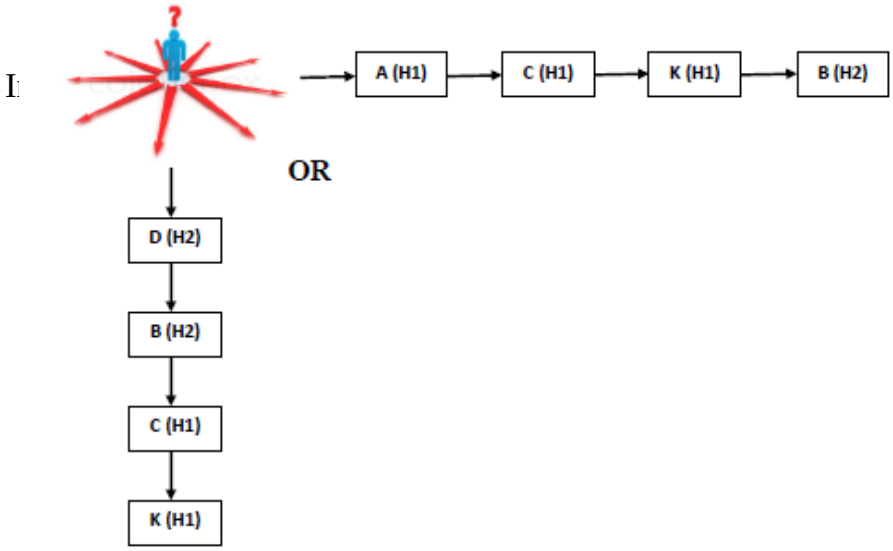


Fig. 5.15 BMET thinking about the optimal sequence has to follow for medical equipment PM in two hospitals (H1&H2).

The second SPMS algorithm tries to answer this question considering priority index of equipment. In our data set, we have two hospitals each of them is not adjacent to the other. The data set of medical equipment is collected from 16 departments for every hospital, meaning we have 32 departments as a total number of departments for the two hospitals. In this case, we develop an algorithm that regards also the time spent by the technician in order to move in different departments of the same hospital and between the two hospitals.

The heuristic function of the second SPMS algorithm is reformulated as shown in (5.3). It maximizes the total number of medical equipment taking into account the distance between the hospitals in addition to the distances between the departments as well as the priority index for PM. The ant's number of this algorithm is the same as in the first SPMS algorithm, 30 ants.

$$F\ (max) = \sum_{i=1}^{N} Wi\ \left(1 - \frac{Di}{T}\right) - \left[\frac{\sum_{i}^{N} Si}{\max S*(N-1)}\right] \qquad (5.3)$$

In the heuristic function, the distance index S_i is modeled as three values; 10 if two consecutive devices in the list are in different hospitals, 5 if two consecutive devices are in the same hospital but in different departments, and 0 when the devices are in the same department. We suggested the distance index with highest score for the far distance and lowest score for the adjacent distance to reflect the role of distance between equipment in final PM schedule. We should note that, the second term of (5.3) presents the penalty term of this equation to maximize the resultant heuristic function.

The second algorithm follows the same procedures that are described for the first one using the same initial values in terms of number of equipment e, the evaporation rate ρ, the number of ants m, the delay time D_i, the total maintenance duration T, and the weighting factor W_i. The second algorithm uses the optimal values for α and β that we determined in the first algorithm, thus, the second SPMS algorithm starting from first SPMS algorithm. The forecasting of the second algorithm is to improve the mobility frequency of the technician between hospitals by considering the location of the device in this algorithm. Appendix D contains a copy of the second SPMS algorithm.

5.5.3 Results of Proposed Algorithms

To evaluate the performance of the developed ACO algorithms, we relied on the list of prioritized medical equipment. Consequently, 182 pieces of medical equipment are considered as the input list for PM. We developed two different versions of ACO algorithms to solve the problem of optimal PM sequence. The algorithms have been coded in MATLAB and run on 3.1 GHZ CPU, Intel core 2 Duo with 8 GB of memory and the operating system is Windows 7 professional.

The maximum number of iterations is set to be 100 for both versions and each algorithm is repeated ten times starting from the same initial conditions in order to test the solution stability. In fact, implementation of the iterations on a computer with these specifications means that every iteration

takes approximately 10 minutes. Accordingly, every trail, which encompasses of 100 iterations consumes approximately 17 hours, taking in to account also that the algorithms have been run on more than one computer.

5.5.3.1 Results of First SPMS Algorithm

At beginning of algorithm implementation, we had to determine the optimal values for α and β to construct the solutions of the algorithm. Table 5.13 illustrates the trails we already performed to identify the best combination of α and β to find the best solution. The best solution is the solution that leads to considering the whole set of prioritized medical equipment in the optimal path over a planning horizon of time (three months in our case) and also gives us the maximum value for the heuristic function.

As we have ten best solutions for every α and β combination (one for every repetition), to evaluate the results of the algorithms in a satisfactory way, we decided to compare the results by means of a set of statistical parameters calculated on the resultant heuristic functions, in order to check the variability among the best ten solutions of the trails.

Table 5.13 Results of first SPMS algorithm in terms of μ and σ, median, and mode of heuristic functions, for different values of α and β.

A	B	μ	σ	Median	Mode
0.5	0.5	119.94	0.12	119.95	120.03
0.6	0.4	120.07	0.31	120.125	N/A
0.8	0.2	120.01	0.25	120.05	120.19
0.4	0.6	119.97	0.27	119.96	119.96
0.2	0.8	120.01	0.27	119.95	119.82

The results in Table 5.13 are shown in terms of mean value (μ), standard deviation (σ), median, and mode of the heuristic functions of all solution obtained for every combination of α and β. The results demonstrate that no wide variation in the standard deviations (σ) of the last three combinations of α and β. Moreover, all solutions include the whole set of equipment in PM list. In

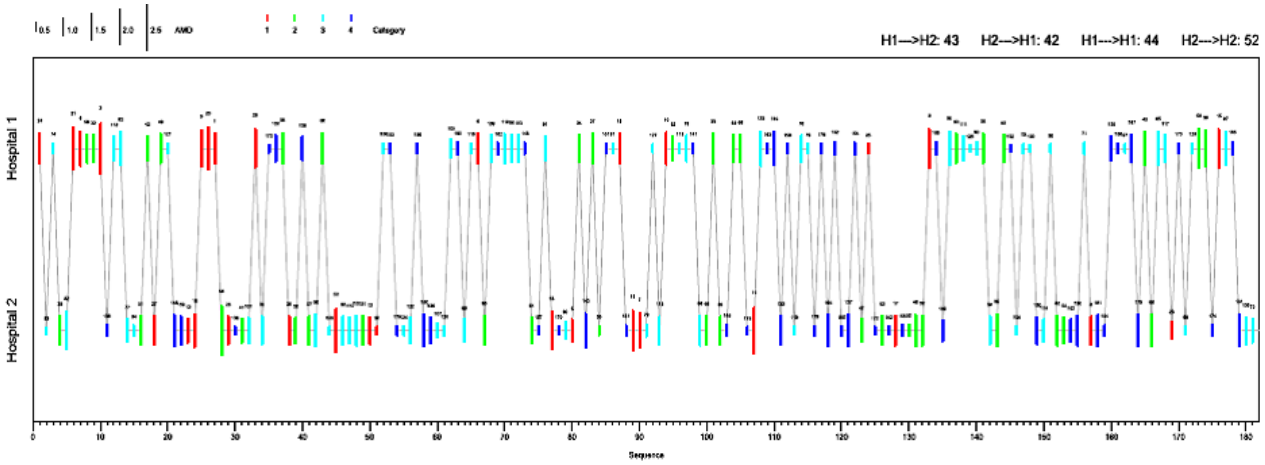
deduction, by regarding these aspects, we consider only the last three combinations for α and β for the second algorithm implementation. As shown in Table 5.13, the proposed values for α and β are ranging between 0.2 and 0.8.

The results obtained with the three optimal set of parameters are depicted in Fig. 5.16 implies the best sequences of PM of medical equipment. The figure illustrates the optimal sequence for the technician in order to perform PM between two hospitals. Fig. 5.16 (a) reports the optimal sequence for PM obtained with α = 0.8 and β = 0.2. Fig. 5.16 (b) presents the optimal sequence in case of α = 0.4 and β = 0.6. Finally, the last sequence that is presented by Fig. 5.16 (c) reveals the optimal sequence with α = 0.2 and β = 0.8. Hence, the technician in this case can choose one of the resultant optimal sequences to follow or has another choice, which is to select the shortest path with respect to his PM schedule.

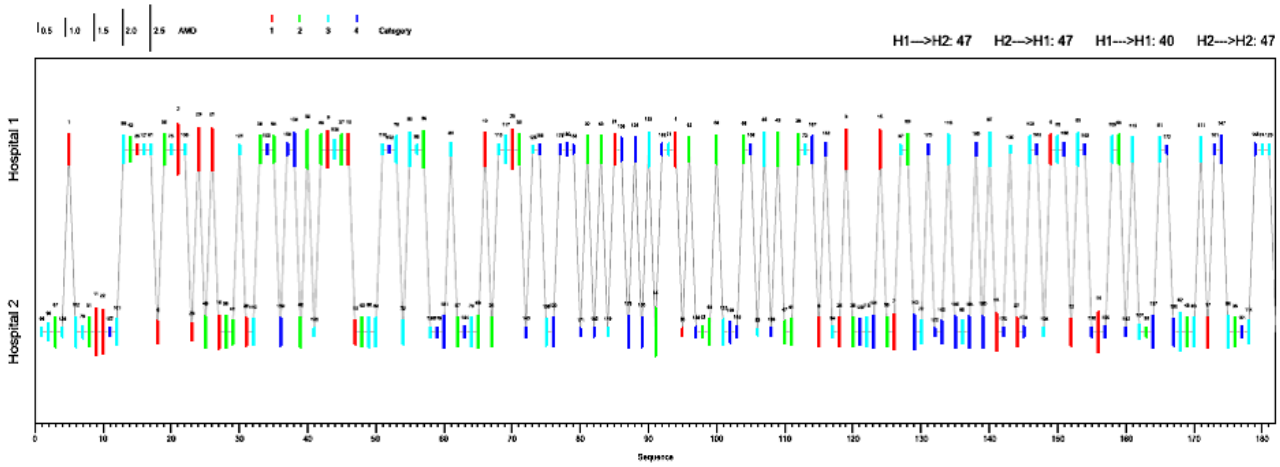
For each graph in the Fig. 5.16, the sequence is presented on X-axis in terms of number of the device, since we have a list starting from 1 to 182, whereas the hospital is presented on Y-axis, since we have two hospitals in our case. The total number of movements or mobility frequencies between different departments of the same hospital (H1→H1 and H2→H2) and between the two hospitals (H1→H2 and H2→H1) is shown at the top of each graph in the figure.

Furthermore, as we have four categories for priority list, we addressed it with color codes in which red color is given for highest priority, green is used for second priority, cyan is used for third category, and blue color is given for the lowest priority. In addition, we presented the AMD separately for each device, modifying the dimension of the maintenance duration for everyone. AMD scale starting from 0.5 to 2.5 as illustrated in top far left of the figures.

Panel (a)



Panel (b)



Panel (c)

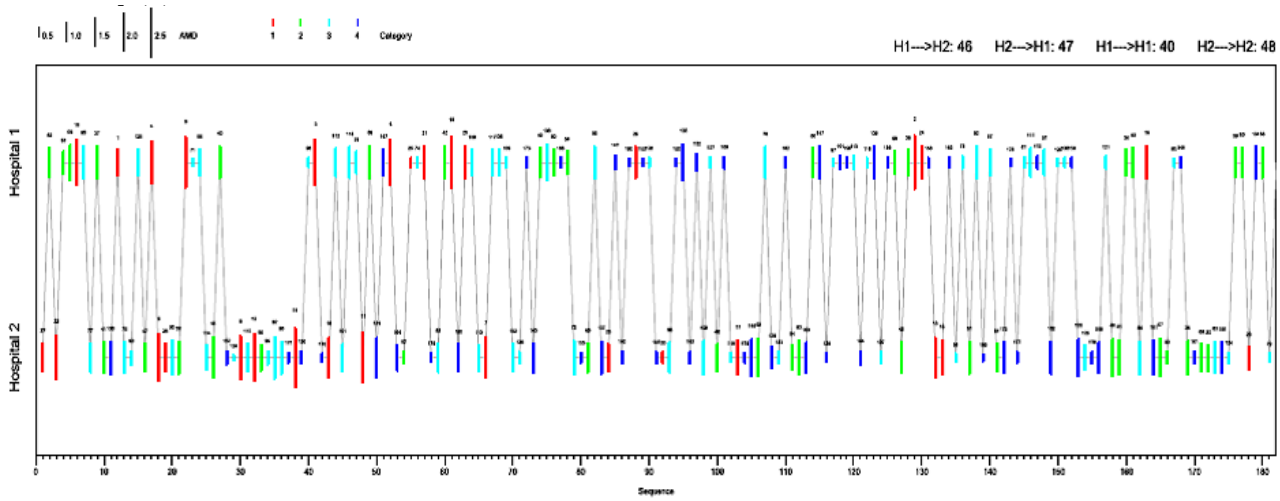


Fig. 5.16 The optimal PM sequence results using first SPMS algorithm with different three combinations of α and β: (a) α = 0.8 and β = 0.2, (b) α = 0.4 and β = 0.6, (c) α = 0.2 and β = 0.8 respectively.

5.5.3.2 Results of Second SPMS Algorithm

The second SPMS algorithm has been implemented using the three optimal combinations for α and β. All the other parameters, such as number of ants, number of iterations and repetitions, and evaporation rate for every combination are kept unchanged with respect to the first one. As in the first algorithm, the statistical analysis results for the heuristic function are made and presented in Table 5.14 for each tested α and β combination.

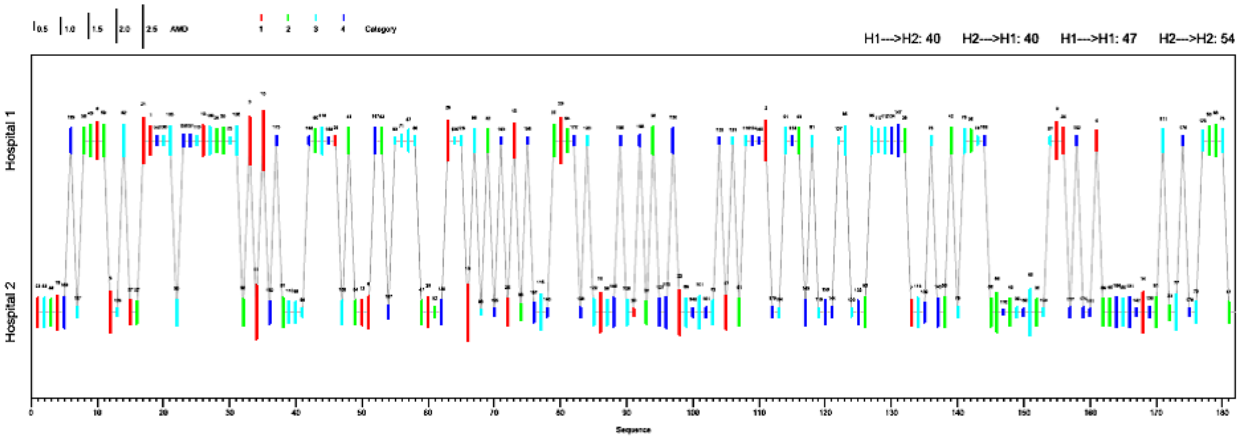
Table 5.14 Results of second algorithm in terms of μ and σ, median, and mode of heuristic functions, for different values of α and β.

A	B	μ	σ	Median	Mode
0.8	0.2	119.89	0.37	119.92	120.01
0.4	**0.6**	119.88	0.15	119.89	120.02
0.2	0.8	119.99	0.28	119.89	119.89

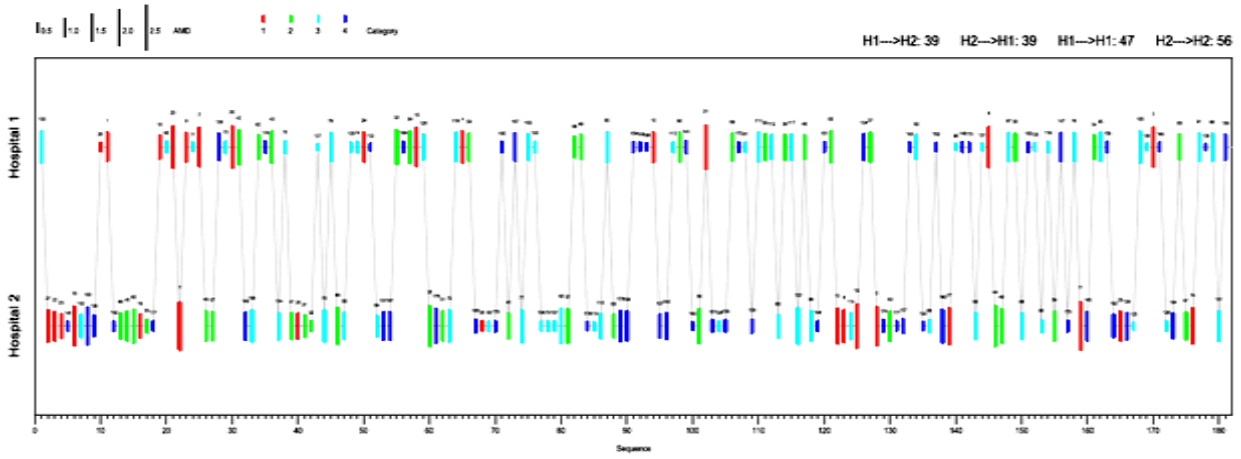
Obviously, Table 5.14 emerges that the combination of α = 0.4 and β = 0.6 gives the lowest standard deviation for the heuristic function of this combination. Accordingly, this reflects the existence of low variability within the solutions of the heuristic function. As the algorithm considers the location of the equipment, therefore, an improvement is expected to be occurred in the optimal sequence of PM by reducing the mobility frequency between hospitals.

Figure 5.17 illustrates the optimal sequence of medical equipment based on the second SPMS algorithm with three different combinations of α and β. The results of mobility frequency obtained in Fig. 5.17(b) reveals that consistency of proposed second algorithm. The combination of α = 0.4 and β = 0.6 gives the lowest number of movements between two hospitals. Therefore, this reflects the consistency of the combination and the algorithm.

Panel (a)



Panel (b)



Panel (c)

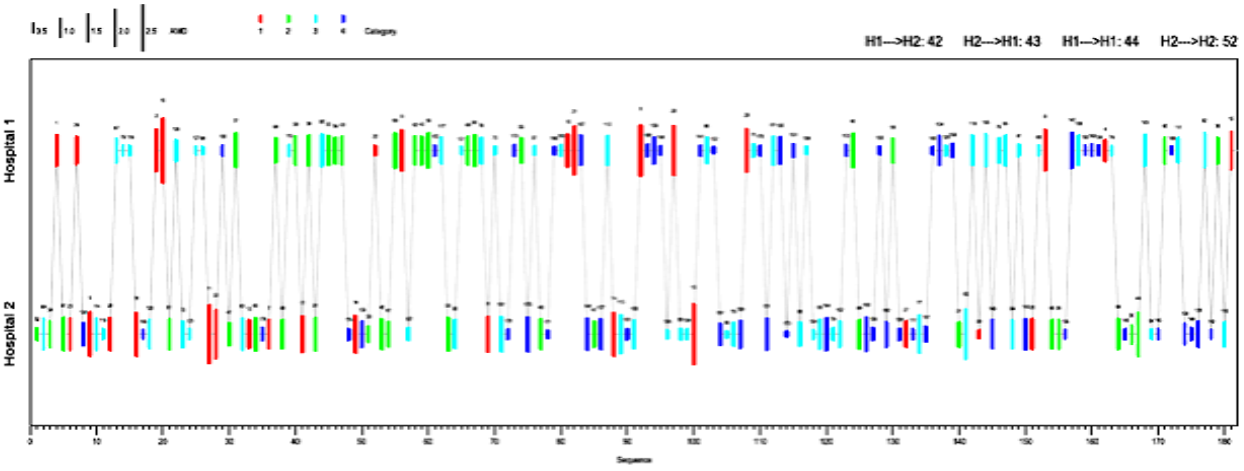


Fig. 5.17 The optimal PM sequence results using second SPMS algorithm with different three combinations of α and β: (a) α = 0.8 and β = 0.2, (b) α = 0.4 and β = 0.6, (c) α = 0.2 and β = 0.8 respectively.

5.5.3.3 Discussion

In this section, two versions of SPMS algorithms are developed based on ACO algorithm in order to identify the optimal sequence of medical equipment for PM task. The results of both algorithm versions are recorded through Fig. 5.16 and Fig.5.17 respectively. The best sequence is the one that maximizes the required list for PM and at the same time minimizes the mobility frequency between the hospitals.

By regarding these criteria between the resultant solutions of both SPMS versions, we can easily reveal the resultant optimum sequence. In particular, by comparing Fig. 5.16 (a) versus Fig. 5.17 (a), we realized that the movements are reduced from 85 to 80 between the two hospitals, i.e. there is a decrease of mobility about 6%. Comparing Fig.5.16 (b) versus Fig.5.17 (b), we found that the mobility frequency is reduced from 94 to 76, i.e. about 20% of mobility is improved by the second one. Finally, Fig. 5.16 (c) against Fig. 5.17 (c) showing that the movements are decreases from 93 to 85, i.e. the mobility frequency is reduced by 9% approximately.

Although the first algorithm is used essentially to find the best parameters for the ACO implementation, the second one implements a more complex and adequate model of the real problem. Both algorithms allow finding the solution containing all medical equipment that needs PM. Moreover, the second algorithm reduces the time spent by the technician, which means saving labor and costs.

Based on the output result of the second algorithm, we collected the medical equipment in every department for each hospital to present the optimal schedule of PM as illustrated in Fig. 5.18. As we have four classes of medical equipment should be undergo for PM, we address the class by a color code as shown in Fig.5.18. We present the device by adding its number inside a cell, mean while its ranking is written above the device cell as indicated in the figure below.

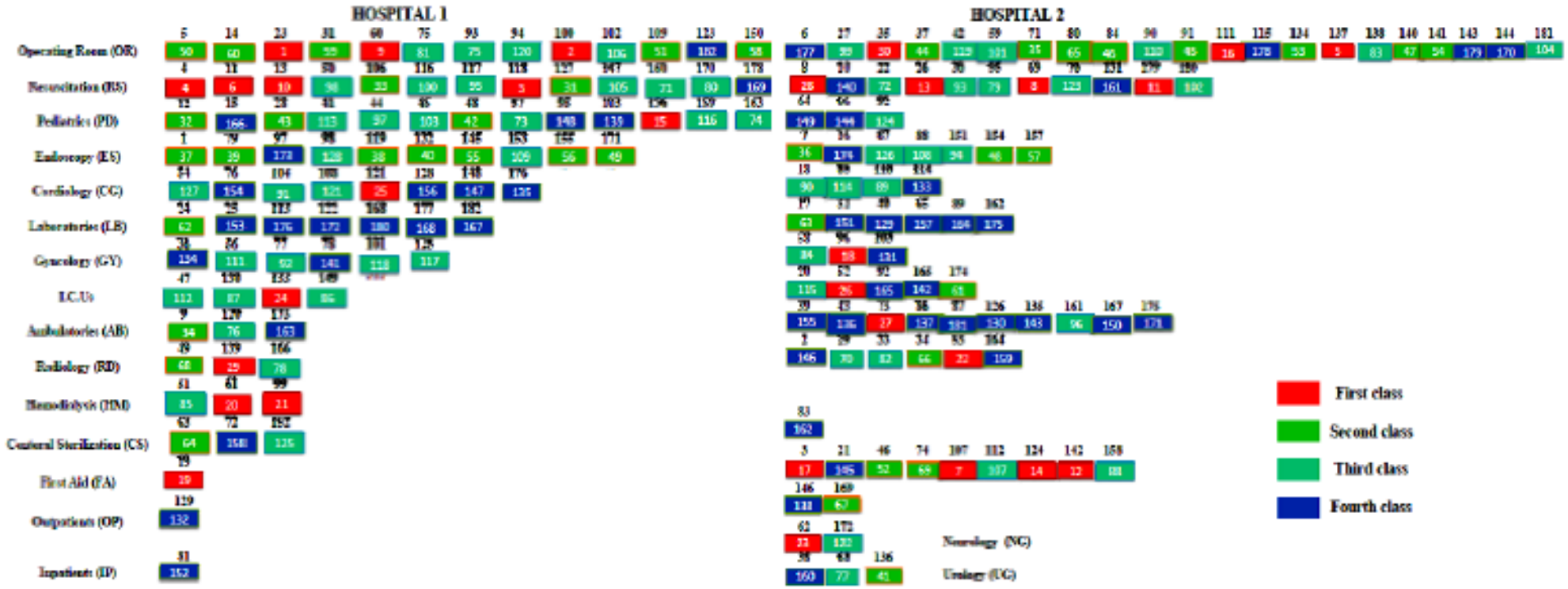


Fig. 5.18 Medical equipment sequence results in different departments of the two hospitals using the optimal solution of second SPMS algorithm, clarifying the equipment number inside the cell and its ranking order above the cell.

5.6 Chapter Conclusions

In this chapter we present new solutions for popular problems of PM of medical equipment. We provide a reasonable prioritization of medical equipment that require PM and at the same time employing this prioritization in order to present optimum scheduling for PM.

The first proposed model is developed using quality function deployment for first time to solve the problem of PM prioritization. The proposed model has proven its validity in real environment correctly separating equipment that needs PM from those that do not need it.

It is important to note that the classification is based on the requirements of patients and clinical staff. By analyzing the results we can state that the risk-based criteria have a great impact on preventive maintenance prioritization decision in addition to criticality and age of medical equipment.

Since QFD technique succeeded in prioritization issue, the developed QFD model can be implemented in other stages of medical equipment management such as replacement of medical equipment.

Also, this work attempts to solve the problem of PM scheduling using ACO algorithm. The authors developed two versions of SPMS for this purpose. Hence, this work presents a first attempt to seek the optimal PM sequence of medical equipment using ACO algorithm.

Both algorithms allow finding a solution containing all the ME that needs PM. Moreover, the second algorithm considers also the location of equipment as an important factor to reduce the time spent by the technician. Reducing the time means also reducing labor and costs. The results proved the consistence of the second algorithm by decreasing the mobility between hospitals.

The study highlights the importance of existence of a detailed history for every device that helps a decision makers in medical equipment management as well as the importance of a prioritized list of medical equipment to perform PM and scheduling.

The proposed algorithms may be used either by clinical engineering departments or maintenance agencies to organize their activities. In fact, as maintenance agencies deal with several hospitals for different kinds of equipment, it is crucial for them to optimize the PM scheduling in order to reduce the labor and costs.

This is a general algorithm that can handle different scenarios with good results. A future work could be to customize the algorithm modifying the heuristic function. A possible personalization is to add other criteria to better represent the department or agency specificities.

Chapter 6

Prioritization and Optimization of Replacement of Medical Equipment

6.1 Chapter Outlines

This chapter covers the replacement issue of medical equipment in terms of priority and optimization. The problems definition is given in section 6.2. Literature review with some examples is given in section 6.3. Section 6.4 presents the proposed model for replacement of medical equipment. In this section we propose a model integrating quality function deployment and genetic algorithm in one framework. A detailed description of proposed quality function deployment is given in subsection 6.4.1, whereas the details of proposed genetic algorithm are provided in subsection 6.4.2. In section 6.5, we demonstrate the results of the model illustrating the results of quality function deployment and genetic algorithm separately in subsections 6.5.1 and 6.5.2 respectively. Finally, chapter conclusions are presented in section 6.6.

6.2 Problems Definition

The replacement decision is an important feature of technology management when costs-benefits ratio goes to negative. According to hospitals, provided equipment poses no clinical or safety risks to patients or staff, it was rarely replaced at the end of its recommended useful life. Although new equipment is generally more sophisticated, more user-friendly and offers improved diagnosis than the equipment it replaces. However ongoing use of equipment that has exceeded its life expectancy without planning for its eventual replacement increases the risk of disruptions to service delivery [36].

In fact, most of hospital planning process tends to focus on current or short-term needs with little or no consideration of future replacement of medical equipment [15]. Moreover, most of replacement decisions are made based on subjective policies with inadequate regard for criteria that could impact replacement decision as well as poor analysis of equipment information. Taking into consideration, approving decision of replacement for any device, would not be realized without substituting it; funding availability plays an important role in replacement decision.

An equipment replacement plan will help to guide the hospital on potential future spending obligations relating to medical devices. To this point, taking into account the previous problems, it is essential for CE department to have a well organized plan that identify properly a list of medical equipment require replacement 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 index for devices require replacement.

Because of the worldwide economic crisis and limited resource, most hospitals do not have sufficient capital funds to approve all equipment replacement requests. Therefore, approved funds that are directed to substitute replacement should be distributed carefully. Thus, it is essential to optimize medical devices require replacement considering their priority and the budget

constraint. Typically replacement is a series of actions and activities that should be carried out by various entities within hospital. Regarding our point of view for replacement process, the synopsis diagram and workflow diagram are given in Fig.6.1 and Fig.6.2 respectively. It is worthwhile to mention that, in this thesis we handle only activities in red color boxes in Fig.6.2.

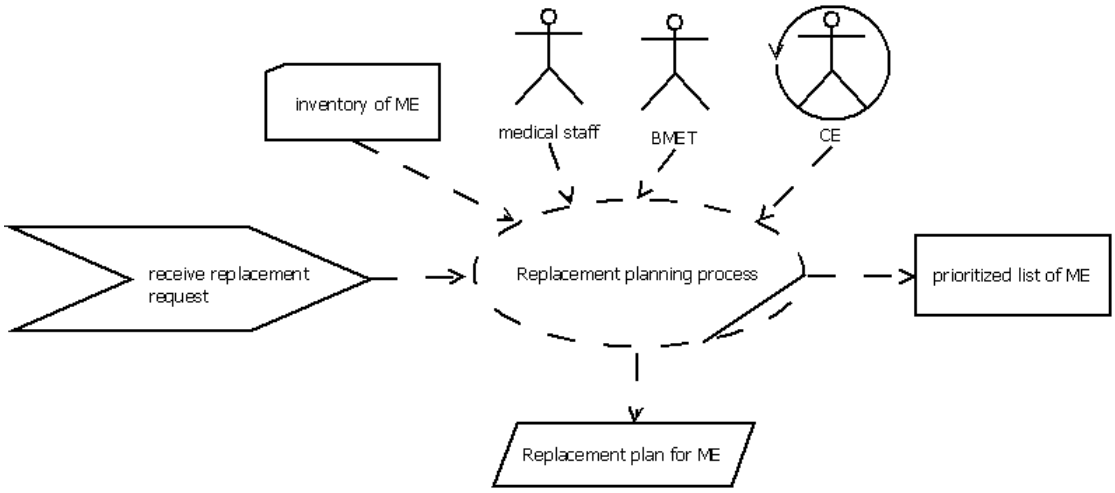


Fig. 6.1 Synopsis diagram of replacement process of medical equipment

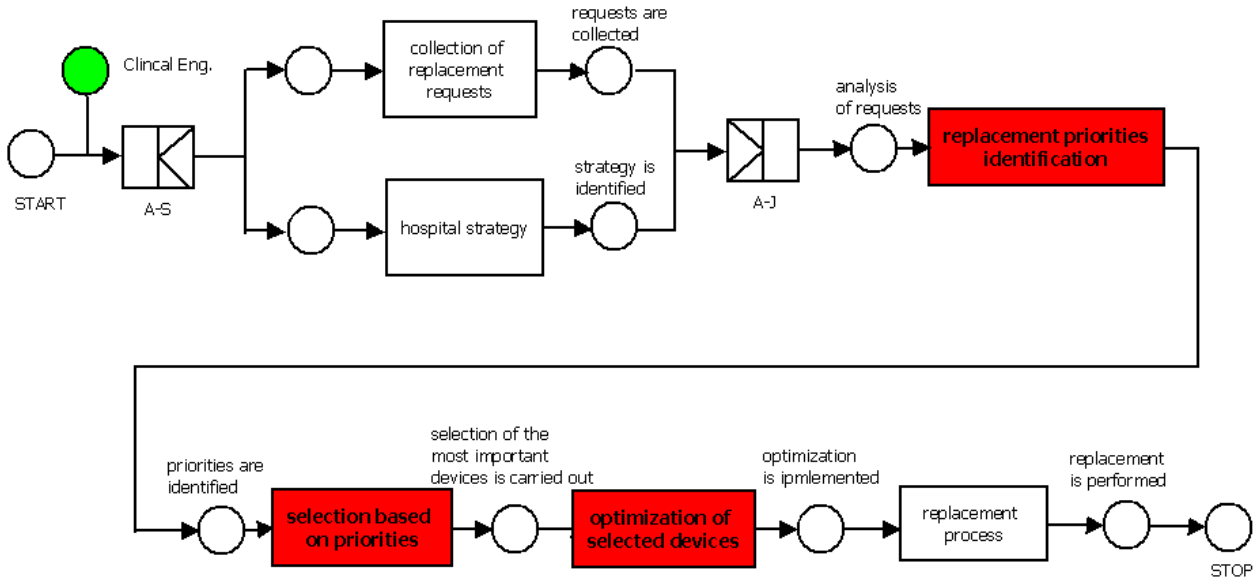


Fig. 6.2 Workflow diagram of replacement process describing the major activities within the process.

6.3 Literature Review

Lawrence Gitman, in his text box on managerial finance, notes that: "Actually, all capital budgeting decisions can be viewed as replacement decision; expansion decisions are merely replacement decisions in which all cash flows from the old asset are zero" [55]. Since 1980s, there are numerous publications in the clinical engineering literature proposing medical equipment replacement planning of particular influence have been recommended, published by recognized professional organizations e.g., Emergency Care Research Institution (ECRI), Association for the Advancement of Medical Instrumentation (AAMI), and the American Society of Hospital Engineering (ASHE); highly regarded journals (e.g.; journal of clinical engineering and biomedical instrumentation & technology).

According to [80, 81], the approaches that are used for replacement of medical equipment are either qualitative or quantitative. In qualitative approach, a combination of different criteria is regarded to approve replacement decision; meanwhile in quantitative approaches, a mathematical model is developed to determine replacement thresholds which lead to a realistic replacement decision. In the following survey, we present examples of qualitative and quantitative approaches.

6.3.1 Qualitative Replacement Approach

Qualitative approaches are based on evaluation of a set of criteria that lead to replacement of medical equipment. These criteria are a combination of different attributes that have impact on replacement decision, such as age, life-cycle costs, risk assessment, durability, user satisfaction etc. The replacement decision is approved according to the contribution of these factors. For more illustration, we present some examples.

One study [30] considered the prioritization of medical equipment by following the next procedure. Compile a list of medical equipment with basic

information, then sort the devices based on their retirement date. Add another column calculating the cumulative cost of replacement. Determine where the medical equipment "cut off" line is, based on the available budget for replacement as shown in Table 6.1, and then prioritize replacement.

Table 6.1 Sorted basic data matrix with cumulative replacement cost column, a "cut-line" has been established at $27000 as an example of life-cycle cost [30].

Equipment Name	Manufacturer	Model #	Serial #	Manuf Date	Life Exp (Yrs)	Ret Date	Repl Cost	Cum Repl
Audiometer	Brand A	ABCD 1	1	1987	10	1997	$4,646	$4,646
EKG	Brand B	ABCD2	2	1993	8	2001	$4,220	$8,866
EKG	Brand C	ABCD 3	3	1993	8	2001	$4,220	$13,086
EKG	Brand D	ABCD 4	4	1993	8	2001	$4,220	$17,306
EKG	Brand E	ABCD 5	5	1994	8	2002	$4,220	$21,526
Centrifuge	Brand F	ABCD 6	6	1994	8	2002	$4,571	$26,097
Centrifuge	Brand G	ABCD 7	7	1995	8	2003	$1,117	$27,214
Vital Signs M	Brand H	ABCD 8	8	1996	8	2004	$1,693	$28,907
Centrifuge	Brand I	ABCD 9	9	1997	8	2005	$1,117	$30,024
Audiometer	Brand J	ABCD 10	10	1997	10	2007	$4,646	$34,670
Audiometer	Brand K	ABCD 11	11	1998	10	2008	$4,646	$39,316
Scale	Brand L	ABCD 12	12	1996	14	2010	$725	$40,041

Cut Line

Another example considering this approach is given by [29]. The authors proposed replacement planning could be estimated based on system value changes. The system value can be defined as the estimation of annual revenue projections relied on anticipated procedures and charges. Then the annual revenue is added to the initial system cost to yield the positive portion of system value using data collected through client consultations. Although the validity of this method has not been demonstrated, it represents a simplified approach to life cycle cost analysis and is intended to provide a standard method by which system replacement planning may be quantified.

6.3.2 Quantitative Replacement Approach

Quantitative approach for replacement of medical equipment is based on designing and/or developing a mathematical model or generates a range of scores that contribute in a realistic and comprehensive way for replacement decision. Developing mathematical models for replacement purpose is considered usually employing a set of criteria. Often, the output of these models generates thresholds that help and guide decision makers to approve appropriate decision. The literature is full with extensive models that are used for replacement as presented in the next examples.

In [81], the authors developed a quantitative tool for replacement of medical equipment using fault tree analysis (FTA) tool. The model used a set of technical, financial, and safety criteria to measure the impact of these criteria on replacement decision. The authors consider hazards and alerts as a safety criterion, and the cost & unavailability of medical equipment as financial criteria. For technical criteria, the useful life time of medical equipment is considered, in addition, for first time the vendor support is considered as fundamental technical criteria in replacement model. The authors proposed four groups to classify the replacement priority.

One study developed Equipment Replacement Planning System (ERPS) score index to identify medical equipment most in need of replacement. ERPS consists of a skeleton data base in which the replacement rules have been programmed [84]. Data from clinical engineering department are evaluated by a program from the replacement–rules base to produce a Relative Replacement Number (RRN) for each device in the inventory of a hospital, enabling prioritization of all medical equipment require replacement. The system utilized a set of technical, safety, and financial rules to produce RRN number for every device.

Analytical Hierarchy Process (AHP) is used as analysis tool for decision making in replacement of medical equipment. The structure of AHP takes a

hierarchy form the top considers the goal (replacement decision) followed by criteria and sub-criteria followed by alternatives at the bottom of the hierarchy. The concept of AHP includes two types of measurement; absolute comparison, and relative comparison. The contribution of criteria is evaluated and weighted in this approach by an expert. AHP analysis is performed by software program, once; the weight matrix of criteria and sub-criteria is assigned, the program automatically runs the necessary mathematical operations to prioritize and calculate alternatives final weights. Raw priorities are normalized to facilitate calculations. According to these normalized priority scores, appropriate actions should be considered [50]. The model verification was carried out on a set of nine hemodialysis machines.

Another example uses fuzzy AHP methodology to solve replacement problem in fuzzy environment [18]. Linguistic values are used to assess the ratings and the weights for key components. These linguistic ratings can be expressed in trapezoidal fuzzy numbers. Euclidian distance method is used to calculate the distance between two trapezoidal numbers. Finally, a closeness coefficient of each alternative is defined to determine the ranking order of all alternatives (key components). The proposed model is a general model that could handle different areas for replacement problem solution.

One example proposed solving replacement problem by utilizing heuristic techniques [24]. The authors employed artificial neural network (ANN) for replacement of medical equipment application. According to service cost to acquisition cost ratio and calculating current age to expected useful age ratio and through applying Perceptron ANN software program, the equipment life status is classified into three zones. Zone I remove the equipment from inventory, zone II, the equipment should be under surveillance, and zone III maintain equipment in inventory of medical equipment.

6.4 Methodology

The goal of this chapter is to address the replacement problems of medical equipment in terms of prioritization and optimization according to funding constraint. Since QFD is utilized as a common approach in this thesis as well as its consistency in prioritization process, it will be used in this problem. In addition, the main application of genetic algorithm is to solve optimization problems. Accordingly, we propose to integrate QFD and GA in one framework as shown in Fig.6.3 in order to generate priority index for replacement of medical equipment and then optimize the prioritized list with respect to available budget for substitution.

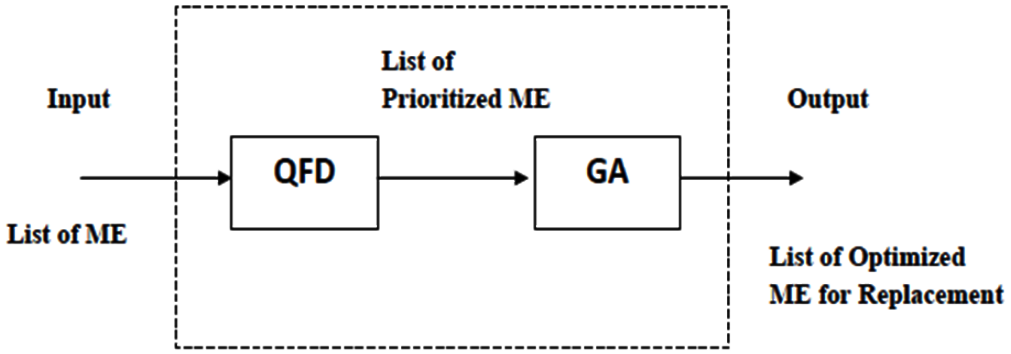


Fig. 6.3 Proposed framework of QFD - GA model for prioritization of replacement of medical equipment

6.4.1 Quality Function Deployment Model

Quality function deployment is used in this model to build the base of proposed model by selecting the most important criteria that impact on replacement decision of medical equipment. By considering these criteria with its resultant weight, a priority index is generated for all devices to find out the prioritized list. The input of QFD is a list of medical equipment provided from general inventory of medical equipment and the output of QFD is the same list of devices but in ranking order.

6.4.1.1 Customer Requirements

In replacement planning, clinical engineering department should consider all old and high risk devices as well as all requests for replacement. Based on our experience, typically, the medical staff including physicians and nurses is responsible to ask replacement considering some reasons such as procurement of new technology and disposal of poor user's interface devices. In addition, BMETs also could ask replacement since they are responsible for maintenance, in case of reporting devices with increasing risk level and deteriorating reliability. Thus, in case of replacement of medical equipment, the medical staff and BMETs are the customers of proposed QFD [94]. The customer requirements are listed relied on both literature and experience of authors as following

- Disposal of poor function devices
- Disposal of obsolete devices
- Disposal of poor physical conditions
- Disposal of high service costs
- Disposal of high risk devices
- Disposal poor user's interface
- Disposal of old devices
- Disposal of unreliable devices
- Disposal of unsupported devices
- Disposal of low utilization level devices

6.4.1.2 Technical Requirements

Technical specifications are designed to meet customer requirements. In case of replacement of medical equipment, clinical engineer is responsible to take appropriate actions towards replacement decision; hence, CE is considered voice of engineer (VOC). By regarding literature [80, 81], technical requirements for replacement are classified into three classes; technical, financial, and safety as shown in Table 6.2.

Table 6.2 Technical requirements for replacement of medical equipment

No	Category	Technical specifications
1	Technical	Technology obsolescence (OS)
2		High downtime (DR)
3		High failure rate (FR)
4		Excessive life ratio (LR)
5		Unavailable spare parts (USP)
6	Safety	Recalls and alerts (RA)
7	Financial	High costs ratio (CR)
8		Back up ratio (BR)

6.4.1.3 Planning Matrix

Planning matrix is considered the landmarks of customer requirements. In this case, customer requirements are evaluated through a competition between Italian hospital and Egyptian hospital. The importance of customer requirements is calculated with respect to the Egyptian hospital as shown in Fig. 6.4. The ranking order of customer requirements reveals that disposal of high risk devices followed by disposal of high service costs come at top ranking of customer requirements [94].

6.4.1.4 Relationship Matrix

Relationship matrix measures the level of relationship between customer requirements and technical specifications. Also, in this application, Cohen scale is used as 9, 3, 1 for strong, medium, and weak respectively. As shown in Fig. 6. 4, among technical criteria and according to the evaluation of investigated hospitals, we notice that technology obsolescence and excessive life ratio of devices have more relations with customer requirements than other technical specifications. In contrast, recalls & alerts and back up ratio have fewer relations with customer requirements than other criteria.

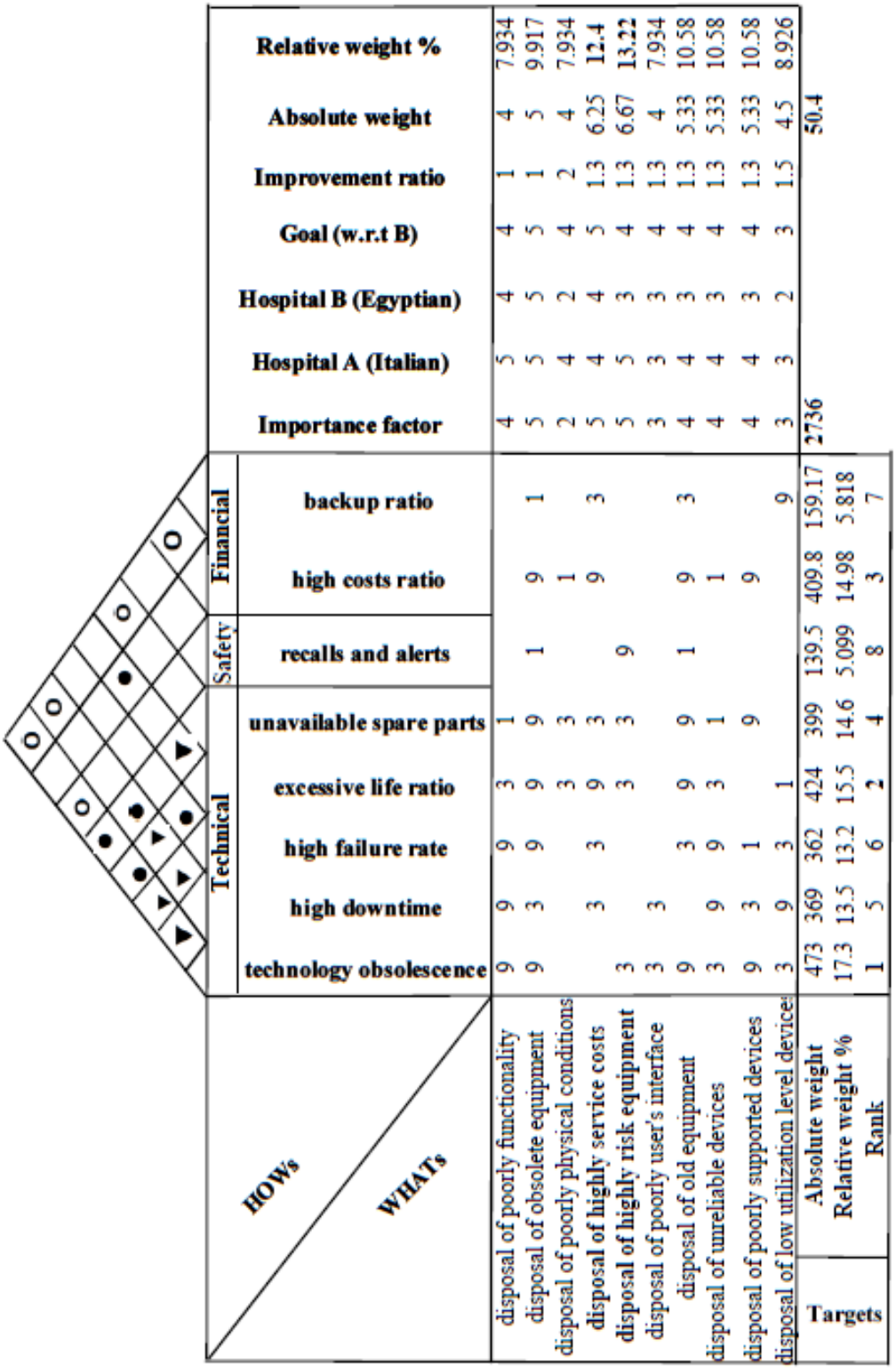


Fig. 6.4 Proposed HOQ matrix for replacement prioritization of medical equipment.

6.4.1.5 Technical Target Matrix

Technical target matrix is output of HOQ matrix. The matrix is developed regarding importance level of customer requirements to identify the most relevant criteria of replacement process. According to the resultant relative weight of technical characteristics the influential specifications are identified. The output of this matrix is an equation that reflects importance weight of every technical criterion to produce the priority score of each device. Equation 6.1 presents the priority score index for replacement as a result of proposed HOQ. The abbreviations refer to the terms that are described in Table 6.2.

$$R = 17.3\,OS + 13.5\,DR + 13.2\,FR + 15.5\,LR + 14.6\,USP + 5.1\,RA + 14.9\,CR + 5.8\,BR \quad (6.1)$$

In order to determine the priority score for devices, the technical specifications must be assessed. Table 6.3 summarizes proposed score index for replacement priority. Some of these terms are assessed using the same score index for preventive maintenance prioritization such as downtime ratio, failure rate, and life ratio. The other terms are suggested as listed below

- **Technology obsolescence**: it means the device is nearing the end of its rated useful life time. When equipment has been identified for obsolescence in at least two years, work begins on selecting replacement. Well –maintained devices that are retired in favor of newer technology may be considered for donation [36].
- **Unavailable spare parts**: the spare parts unavailability reflects the discontinuation of any medical equipment where the availability of spare parts can maximize the utilization of medical equipment [80, 81].
- **Recalls and alerts**: unfortunately medical equipment can cause harm to both patients and users if it is used improperly or it fails to perform

safely [113]. Recalls and alerts mean the notification of adverse events existence from regulatory agencies and/or manufacturers due to accident investigations [81].

- **Costs ratio**: the term is the ratio between all expenditures of medical equipment including operation such as accessories and service costs such as repair parts to the acquisition price of the device. Based on our experience, we propose thresholds to classify the term.

Table 6.3 Description of technical terms of proposed HOQ and their score index [94]

Parameter	Description	Thresholds	Score
Technology obsolescence	Technology status	Yes	1
		No	0
Downtime ratio	Ratio between downtime in days to days ayear	Ratio ≥ 20 %	3
		10% ≤ Ratio<20%	2
		Ratio < 10 %	1
Failure rate	Number of failures a year based on device criticality	≥2 for critical, ≥4 for important, ≥5 for necessary	3
		1 for critical, 2-3 for important, 3-4 for necessary	2
		0 for critical, ≤1 for important, ≤2 for necessary	1
Life ratio	Ratio between age to expected life time of a device	Ratio > 80 %	3
		50% < Ratio ≤80%	2
		Ratio ≤ 50 %	1
Unavailable spare parts	Checking spare parts availability	Yes (unavailable)	1
		No (available)	0
Recalls & alerts	Existence of recalls & alerts threat safe utilization of the device	Yes	1
		No	0
Costs ratio	Ratio between all services costs to purchasing price	Ratio ≥ 45 %	3
		25% ≤ Ratio<45%	2
		Ratio < 25 %	1
Back up ratio	Ratio between low utilization devices to all devices in the department	Ratio ≥ 25 %	3
		10% ≤ Ratio<25%	2
		Ratio < 10 %	1

- **Back up ratio**: this factor was previously defined as the number of available alternatives in case of a given piece of equipment unavailability [107]. Since this definition is not widely adopted especially in developing countries because of limited resources, we assume new assessment for this factor. It is the ratio between low utilization devices to all devices in the department. Identification of low utilization devices depends on department strategy.

6.4.2 Genetic Algorithm Model

A genetic algorithm (GA) is a search technique that imitates the natural selection and biological evolution process. GA has been used in a wide variety of applications, particularly in combinatorial optimizations problems and they were proved to be able to provide near optimal solutions in reasonable time [62]. The purpose of GA application in this study is to optimize the prioritized list of medical equipment requires replacement considering the priority weight and the available budget for replacement. In general, GA procedure requires objective function formulation based on the optimization problem, algorithm development, and parameters adaption. The following subsections describe the details of the procedure.

6.4.2.1 Objective Function Formulation

In this study, we model the problem of optimizing the medical equipment for replacement considering their priority weight and the available budget for replacement. In particular, according to the limited resources we propose optimizing only top priority devices. To this point, this implies the urgent and critical devices that should be replaced in order to decrease their probable risk and prevent enduring hospitals with increasing costs. In this case, to optimize devices according to available budget, we should first estimate the prices of new devices to compare it against budget. The proposed objective function of the model is given in Equations 6.2 and 6.3 respectively with their notations.

$$Z = \boldsymbol{max}\left[\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} - \frac{B - \sum_{i=1}^{n} p_i x_i}{B}\right] . K \quad \textbf{(6.2)}$$

$$K = \begin{cases} 0 & \sum_{i=1}^{n} p_i x_i > B \\ 1 & \sum_{i=1}^{n} p_i x_i \leq B \end{cases} \quad \textbf{(6.3)}$$

Z: objective function

w: priority weight of the device

x: the device

p: estimated purchasing price of new device

B: available budget

i: device index

n: top priority devices for replacement

K: budget constraint factor

6.4.2.2 Algorithm Development

Algorithm development in this problem follows the general steps that adopted in GA development. The major steps of algorithm are usually starting with randomly selected populations. The new populations are generated by selecting the fittest solutions by evaluating the objective function, then applying crossover and mutation operators to produce new offspring. The process is repeated until some criteria are met or acceptable solutions are found. In our case, according to the replacement problem and budget constraint, we need to initialize the algorithm with priority weight of devices, the estimated purchasing prices, and available replacement budget and then follow the traditional steps. The proposed GA is developed as follow

1- Insert weights, prices, and budget;
2- Set the generation counter, t=0;
3- Initialize the control parameters;
4- Create the population, P (i);
5- ***While*** the stopping criteria not met ***do***
6- Evaluate the fitness of the solutions;
7- Select parents via Roulette Wheel;
8- Perform crossover to produce offspring;
9- Mutate offspring;
10- Reconstruct new population;
11-end

6.4.2.3 Parameters Adaption

Due to GA being one of random calculations, the calculation of GA is affected by its parameter settings such as population, crossover rate, and mutation rate. In order to optimize the number of replacements of medical equipment, the parameters of GA should be optimized firstly to increase solutions accuracy and avoid redundant running of algorithm. In application, different combinations of populations, crossover probability (Pc), and mutation probability (Pm) as well as iteration numbers are tested to find out the optimum parameters. The research sets up the following combinations of population, iterations, crossover rates, and mutation rates as follow

Populations: 500, 600, 700, 800, 900, 1000, 1200, 1500.

Iterations: 400, 450, 500.

Crossover probability: 0.6, 0.7, 0.8, 0.9, 1.

Mutation probability: 0.1, 0.2, 0.3, 0.4.

6.5 Results

Model validation is implemented using a data set of medical equipment in an Egyptian public hospital. Data set includes 60 pieces of medical equipment for 12 different types belonging to one department; Neonatal Intensive Care Unit (NICU) during three years from 2007 to 2009. As the proposed framework is divided into two models, we present the results separately for every model as illustrated.

6.5.1 Results of QFD Model

The output of proposed QFD as explained in section 6.4.1.5 is the priority index that indicates priority level for investigated devices. In order to obtain the priority score for investigated devices, we classify data set into 3 categories; raw data, derived data, and score data. Raw data includes the basic information like purchasing date, operation costs, and etc. As no hazards or alerts are reported in data set, we assume this term for all devices equal 0. Derived data contains data ratio as well as estimation of levels based on available raw data such as failure rate level. Final score data translates the derived data into score data by utilizing Table 6.3. Examples of raw data, derived data, and score data are given in Table 6.4, Table 6.5, and Table 6.6 respectively.

By applying the data as described above to the proposed QFD, we obtain the output priority score for the investigated devices as shown in Table 6.6. According to the resultant priority score, we propose to classify the replacement priority into ***four*** classes; *very high*, *high*, *medium*, and *minimal or no need for replacement*. The proposed replacement priority classes are depicted in Fig. 6.5. As shown in Fig. 6.5, very high priority contains equipment with R% equal to or greater than 70 %. In second class, replacement should be considered high if R% in range 60% to 70%. Class medium priority contains all equipment within range 50% to 60%. Finally, all equipment with devices less than 50% are considered no need for replacement.

Table 6.4 Data sample of raw data of investigated devices for replacement

Device	Price (L.E)	Purchase Year	Expected life [re]	Age	OP. costs (L.E)	Service costs (L.E)	Total costs (3Y)	Criticality	Downtime (Days/3Y)	Failure rate (#/3Y)	OS	L.U. devices	Total devices
Bilirubinometer, drager	18000	2000	8	9	7500	750	8250	Important	300	7	No	0	3
Ventilator , bearcub 750	70000	1998	10	11	18000	2340	20340	Critical	10	3	Yes	4	14
Infusion pump, sabratec	6700	2000	8	9	3960	0	3960	Important	39	3	No	2	16
Incubator, caleo, drager	90000	2004	10	5	6000	50030	56030	Important	377	3	No	6	32
Infusion pump, aitecs	4900	2004	8	5	3000	890	3890	Important	180	10	No	2	16
Ventilator Takaoka	49000	2005	10	4	21000	5880	26880	Critical	90	5	No	4	14
Blood gases, Roche, cobas	130000	2008	8	1	40000	13800	53800	Important	20	10	No	1	2
Pulse oximeter, nelcor 295	12000	2004	5	5	3000	1800	4800	Necessary	437	3	No	2	18
Monitor, dragger, infinity	40500	2004	10	5	3000	8800	11800	Important	171	2	No	0	9
Mobile X-ray, GE, Shimadzu	115000	2007	8	2	0	0	0	Important	0	0	No	0	1

Table 6.5 Data sample of derived data of investigated devices for replacement

Device	DR %	LR	CR%	BR%	DR Class	FR Class	LR Class	CR Class	BR Class
Bilirubinometer, drager	27.39	1.125	45.83	0	High	High	High	High	Low
Ventilator , bearcub 750	0.91	1.1	29.06	28.5	Low	High	High	Medium	High
Infusion pump, sabratec	3.65	1.125	59.10	12.5	Low	Medium	High	High	Medium
Incubator, caleo, drager	34.43	0.5	62.25	18.75	High	Medium	Low	High	Medium
Infusion pump, aitecs	16.44	0.5	79.38	12.5	Medium	High	Low	High	Medium
Ventilator Takaoka	8.22	0.4	54.86	28.5	Low	High	Low	High	High
Blood gases, Roche, cobas	1.83	0.125	41.38	50	Low	High	Low	High	High
Pulse oximeter, nelcor 295	39.9	0.625	40	11.11	High	Low	Medium	Medium	Medium
Monitor, drager, infinity	15.61	0.5	29.13	0	Medium	Low	Low	Medium	Low
Mobile X-ray, GE, Shimadzu	0	0.25	0	0	Low	Low	Low	Low	Low

Table 6.6 Data sample of score data of investigated devices for replacement

Device	OS	DR	FR	LR	USP	RA	CR	BR	RS	RS%
Bilirubinometer, drager	0	3	3	3	1	0	3	1	195	85
Ventilator , bearcub 750	0	1	3	3	1	0	2	3	164	71
Infusion pump, sabratec	0	1	2	3	0	0	3	2	145	63
Incubator, caleo, drager	0	3	2	1	0	0	3	2	141	61
Infusion pump, aitecs	0	2	3	1	0	0	3	2	141	61
Ventilator Takaoka	0	1	3	1	0	0	3	3	133	58
Blood gases, Roche, cobas	0	1	3	1	0	0	3	3	133	58
Pulse oximeter, nelcor 295	0	3	1	2	0	0	2	2	128	55
Monitor, drager, infinity	0	2	1	1	0	0	2	1	93	40
Mobile X-ray, GE, Shimadzu	0	1	1	1	0	0	1	1	64	27

OS: Obsolescence

DR: Downtime Ratio

FR: Failure Rate

LR: Life Ratio

USP: Unavailable Spare Parts

RA: Recalls & Alerts

CR: Cost Ratio

BR: Backup Ratio

RS: Replacement Score

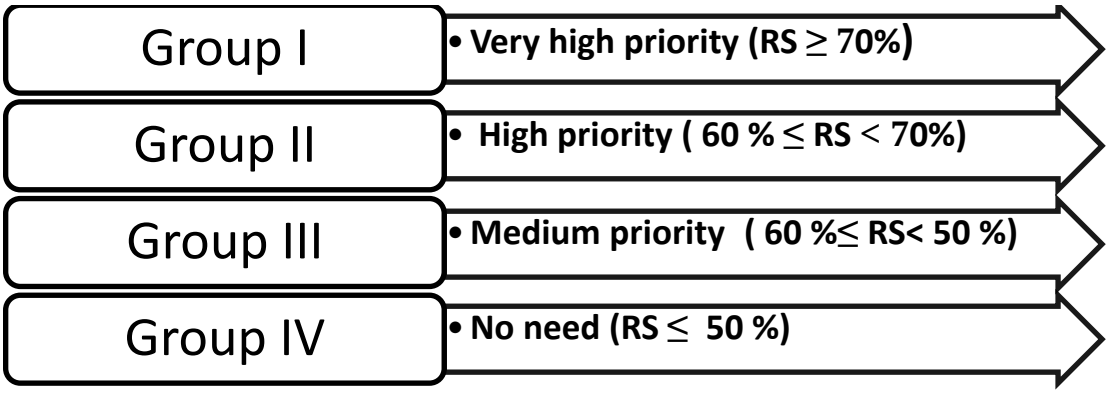


Fig. 6.5 Classification of replacement priority based on proposed QFD model

In application, the data set demonstrates that only 8 devices come as very high priority that requires immediate replacement. In high priority class, 15 devices are the result of this class; their replacement procedures should start as soon as possible. In medium class, 17 devices are considered for medium priority taking into account that this class should be under surveillance. Finally, no need for replacement is the priority result of 20 devices. The pie chart in Fig.6.6 illustrates the proposed replacement classification of investigated medical equipment.

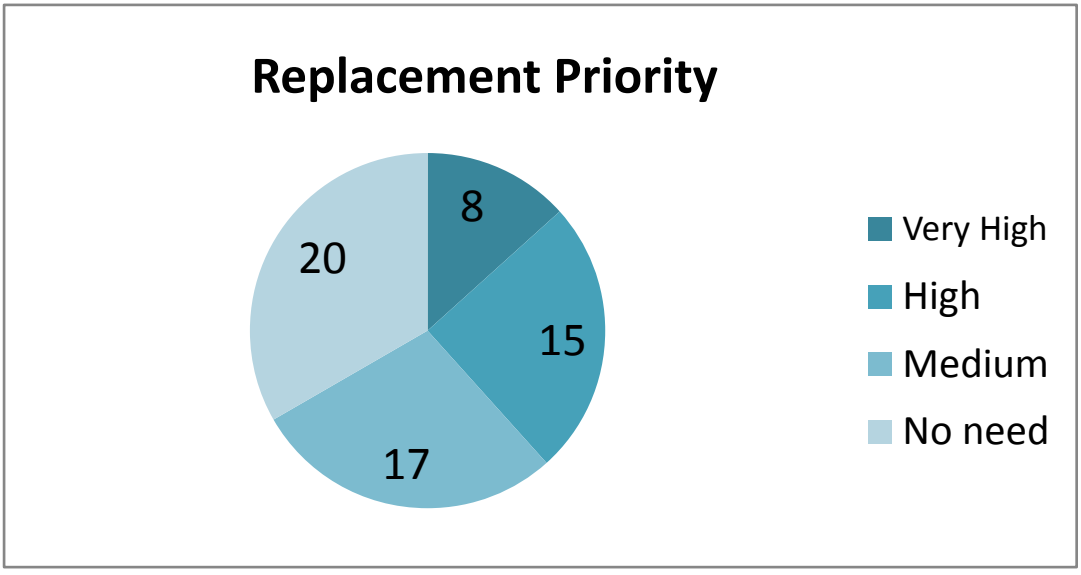


Fig. 6.6 Results of replacement priority of investigated devices using proposed QFD.

6.5.2 Results of GA Model

The purpose of GA model is to optimize top priority devices for replacement considering their priority and the budget constraint. In this study, we assume that the available budget of substitution is less than 30 % of estimated prices of the investigated medical equipment, which are assumed to be estimated in Units. QFD results show that 23 pieces of medical equipment attained top priority of medical equipment that require replacement i.e. 38 % of investigated equipment came at top ranking order. The procedure of replacement of these devices should start as soon as possible. Based on our assumption, the list of 23 pieces of medical equipment is the input of proposed GA. According to device status and our experience, we assume that the estimated prices are 972 units and the available budget is 680 units.

Due to GA being one of random calculations, the final solution may come out differently with different trails. Accordingly, we propose the algorithm is calculated 20 times for every combination in order to find out the optimum parameters of the algorithm as described in section 6.4.2.3 that optimize solutions of the problem. The algorithm has been coded in MATLAB utilizing guidelines in [41] and has been run on 2.1 GHZ CPU, Intel core 2 Duo with 1.96 G RAM Computer.

As we have twenty solutions, we compare the results of algorithm by means of a set of descriptive statistics in terms of mean and standard deviation calculated on the resultant objective functions to find out the optimum solutions with optimum parameters. The first combination is to run different initial populations with different iterations to optimize both of them assuming constant Pc and Pm. The results in Table 6.7 are shown in terms of populations, iterations, mean value (μ), standard deviations (σ), and maximum solutions for every repeat. Moreover, Fig. 6.7 illustrates the relationships between initial populations and best solutions of algorithm in different cases of iterations. The results indicate that the best combination that maximizes solutions with highest

mean value of calculated objective function is **600 populations** with **500 iterations**. It is worthwhile to mention that these parameters are calculated assuming crossover probability is 0.6 and mutation probability is 0.4.

Table 6.7 Results of populations and iterations combinations of proposed GA assuming Pc = 0.6 and Pm = 0.4.

No.	Populations	Iterations	μ	σ	Max. solutions
1	500	400	0.83538	0.033113	3
2	500	450	0.838665	0.03163	4
3	500	500	0.832698	0.029501	3
4	600	400	0.827682	0.022999	1
5	600	450	0.829642	0.025831	2
6	**600**	**500**	**0.846568**	**0.038483**	**7**
7	700	400	0.846968	0.031999	5
8	700	450	0.844823	0.032081	5
9	700	500	0.834844	0.023679	2
10	800	400	0.836933	0.02801	3
11	800	450	0.840108	0.027933	3
12	800	500	0.84149	0.031003	4
13	900	400	0.847441	0.031556	5
14	900	450	0.841699	0.027152	3
15	900	500	0.842504	0.034223	5
16	1000	400	0.831587	0.02017	1
17	1000	450	0.848005	0.030791	5
18	1000	500	0.833828	0.024759	2
19	1200	400	0.84733	0.031663	5
20	1200	450	0.855908	0.031525	6
21	1200	500	0.851081	0.032152	6
22	1500	400	0.852715	0.027576	5
23	1500	450	0.849503	0.026441	4
24	1500	500	0.840805	0.03073	7

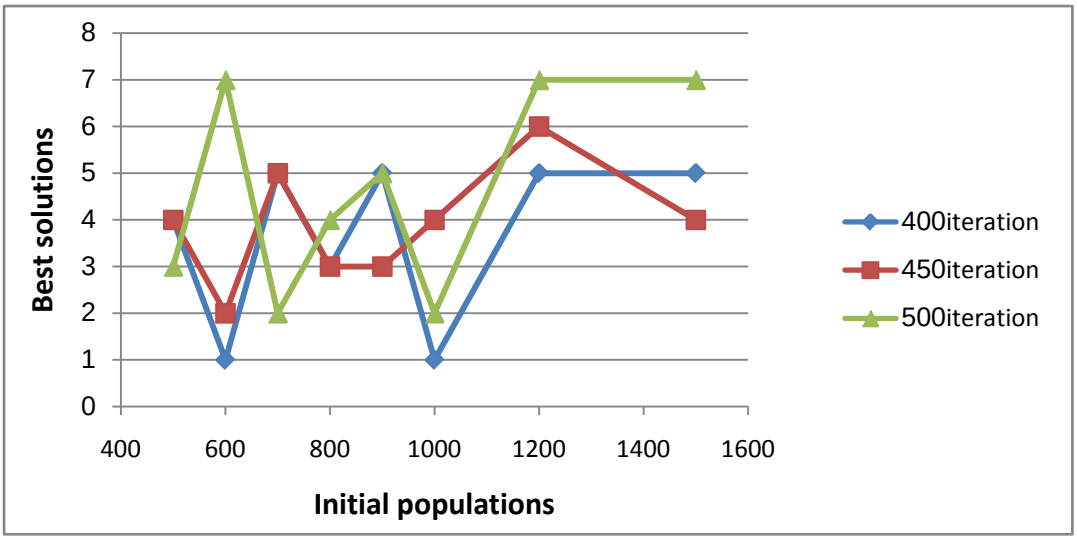


Fig. 6.7 Optimization of initial populations with iterations configuration for proposed GA assuming Pc = 0.6 and Pm = 0.4.

On the other hand, the second combination is to optimize crossover probability with mutation probability utilizing the resultant optimal parameters of populations and iterations. The same procedure is adopted here; we compare the results in terms of mean and standard deviation calculated on results of the objective function, in addition to the results of maximum solutions for every combination. Table 6.8 lists the different combinations results of crossover probability and mutation probability. Figure 6.8 presents a schematic diagram of implementing different rates of crossover probability versus best solutions with different rates of mutation probability.

The results reveal that the maximum best solutions are obtained in case of **crossover** probability equals **0.9** and **mutation** probability equals **0.4** with 600 populations and 500 iterations. In all different combinations, the maximum solution result is 21 of 1's among 23 inputs (21 equal 1's and 2 equal 0's); i.e. every best combination reveals that 21 devices could be replaced among 23 devices. As the algorithm repeated 20 times for every combination, it is possible to get a number of best solutions as shown in Table 6.7 and Table 6.8; considering the best solution is the one that yields maximum number of solutions with maximum mean value of objective function.

Table 6.8 Results of mutation probability (Pm) and crossover probability (Pc) of proposed GA in case of populations = 600 and iterations = 500.

No.	Pm	Pc	μ	σ	Max. solutions
1	0.4	0.7	0.832545	0.024744	2
2	0.4	0.8	0.839448	0.03485	5
3	**0.4**	**0.9**	**0.860304**	**0.035853**	**9**
4	0.4	1	0.858907	0.031819	7
5	0.3	0.6	0.847611	0.034075	6
6	0.3	0.7	0.828496	0.021169	1
7	0.3	0.8	0.826728	0.021443	1
8	0.3	0.9	0.841199	0.027732	3
9	0.3	1	0.848936	0.030452	5
10	0.2	0.6	0.835854	0.029202	3
11	0.2	0.7	0.833749	0.033482	4
12	0.2	0.8	0.832321	0.022515	1
13	0.2	0.9	0.834174	0.033146	4
14	0.2	1	0.858172	0.033868	8
15	0.1	0.6	0.822017	0.022086	1
16	0.1	0.7	0.831278	0.028887	2
17	0.1	0.8	0.827002	0.022941	1
18	0.1	0.9	0.854004	0.039659	9
19	0.1	1	0.851316	0.033293	6

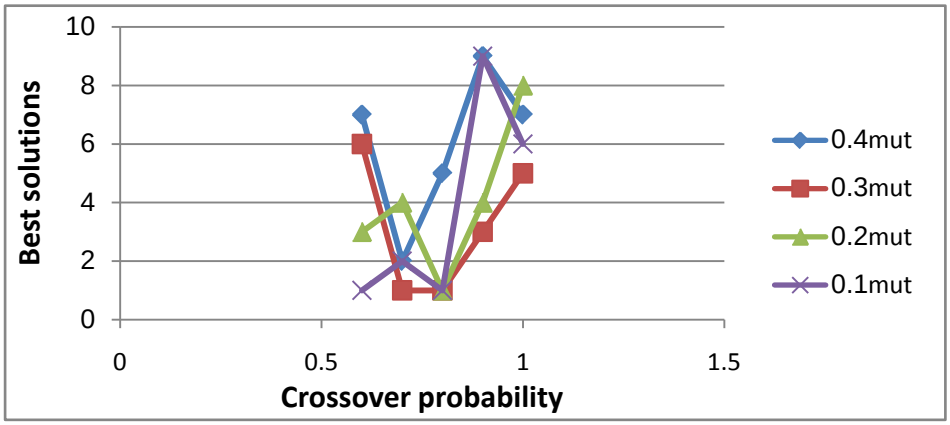


Fig. 6.8 Optimization of crossover probability with mutation probability configuration for proposed GA in case of populations = 600 and iterations = 500.

In fact, as GA starting with initial populations randomly selected, we decided to check alternating the initial populations twice utilizing the resultant optimum parameters on the results of best solutions. Table 6.9 presents the obtained results of the best solutions employing the optimal parameters of populations, iterations, crossover rate, and mutation rate of proposed algorithm. The results reveal that random population 3 with number 600, iterations 500, and crossover rate equals 0.9 & mutation rate 0.4 give the maximum number of solutions (21 devices) 11 times as shown in Fig. 6.9. The results show that, all optimum solutions exclude expensive devices that consume a large amount of available budget (D4 & D5) to give better chance for other devices.

Table 6.9 Results of optimum solutions by alternating populations with optimal parameters of proposed GA.

Alternatives	Pops.	Its.	Pm	Pc	μ	σ	Max. solutions
Population 1	600	500	0.4	0.9	0.860304	0.035853	9
Population 2	600	500	0.4	0.9	0.852565	0.022574	4
Population 3	**600**	**500**	**0.4**	**0.9**	**0.868762**	**0.032199**	**11**

D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	TOT.
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	19
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	19
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	19
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	19
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21
1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	19
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	20
1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	21

Fig. 6.9 Optimum solutions result of medical equipment require replacement using GA with populations = 600, iterations = 400, Pm = 0.4, and Pc = 0.9.

6.6 Chapter Conclusions

Due to the importance of replacement of medical equipment in medical equipment management especially in developing countries, we developed a new model that integrates quality function deployment and genetic algorithm in one framework to prioritize and optimize the medical equipment require replacement.

The model was built based on a set of technical, financial, and safety criteria that could impact replacement decision taking into account the entire entities requirements represented in medical staff and biomedical engineering technicians within hospital for replacement of medical equipment.

The proposed model proved its robustness, since it can efficiently prioritize and optimize a given list of medical equipment correctly separating the equipment that needs replacement (urgent replacement) from those that do not need it, also according to our point of view it acts successfully by avoiding substitution of medical equipment that consumes large amount of available budget.

The research gives more attention to some factors that play important role in replacement decision such as technology obsolescence and spare parts availability. Moreover, it presents new presentation for some factors such as backup ratio, which enable the decision makers to identify appropriate thresholds.

The study highlights the importance of existence of a detailed history of medical equipment that contains significant technical terms such as failure rate and downtime durations. Tracking such parameters could decrease risks associated with medical equipment utilization and influence important decisions like maintenance and replacement.

The research argues a new objective policy that could guide the decision makers within hospitals by presenting quality function deployment in this model for replacement of medical equipment as well as considering at the same

time the financial resources or available funding in order to guide the hospital administration how they should plan for substituting medical equipment after replacement process.

The proposed model could be customized by adding new devices with new criteria such as radiology equipment, and also by modifying the proposed objective function for better representation for the departments and medical equipment characteristics.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

In this thesis, we select the key decisions of medical equipment management; purchasing of medical equipment, preventive maintenance, and replacement or removal of medical equipment to be conducted through presenting new frameworks for management to solve a range of problems usually embraces such issues.

Quality function deployment is a well known quantitative management tool in manufacturing area used mainly to satisfy customer requirements. Despite its advantages, it is rarely utilized in medical equipment management; therefore, QFD is proposed to be the core method around which the comprehensive frameworks are constructed.

For first decision, purchasing of medical equipment, we propose a realistic framework by integrating QFD with fuzzy logic to solve the problem of

purchasing priority through developing a priority ranking order for purchasing requests. QFD is utilized in this framework to conclude the most important criteria that could impact priority decision; meanwhile, a fuzzy logic model is used to classify purchasing requests priority based on these criteria.

The second issue is preventive maintenance of medical equipment. As PM is the mainstay of medical equipment management, we present a plan that provides a reasonable priority for devices that require PM as well as optimizes the schedule of medical equipment for PM purpose.

Prioritization of medical equipment PM takes place by developing a 3 domain framework utilizing QFD in order to generate a priority score for every device that indicates the priority ranking order. The priority index is developed based on a set of criteria classified into risk-based, mission-based, and maintenance-based criteria.

Optimum scheduling of medical equipment PM is developed regarding a new point of view; scheduling the devices themselves for PM based on their priority. Ant Colony Optimization method is employed in this study to develop two versions of algorithm that produce Sequential Preventive Maintenance Schedule (SPMS). First SPMS version is developed taking into account the PM priority weight of medical equipment. The second SPMS version considers not only PM priority weight, but also the location of the device.

The replacement of medical equipment is the last stage of medical equipment. We propose a comprehensive framework that combines QFD with genetic algorithm (GA). The role of QFD model is to generate a priority index for a list of devices by exploiting a set of technical, financial, and safety criteria. Then, the output top ranking orders devices are optimized by GA to find out the optimum number of devices require replacement considering the priority weight and the budget constraint for substitution.

QFD has proven its validity in medical equipment management. Successfully, QFD is utilized for first time with different scenarios, either by producing final scores or by introducing the most significant criteria to provide a reasonable priority index for various stages in medical equipment management.

QFD has proven its consistency by integrating with other methods to develop comprehensive frameworks that could guide the decision makers to improve medical equipment management system.

According to the basics of QFD, considering different entities within hospital, such as patients, medical staff, financial department, and the general administration could improve decision making in medical equipment management.

The study gives more attention to a variety of criteria that could impact on various decisions within medical equipment management life cycle. Moreover, it presents new thresholds for some factors such as failure rate, utilization level, and backup.

The study presents new concept for optimization of PM scheduling by optimizing the sequence of devices themselves regarding the priority weight and the device location instead of optimizing the intervention durations or PM frequencies. Such scheduling reduces time spent by technicians, labor, and consequently PM costs.

The study highlights the importance of existence of a detailed history for medical equipment. Tracking medical equipment by this history could reduce the risk level of some devices.

In conclusion, the study presents new contributions by involving QFD for first time in medical equipment management through introducing important decisions within management lifecycle, in addition to, presenting new concepts either for some criteria or some decisions.

7.2 Future Work

As shown in this study, comprehensive frameworks are developed to improve medical equipment management considering a variety of criteria for different stages. In future, we can customize these frameworks by adding more devices and more criteria such as reliability and user errors to introduce better representation for medical equipment characteristics.

The customer requirements in QFD models could be classified according to Kano's model to measure different customer satisfaction attributes and its impact in developing voice of engineers.

The proposed algorithms for PM scheduling could be used either by clinical engineering departments or maintenance agencies to organize their activities. In fact, as maintenance agencies deal with several hospitals for different kinds of medical equipment, it is possible for them to adapt the proposed heuristic functions based on their activities.

The validation of the proposed models was tested on public hospitals. We recommend extending the application considering private hospitals to differentiate the evaluation level of some factors such as costs analysis and utilization level between two sectors on the results.

In this study, we used Ant Colony Optimization and Genetic Algorithm for optimization; other optimization methods like Tabu Search could be used also. The difference could be recorded by a comparison between these methods.

For purchasing of medical equipment, we can introduce new framework by optimizing the purchasing requests according to the available budget of purchasing in addition to the priority of requests.

The proposed frameworks can be considered as general frameworks that could handle different scenarios within different organizations to improve the mechanism of decision making to be considered based on relatively objective policies.

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APPENDIX A

Rule Base for Fuzzy Output

No.	Service	Technology	Risk	Budget	Costs	Fuzzy Score
1	High	V. Good	High	Available	Low	V. High
2	High	V. Good	High	Donation		V. High
3	High	V. Good	High	Available	Medium	V. High
4	High	V. Good		Available		V. High
5	High	V. Good	High	Available	High	High
6	High	Good	Medium	Available	Low	High
7	High	Good	High	Available		High
8	High	V. Good		Donation		High
9	Medium	V. Good	High	Available		High
10	High		High	Available	Low	High
11	Medium	Good	Medium	Available	Medium	Medium
12	Medium	V. Good	Medium	Donation		Medium
13	High	Good		Available	Medium	Medium
14	Medium		High	Available	Medium	Medium
15	High	Poor	Medium	Available	Medium	Medium
16	High	Good		Available		Medium
17	Medium	Good	High	Available		Medium
18	High	V. Good	High	Available	Low	Medium
19	High		High	Donation		Medium
20	Low	Good	Low	Available	High	Low
21	High	V. Good	Low	Not Available	High	Low
22	Low	Poor		Available		Low
23	Medium	Poor	Medium	Donation		Low
24		Good	Medium	Donation	Low	Low
25	Medium	Good		Donation		Low
26	Low	Poor	Low	Not Available	High	Almost No
27	Low	Poor	Low	Not Available		Almost No
28	Low	Good	Low	Donation	High	Almost No
29	Low	Poor	Low	Donation		Almost No
30		Poor	Low	Available		Almost No

APPENDIX B

Italian Hospitals Data

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
1	Anesthesia unit	1	Datex ohmeda	Astiva 3000	Operating Room (O.R)	01/01/1998	14	10	2	2	22/08/2012
2	Anesthesia unit	1	Datex ohmeda	S/5 avance care station	Operating Room	15/02/2007	5	10	10	117	26/04/2012
3	Ventilator	1	Dragger	Evita 2 dura	Resuscitation	01/05/2002	10	10	2	2	04/09/2012
4	Ventilator	1	Dragger	Evita 2 dura	Resuscitation	01/01/1998	14	10	3	3	04/09/2012
5	Anesthesia unit	2	Datex ohmeda	S/5 avance care station	Operating Room	15/02/2007	5	10	3	3	01/10/2012
6	Ventilator	1	Datex ohmeda	Engstrom	First aid	13/01/2006	6	10	5	5	04/09/2012
7	Ventilator	2	Bear	Bear 1000	Resuscitation	01/01/2000	12	10	1	1	31/12/2011
8	Ventilator	2	Siemens	Servo i	Resuscitation	09/08/2004	8	10	0	0	31/12/2011
9	Anesthesia unit	1	Datex ohmeda	Excel 210	Operating Room	01/01/1995	17	10	0	0	22/08/2012
10	Ventilator	1	Dragger	Evita 4	Resuscitation	13/01/2010	2	10	3	3	04/09/2012
11	Ventilator	2	Nellcor	NPB-840	Resuscitation	18/10/2004	8	10	4	9	04/05/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
			puritan								
12	Ventilator	2	Infrasonics	Adult star	First aid	01/01/2000	12	10	0	0	31/12/2011
13	Ventilator	2	Bennett	NPB 840	Resuscitation	16/04/2009	3	10	1	1	04/06/2012
14	Ventilator	2	Carefusion	AVEA	First aid	25/01/2005	7	10	2	2	13/07/2012
15	Ventilator	1	Fisher & paykel	Infant flow	Pediatrics	01/04/2004	8	10	2	8	29/05/2012
16	Ventilator	2	Datex ohmeda	Engstrom pro	Operating Room	29/07/2010	2	10	0	0	19/9/2012
17	Defibrillator	2	Nihon kohden	Cardiolife tec 7731R	First aid	04/01/2005	7	8	5	180	18/01/2012
18	Anesthesia unit	2	Soxil SPA	Jollytronic	Operating Room	01/01/1998	14	10	1	16	05/09/2012
19	Defibrillator	1	Nihon kohden	Cardiolife tec 7731K	First aid	18/08/2010	2	8	4	4	21/06/2012
20	Hemodialysis unit	1	Hospal	Integra	Hemodialysis	01/01/2001	11	5	0	0	31/12/2011
21	Hemodialysis unit	1	Gambro	AK200	Hemodialysis	27/02/2002	10	5	0	0	31/12/2011
22	Mammography	2	Siemens	Mammomat 3000 Nova	Radiology	01/01/2000	12	10	2	38	31/12/2011
23	Defibrillator	2	Esaote	MDF+	Neurology	17/12/2003	9	8	2	65	19/01/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
24	Defibrillator	1	Nihon kohden	Cardiolife tec 7300K	I.C.U	01/01/1994	18	8	1	1	31/12/2011
25	External pacemaker	1	Osypka	Pace 100	Cardiology	08/05/2003	9	5	1	1	31/12/2011
26	Defibrillator	2	Zoll	PDMA 8	Cardiology C.U.	01/06/2002	10	8	0	0	19/11/2012
27	Defibrillator	2	Esaote	MDF+	Cardiology	28/09/2000	12	8	1	1	31/12/2011
28	Defibrillator	2	Nihon kohden	Cardiolife tec 8251	Resuscitation	19/12/1997	15	8	1	1	18/01/2012
29	Mammography	1	GE	Stenographe 800T	Radiology	01/01/2000	12	10	1	3	31/12/2011
30	Infusion pump	2	Abbott	Life care 5000	Operating Room	02/11/1999	13	5	0	0	31/12/2011
31	Blood gases analyzer	2	Radiometer	ABL 735 GL	Resuscitation	24/09/2003	9	8	30	90	31/12/2011
32	Infant incubator	1	Atom	V808 TR	Pediatrics	05/01/2005	7	10	3	118	28/06/2012
33	Infusion pump	2	Abbott	Life care 5000	Resuscitation	13/02/2002	10	5	0	0	31/12/2011
34	Defibrillator	1	Meditronic	Lifepack CR+	Ambulatory	16/03/2005	7	8	1	22	14/05/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
35	C-arm	2	Gilardoni	Mobil gil	O.R.	01/01/2000	12	10	6	48	03/04/2012
36	Video colonoscope	2	Olympus	CF-Q1451	Endoscopy	01/01/1996	16	5	4	104	31/12/2011
37	Video colonoscope	1	Pentax	EC-3840F	Endoscopy	01/01/1995	17	5	6	244	31/12/2011
38	Video colonoscope	1	Pentax	EC-3840F	Endoscopy	17/01/2002	10	5	4	180	31/12/2011
39	Video gastroscopy	1	Pentax	EG-2940	Endoscopy	01/01/1997	15	5	4	133	31/12/2011
40	Video gasroscopy	1	Pentax	EG-2940	Endoscopy	23/01/2003	9	5	4	181	31/12/2011
41	Defibrillator	2	Nihon kohden	Cardiolife tec 5521K	Urology	16/03/2005	7	8	0	0	08/11/2012
42	Infant incubator	1	Datex ohmeda	Giraffe omnibed	Pediatrics	05/01/2005	7	10	2	8	28/06/2012
43	Infant incubator	1	Datex ohmeda	Giraffe omnibed	Pediatrics	05/01/2005	7	10	2	2	28/06/2012
44	Mobile C-arm	2	Philips	BV libra 9	O.R.	26/11/2004	8	10	4	25	31/12/2011
45	Electrosurgical unit	2	Erbe	VIO 300D	O.R.	01/04/2011	1	10	4	170	31/12/2011
46	Cystoscope	2	Karl storz	27005BA	O.R.	01/01/2006	6	10	2	33	31/12/2011
47	Electrosurgical uni	2	Erbe	Erbotomt	O.R.	01/01/2000	12	10	3	6	31/12/2011
48	Bronchoscope	2	Olympus	BF-Q180	Endoscopy	30/05/2007	5	6	1	30	31/12/2011
49	Video colonoscope	1	Pentax	EC-3840F	Endoscopy	02/08/2004	8	5	3	70	31/12/2011
50	Arthroscope	1	Karl storz	2872	O.R.	01/01/2005	7	10	1	44	31/12/2011

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
51	Electrosurgical unit	2	Coremec SRL	RT0400TA	O.R.	01/01/1996	16	10	3	3	19/03/2012
52	Infusion pump	2	Abbott	Lifecare XL	First aid	07/09/2000	12	5	0	0	31/12/2011
53	Electrosurgical unit	2	Erbe	VIO 300D	O.R.	01/04/2011	1	10	2	253	31/12/2011
54	Electrosurgical unit	2	Karl storz	Autocon II 400	O.R.	12/09/2008	4	10	2	81	31/12/2011
55	Video colonoscope	1	Olympus	CF-H180 AL	Endoscopy	29/02/2008	4	5	3	97	31/12/2011
56	Video bronchoscope	1	Pentax	EB-1570	Endoscopy	01/01/2005	7	6	2	24	31/12/2011
57	Video gastroscopy	2	Pentax	EG-2970K	Endoscopy	26/05/2005	7	5	2	36	31/12/2011
58	Laporascope	1	Karl storz	26003 AA	O.R.	01/01/2005	7	10	1	13	31/12/2011
59	Rigid cystoscope	1	Karl storz	27005FA	O.R.	09/03/2006	6	10	1	26	31/12/2011
60	Laporascope	1	Karl storz	26003BA	O.R.	13/06/2006	6	10	1	20	31/12/2011
61	Transport infant incubator	2	Air shield	Isolette TI500	Neonatal I.C.U.	01/01/1996	16	8	1	2	11/07/2012
62	Automated chemistry analyzer	1	Hitachi	917 DISC	Laboratories	01/01/2000	12	8	0	0	31/12/2011
63	Blood gases analyzer	2	Radiometer	ABL 700	Laboratories	20/05/2010	2	8	21	40	31/12/2011
64	Autoclave	1	CISA	6410	Central sterilization	01/06/2004	8	12	13	100	31/12/2011

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
65	Electrosurgical unit	2	Valley lab	Ligasure 8	O.R.	09/04/2003	9	10	1	10	31/12/2011
66	Ultrasound	2	Esaote	Technos	Radiology	02/03/2001	11	12	2	2	31/12/2011
67	Ultrasound	2	Acuson corp	Sequia 256C	Cardiology	20/07/1998	14	12	3	305	12/11/2012
68	Ultrasound	1	Philips	IU22	Radiology	01/06/2004	8	12	4	27	31/12/2011
69	Ultrasound (bladd)	2	Verthon	BVI 6100	First aid	02/10/2009	3	12	2	99	18/04/2012
70	Ultrasound	2	Esaote	Technos MP	Radiology	27/09/2002	10	12	0	0	31/12/2011
71	Syringe pump	1	B.Braun	Perfusor compact	Resuscitation	01/03/2004	8	10	5	10	04/09/2012
72	Monitor	2	Fukuda denshi	Dynascope DS-5300	Resuscitation	19/12/2003	9	10	4	5	18/01/2012
73	Radiant heater	1	Dragger	Babytherm 8010	pediatrics	19/11/2004	8	10	5	12	27/06/2012
74	Radiant heater	1	Dragger	Babytherm 8010	pediatrics	19/11/2004	8	10	5	36	27/06/2012
75	Radiant heater	1	Fisher & paykel	TW 900	O.R.	28/09/2008	4	10	2	2	31/12/2011
76	Ultrasound	1	HP	Sonos 4500	Cardiology	05/06/2003	9	12	3	10	31/12/2011

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
77	Cystoscope	2	Karl storz	27005AA	Urology	25/05/2006	6	10	1	28	31/12/2011
78	Ultra sound	1	Esaote	Technos mp	Radiology	25/03/2005	7	12	1	34	31/12/2011
79	Syringe pump	2	Terumo	TE 371	Resuscitation	05/05/2006	6	10	3	21	31/12/2011
80	Syringe pump	1	B.Braun	Perfusor compact	Resuscitation	01/03/2004	8	10	2	45	04/09/2012
81	Surgical lamp	1	Martin	ML 501	O.R.	01/01/1998	14	10	4	28	31/12/2011
82	X-ray unit	2	Philips	981E+11	Radiology	01/01/1999	13	10	2	5	31/12/2011
83	Monitor	2	Datex ohmeda	Cardiocap II	O.R.	01/01/1998	14	10	2	21	11/10/2012
84	Fetal monitor	2	Sonicaid	Oxford	Gynecology	01/01/1996	16	10	5	24	17/01/2012
85	Ultra sound	1	Esaote	Technos mp	Nephrology	01/07/2003	9	12	2	2	31/12/2011
86	Monitor	1	Philips	MP90	I.C.U.	12/12/2005	7	10	9	9	05/09/2012
87	Central monitor station	1	Philips	NA	I.C.U	12/10/2007	5	7	4	4	05/09/2012
88	Monitor	2	Nihon kohden	Life scope NPV/500	First aid	26/01/2006	6	10	6	6	18/01/2012
89	Monitor	2	Fukuda denshi	Dynascope DS-5300w	Cardiology	01/01/2000	12	10	5	5	19/11/2012
90	Portable X-ray	2	Gilardoni SPA	Caleidon HF	Cardiology	01/01/1999	13	8	1	1	31/12/2011

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
91	ECG holter	1	Del mar reynolds	NA	Cardiology	19/03/2007	5	8	7	21	06/06/2012
92	Resuscitator	1	Datex ohmeda	Infant resuscitator	Inpatients	01/01/1996	16	8	1	1	31/12/2011
93	Syringe pump	2	Terumo	TE 371	Resuscitation	05/05/2006	6	10	1	22	31/12/2011
94	Light source	2	Wolf	4.251.001	Endoscopy	01/01/1996	16	8	11	64	10/10/2012
95	Portable X-ray	1	Gilardoni SPA	Caleidon 300	Resuscitation	01/01/2001	11	8	3	4	04/09/2012
96	Processor	2	Pentax	EPK 700	Endoscopy	01/01/1989	23	10	1	51	18/01/2012
97	Phototherapy	1	Datex ohmeda	Biliblanket+	Pediatrics	23/12/2004	8	10	3	112	31/12/2012
98	Syringe pump	1	B.Braun	Perfusor compact	Resuscitation	01/03/2004	8	10	1	1	28/08/2012
99	Light source	2	Wolf	4015 LP	O.R.	01/01/1992	20	8	1	1	14/05/2012
100	Syringe pump	1	B.Braun	Perfusor compact	Resuscitation	17/06/2010	2	10	2	29	27/08/2012
101	Autoclave	2	ICOS	U63 PEI	O.R.	02/09/2004	8	12	13	34	31/12/2011
102	Monitor	2	Fukuda denshi	HS-700	Resuscitation	05/03/2007	5	10	3	4	18/01/2012
103	Monitor	1	Datascope	Passport	Pediatrics	01/01/1997	15	10	2	25	28/06/2012
104	Insufflators	2	Asema	CTV/B	O.R.	16/05/2005	7	10	1	1	26/03/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
105	Monitor	1	Siemens	Infinity SC	Resuscitation	26/03/2003	9	10	0	0	04/09/2012
106	Surgical lamp	1	Martin	701	O.R.	01/01/1999	13	10	1	1	31/12/2011
107	ECG	2	Remco italia	Cardio line delta 3	First aid	17/08/2004	8	8	5	5	18/01/2012
108	Endoscopy sterilizer	2	CISA	ERS2	Endoscopy	30/07/2004	8	8	19	99	04/05/2012
109	Sterilizer	1	CISA	ERS2	Endoscopy	30/07/2004	8	8	20	218	05/07/2012
110	Bladder ultra sound	2	Verthon	BVI 6100	Day surgery	29/11/2010	2	12	1	30	28/02/2012
111	Monitor	1	Datex ohmeda	Cardio cap II	O.R.	01/01/1996	16	10	1	5	22/08/2012
112	Monitor	1	Philips	MP 90	I.C.U.	12/12/2005	7	10	1	1	05/09/2012
113	Syringe pump	1	B.Braun	Perfusor compact	Pediatrics	01/08/2003	9	10	0	0	31/08/2012
114	Monitor	2	Fukuda denshi	Dynascope DS-5300	Cardiology	28/02/2000	12	10	1	14	16/11/2012
115	ECG holter	2	ELA medical	Spider flash	Cardiology C.U	26/09/2007	5	8	1	20	31/12/2011
116	Phototherapy	1	Datex ohmeda	Biliblanket+	Pediatrics	07/07/2004	8	10	1	1	26/06/2012
117	Fetal monitor	1	Philips	Series 50A	Gynecology	17/12/2004	8	10	3	3	28/05/2012
118	Fetal monitor	1	Sonicaid	Oxford	Gynecology	31/03/2008	4	10	5	28	28/05/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
119	Surgical lamp	2	Trumpf	5300	O.R.	20/05/2011	1	10	1	23	31/12/2011
120	Insufflator	1	Asema	CTV/B/EL	O.R.	12/03/2005	7	10	1	1	11/05/2012
121	Syringe pump	1	B.Braun	Perfusor compact	Cardiology	19/07/2004	8	10	1	1	05/09/2012
122	Monitor	2	Fukuda denshi	Dynascope DS-5100	Neurology	18/12/2003	9	10	1	2	19/01/2012
123	Surgical aspirator	2	Siem nova	6110A3	Resuscitation	24/11/2006	6	10	0	0	31/12/2011
124	Surgical aspirator	2	laerdal	8800505040	Pediatrics	11/06/2010	2	10	2	2	18/01/2012
125	Washing&disinfection machine	1	ICOS impanti	ML80NE	Central sterilization	10/16/2005	7	8	7	111	29/03/2012
126	Light source	2	Karl storz	Xenon nova	Endoscopy	27/11/2009	3	8	1	18	31/12/2011
127	Syringe pump	1	B.Braun	perfusor	Cardiology	01/03/2004	8	10	1	1	05/09/2012
128	Syringe pump	1	Carefusion	Asena CC	Endoscopy	05/08/2004	8	10	0	0	31/08/2012
129	ELIZA analyzer	2	Sorin	Eti lab	Laboratories	01/01/1999	13	8	0	0	31/12/2012
130	ECG holter	2	Del mar reynolds	Life cardCF12	Cardiology	01/01/1998	14	8	2	171	16/11/2012
131	Fetal monitor	2	Sonicaid	Oxford	Gynecology	08/01/2008	4	10	6	11	17/01/2012
132	ECG	1	Schiller	Cardiovit	Outpatients	01/01/1997	15	8	2	2	18/05/2012
133	ECG holter	2	Del mar	Life	Cardiology	15/10/2009	3	8	3	29	16/11/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
			reynolds	cardCF12							
134	Autoclave	1	Omasa	ELA-62	Gynecology	11/05/1994	18	12	4	14	31/12/2011
135	ECG holter	1	Del mar reynolds	Life cardCF12	Cardiology	15/10/2009	3	8	1	1	31/12/2011
136	ECG	2	HP	Page writer	Cardiology	01/01/1998	14	8	0	0	31/12/2011
137	EMG	2	Micromed	Myohandy 1400ME	Neurology	01/01/2005	7	10	1	20	31/12/2011
138	Surgical aspirator	2	Siem nova	SIEM	Inpatients	01/01/1996	16	10	1	1	31/12/2011
139	Monitor	1	Philips	Intellivue MP 50	Pediatrics	05/12/2005	7	10	1	37	26/06/2012
140	ECG	2	ET medical	AR1200adv	Resuscitation	05/12/2006	6	8	5	6	18/01/2012
141	Surgical aspirator	1	Laerdal	LCSU	Gynecology	16/03/2005	7	10	1	1	30/05/2012
142	ECG	2	Mortara	ELI 350	Cardiology C.U.	12/10/2007	5	8	3	3	16/11/2012
143	EEG	2	Micromed	Brain quick	Neurology	24/01/2011	1	10	3	30	15/10/2012
144	Nebulizer	2	Air liquide	Boreal 2000	Pediatrics	01/01/2001	11	10	0	0	31/12/2011
145	Pulse oximeter	2	Nellcor puritan	NPB-40	First aid	01/06/2004	8	5	2	2	28/02/2012
146	Capnograph	2	Datex ohmeda	Capnomac	Angiography	01/01/1997	15	10	1	9	17/09/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
147	Trade male	1	Mortara	X scribe	Cardiology	01/01/2000	12	8	2	2	06/06/2012
148	Bilirubinometer	1	Spectrx	Bilicheck	Pediatrics	02/10/2002	10	8	1	71	31/12/2011
149	Monitor	2	Mindray	MEC 1000	Pediatrics	14/10/2007	5	10	3	27	28/11/2012
150	EEG	2	Micromed	Brainquick	Neurology	24/01/2011	1	10	1	21	23/04/2012
151	Centrifuge	1	ALC	PK 110	Laboratories	01/01/2000	12	8	1	1	26/09/2012
152	Surgical aspirator	1	Siem nova	6110A	Inpatients	31/08/2005	7	10	1	1	31/05/2012
153	Lab incubator	1	Heraeus	B 6760	Laboratories	01/01/1996	16	10	6	6	15/05/2012
154	ECG	1	Remco italia	Cardioline delta 60+	Cardiology	29/06/2005	7	8	1	1	06/06/2012
155	Audiometer	2	Amplifon	A321	Ambulatory	10/01/2006	6	10	1	1	20/03/2012
156	ECG	1	Philips	Page writer	Cardiology	12/12/2005	7	8	2	9	23/08/2009
157	Centrifuge	2	Heraeus	MEGAFUG	Laboratories	01/11/2003	9	8	3	45	02/11/2012
158	Sealing machine	1	Hawo GMBH	HM 2010DC	Central sterilization	10/12/2004	8	10	3	16	15/06/2012
159	TV monitor	2	Philips	LCM 18	radiology	28/06/2005	7	7	1	1	31/12/2011
160	TV monitor	2	Karl storz	20043001	Urology	30/09/2004	8	10	3	5	18/04/2012
161	Pulse oximeter	2	Datex ohmeda	BIOX 3740	Resuscitation	01/01/1997	15	5	0	0	31/12/2011
162	Endoscopy strilizer	2	Steris corp	System 190	Sterilization	01/01/2000	12	8	4	54	03/05/2012
163	Urine flowmeter	1	Medical	UROCAPIII	Ambulatory	17/04/2009	3	8	2	69	31/12/2011

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
164	Cryostat	2	Leica	CM 1510	Laboratories	27/10/2006	6	10	1	1	31/12/2011
165	Pulse oximeter	2	Nellcor puritan	NPB-290	Neonatal I.C.U	01/01/2000	12	5	2	3	18/01/2012
166	Pulse oximeter	1	Nellcor puritan	N 395	Pediatrics	01/01/2002	10	5	1	5	27/06/2012
167	Cytocentrifuge	1	Thermo fisher	Sytospin IV	Laboratories	14/06/2005	7	8	2	6	26/09/2012
168	Microscope	1	Leica	Dialux	Laboratories	01/01/1994	18	12	1	1	24/05/2012
169	Pulse oximeter	1	Mindray	PM 50	Resuscitation	06/11/2007	5	5	1	1	27/08/2012
170	ECG	2	Fukuda denshi	FCP- 2155	O.R.	20/09/2001	11	8	2	2	18/01/2012
171	Urine flowmeter	2	bioengineering	Smart flow	Urology	17/07/2003	9	8	1	8	18/04/2012
172	Microscope	2	Leica	Laborlux S	Laboratories	01/01/1997	15	12	1	1	12/11/2012
173	Biobsy aspirator	1	Ethicon	Mammotom	Endoscopy	18/10/2004	8	10	2	2	31/12/2011
174	Pulse oximeter	2	Nellcor puritan	NPB-40	Endoscopy	14/06/2005	7	5	1	1	23/03/2012
175	Refrigerated centrifuge	2	Thermo electron	55000	Laboratories	12/06/2006	6	8	2	8	05/11/2011
176	Cell refrigerator	1	NA	NA	Laboratories	28/07/2003	9	8	6	8	15/05/2012
177	Operating table	2	OPT officina	OPT 70	O.R.	01/01/1987	25	15	2	2	31/12/2011
178	Operating table	2	Trumpf	Jupiter	O.R.	12/10/2007	5	15	5	29	31/12/2011

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
179	Operating table	2	trumpf	Tru system	O.R.	24/01/2011	1	15	5	13	31/12/2011
180	Laminar air flow	1	Faster	UL trasafe 48D	Laboratories	01/01/1997	15	10	1	1	31/12/2011
181	Washing&disinfection machine	2	Miele &CIF	G7882	Endoscopy	28/04/2008	4	8	2	2	19/03/2012
182	Operating table	1	OPT officina	OPT 70	O.R.	01/10/2001	11	15	7	15	10/09/2012
183	Examination lamp	1	waldmann	HX35HX	Resuscitation	01/01/1998	14	10	9	12	31/12/2011
184	Pulse oximeter	2	Mindray	PM 50	Outpatients	12/09/2006	6	5	0	0	15/10/2012
185	Pulse oximeter	1	Mindray	PM 50	Inpatients	15/02/2008	4	5	1	1	31/05/2012
186	Microscope	1	Olympus	BX45TF	Laboratories	13/03/2006	6	12	1	1	21/08/2012
187	Tube welder	2	Delecon	Hemo weldB	Laboratories	01/01/2006	6	10	1	1	31/12/2011
188	Biological refrigerator	1	Angelantoni	FCL 3007215	Laboratories	08/09/2000	12	12	2	11	16/03/2012
189	Electrical bed	1	Guido malvesto Ind	3LN930H	Cardiology	12/01/2005	7	12	4	62	31/12/2011
190	Operating table	2	Steris corp	Surgi-stretcher	O.R.	12/10/2006	6	15	1	2	31/12/2011
191	Lab freezer	1	CFDI		Laboratories	24/01/2005	7	10	1	11	14/03/2012

No	Equipment	Hospital	Brand	Model	Department	Acquisition date	Age	Expected Age	Failure rate	Downtime (days)	Last PM
192	Electrical bed	2	Guido malvesto Ind	3LN930H	Cardiac C.U.	13/01/2005	7	12	1	1	16/11/2012
193	Lab incubator	1	KW	W85RF	Laboratories	09/09/2010	2	10	1	1	31/12/2011
194	Lab freezer	2	KW	KFS 600	Laboratories	19/08/2010	2	10	1	1	27/09/2012
195	Hood fume	1	Strola	GS180	Laboratories	27/06/2008	4	12	2	25	15/06/2012
196	Electrical bed	1	Hill rom	Avantguard	Nephrology	01/01/2004	8	12	2	2	07/06/2012
197	Morgue refrigerator	2	Angelantoni	NA	Morgue	01/01/1999	13	12	1	1	19/01/2012
198	X- ray viewer	1	NA	NA	Radiology	01/01/1990	22	12	1	2	25/06/2012
199	Dialysis chair	1	Tassinari bilance	NA	Nephrology	01/01/1998	14	10	1	24	11/06/2012
200	Patient scale	1	Wunder sabi	WB 100PMA	Pediatrics	05/11/2004	8	10	2	2	27/06/2012

APPENDIX C

SPMS _1 Algorithm

```
clear all
close all
clc

%data loading
load('data.mat')

%parameters
iter_max=100;   %number of iterations
ro=0.3; %evaporation rate
neq= length(w); %#equipments
istogramma=zeros(1,neq);
n_ants= 30;  %#ants= # equipments in the first class
%to be adapted!!!
alfa=0.8;
beta=0.2;
Q=0.01; %coefficient...

 %duration calculation
duration=zeros(size(complexity));
duration(complexity==3)=2 +0.4*randn(1,sum(complexity==3));
duration(complexity==2)=1.5 +0.2*randn(1,sum(complexity==2));
duration(complexity==1)=0.5 +0.1*randn(1,sum(complexity==1));

%stopping criterion
time_max=360;

 D_tau_max=0;  %deta tau

%initialization of pheromone matrix
tau=zeros(neq,neq);

%initialization of the amount of pheromone with a random value between
0 and 0.5
for i=1:neq
    for j=1:i-1
        tau(i,j)=rand(1)/2;
        tau(j,i)=tau(i,j);
    end
end

for iter=1:iter_max
    fprintf('\titeration number: %d\n', iter)

    %initial location of the ants
    ant=zeros(n_ants,neq);
    ant(:,1)=1:n_ants;
```

```
    %construction of a path for each ant
     for i=1:n_ants
       flag = 0; %indication that no ant finished its path
       fprintf('ant number: %d\n', i)
       while flag==0
           p_max=0;   %initialization of transition probability
           denom=0;    %initialization of denominator of p

           %calculation of denominator of p
           for k=1:neq
               n=find(ant(i,:)==k);
               if(length(n)==0)  %equipment not in the sequence

                   ind=find(ant(i,:)==0);  %index of the first zero
                   ind=ind(1);
                   ant_temp=ant(i,:);
                   ant_temp(ind)=k;
                   h=0;
                   pen=0;
                   dur_before=0;
                   for ii=1:ind
                       dur_before=sum(duration(ant_temp(1:ii-1)));
                       if dur_before>limit(ant_temp(ii))
                           pen=(dur_before-limit(ant_temp(ii)))/30/12;
                       else
                           pen=0;
                       end
         h=h+w(ant_temp(ii))*(1-pen);  %objective function that you
obtain adding to the current sequence the new equipment k
                   end
                   if isreal(denom)
                   denom=denom+(tau(ant(i,ind(1)-1),k)^alfa)*(h^beta);
                       %  tau(ant(ind(1)-1),k)^alfa)*(h^beta)
                   else
                       denom
                       keyboard
                   end
               end
           end
           p=zeros(1,neq);

 %calculation of p
           for k=1:neq
               n=find(ant(i,:)==k);
               if(length(n)==0)  %equipment not in the sequence

                   ind=find(ant(i,:)==0);  %index of the first zero
                   ind=ind(1);
                   ant_temp=ant(i,:);
                   ant_temp(ind)=k;
                   h=0;
                   pen=0;
                   dur_before=0;
                   for ii=1:ind
                       dur_before=sum(duration(ant_temp(1:ii-1)));
                    if dur_before>limit(ant_temp(ii))
```

```
                            pen=(dur_before-limit(ant_temp(ii)))/30/12;
                        else
                            pen=0;
                        end
            h=h+w(ant_temp(ii))*(1-pen);  %objective function that you
obtain adding to the current sequence the new equipment k
                    end
                    if denom==0
                        p(k)=0;
                    else
                    p(k)=(tau(ant(i,ind(1)-1),k)^alfa)*(h^beta)/denom;
                    end
                end
            end

            best = selection_ant (p);
            ind=find(ant(i,:)==0);
            ant(i,ind(1))=best;
            %  ant(i,:)
            tot_duration=sum(duration(ant(i,1:ind(1))));

%stopping criterion
            if tot_duration>time_max
                ant(i,ind(1))=0;
                flag=1;
            elseif ind(1)==neq
                flag=1;
            end
        end
    end

 %pheromone evaporation
    tau=(1-ro)*tau;

    %pheromone update
    for i=1:n_ants
        ind=find(ant(i,:)==0);
        if isempty(ind)
            ind=size(ant,2)+1;
        end
      D_tau=(ind(1)-1)*Q;  % # of equipments in the sequence * constant
        for j=1:ind(1)-2
            tau(ant(i,j),ant(i,j+1))=tau(ant(i,j),ant(i,j+1))+D_tau;
            tau(ant(i,j+1),ant(i,j))=tau(ant(i,j),ant(i,j+1));
        end
        if D_tau>D_tau_max
            D_tau_max=D_tau;
            sol_best=ant(i,:);
        end
    end
end

save('results3.mat', 'duration', 'ant', 'sol_best', 'alfa', 'beta',
'ro')
```

APPENDIX D

SPMS_2 Algorithm

```
clear all
close all
clc

%data loading
load('data.mat')
load('hospital.mat')
load('duration.mat')

%parameters
iter_max=100;   %number of iterations
ro=0.3; %evaporation rate
neq= length(w); %#equipment
istogramma=zeros(1,neq);
n_ants= 30; %#ants = # equipment in the first class

%%to be adapted!!!
alfa=0.4;
beta=0.6;
Q=0.01; %coefficient...

 %duration calculation
 duration=zeros(size(complexity));
 duration(complexity==3)=2 +0.4*randn(1,sum(complexity==3));
 duration(complexity==2)=1.5 +0.2*randn(1,sum(complexity==2));
 duration(complexity==1)=0.5 +0.1*randn(1,sum(complexity==1));

%stopping criterion
time_max=360;

for r=1:3
    D_tau_max=0;  %deta tau
    fprintf('rip: %d\n', r)

    load('pherom.mat')
    for iter=1:iter_max
        fprintf('\titeration number: %d\n', iter)

        %initial location of the ants
        ant=zeros(n_ants,neq);
        ant(:,1)=1:n_ants;

        %construction of a path for each ant
        for i=1:n_ants
            flag = 0; %indication that no ant finished its path
%
            while flag==0
                p_max=0;   %initialization of transition probability
                denom=0;   %initialization of denominator of p

                %calculation of denominator of p
                p=zeros(1,neq);
                for k=1:neq
                    n=find(ant(i,:)==k);
```

```
                    if isempty(n)  %equipment not in the sequence

                     ind=find(ant(i,:)==0);  %index of the first zero
                        ind=ind(1);
                        ant_temp=ant(i,:);
                        ant_temp(ind)=k;
                        h=0;
                        pen=0;
                        dur_before=0;
                        distance=0;

                      for ii=2:ind
                          dur_before=sum(duration(ant_temp(1:ii-1)));
                            if dur_before>limit(ant_temp(ii))
                                pen=(dur_before-
limit(ant_temp(ii)))/30/12;
                            else
                                pen=0;
                            end

                            if
strcmp(dept(ant_temp(ii)),dept(ant_temp(ii-1)))==1

                                distance=distance+0;

                            elseif
hospital(ant_temp(ii))==hospital(ant_temp(ii-1))

                                distance=distance+5;
                            else

                                distance=distance+10;
                            end
        h+w(ant_temp(ii))*(1-pen);   %objective function that you
obtain adding to the current sequence the new equipment k
                        end

                        h=h-distance/(10*(ind));
                        p(k)=(tau(ant(i,ind(1)-1),k)^alfa)*(h^beta);

                        if isreal(denom)

                  denom=denom+(tau(ant(i,ind(1)-1),k)^alfa)*(h^beta);

                        else
                            denom
                            keyboard
                        end
                    end
                end
                if denom==0
                    p(k)=0;
                else
                    p=p/denom;
                end

                best = selection_ant (p);
                ind=find(ant(i,:)==0);
                ant(i,ind(1))=best;
```

```
                tot_duration=sum(duration(ant(i,1:ind(1))));

                %stopping criterion
                if tot_duration>time_max
                    ant(i,ind(1))=0;
                    flag=1;
                elseif ind(1)==neq
                    flag=1;
                end
            end
        end

        %pheromone evaporation
        tau=(1-ro)*tau;

        fit=zeros(1,n_ants);

%pheromone update
        for i=1:n_ants
            ind=find(ant(i,:)==0);  %index of the first zero
            if isempty(ind)
                ind=length(ant(i,:));
            else
                ind=ind(1)-1;
            end
            h=0;
            pen=0;
            dur_before=0;
            distance=0;
            for ii=1:ind
                dur_before=sum(duration(ant(i,1:ii-1)));
                if dur_before>limit(ant(i,ii))
                    pen=(dur_before-limit(ant(i,ii)))/30/12;
                else
                    pen=0;
                end
                if ii<ind
                    if strcmp(dept(ant(i,ii+1)),dept(ant(i,ii)))==1
                        distance=distance+0;
                    elseif hospital(ant(i,ii+1))==hospital(ant(i,ii))
                        distance=distance+5;
                    else
                        distance=distance+10;
                    end
                end

     h=h+w(ant(i,ii))*(1-pen);  %objective function that you obtain
adding to the current sequence the new equipment k
            end

h=h-distance/(10*(ind));
            fit(i)=h;

            D_tau=fit(i)*Q;  % objective function * constant

 for j=1:ind(1)-1

tau(ant(i,j),ant(i,j+1))=tau(ant(i,j),ant(i,j+1))+D_tau;
                tau(ant(i,j+1),ant(i,j))=tau(ant(i,j),ant(i,j+1));
```

```
            end

            if D_tau>D_tau_max
                D_tau_max=D_tau;
                sol_best=ant(i,:);
            end
        end
    end
    sol_best1(r,:)=sol_best;
end

save('results_rip7.mat', 'duration', 'ant', 'sol_best1', 'alfa',
'beta', 'ro')
```

APPENDIX E

GA Algorithm

```
clear all
close all
clc

% loading of data
load ('weights.mat')
load ('prices.mat')
load ('pool_in.mat')

% Parameter setting
nind =  1000;            %number of solutions in the initial
population
iter = 500;             %number of iterations
ngenitori =  round(nind*0.8);       %number of parents
nrip= 20;              %number of repetitions starting from the same
population
budget=680;

ngen = length(w);           % number of genes in each chromosome
pm = 0.4;                   % mutation probability
pc = 0.6;                   % crossover probability

% Initialization
fit = zeros(nind,1);        % vector containing the fitness values
for each solution in the new population
sol = zeros(1,ngen);        % considered solution
pool = zeros (nind,ngen);   % matrix of solutions
fitpool = zeros (nind,1);   % vector containing the fitness values
for each solution in the initial population
nfeat_min=2;                %minimum number of devices inserted in
the solutions
nfeat_tot=length(w);        %total number of devices
solbest_fin=zeros(nrip,ngen); %matrix of the best solutions
fitbest_fin=zeros(nrip,1);    %vector of the fitness associated to
the best solutions
costs=zeros(nrip,1);          %total cost for each best solution

% creation of an initial random population
% pool_in = creation (nind, nfeat_min, nfeat_tot);
ind=randsample(1000,nind);
pool_in=pool_in(ind,:);

for r=1:nrip
    fprintf('%d\n',r)
    pool=pool_in;
    % calculation of the fitness value for each solution in the
population
    for i = 1:nind
        sol = pool(i,:);
        fitpool(i) = fitness (sol,w,p,budget);
    end

    %Saving of the best current solution
    ind=find(fitpool==max(fitpool));
```

```
    fit_best=fitpool(ind(1));
    sol_best=pool(ind(1),:);

    % Main loop
    for it = 1:iter

        % Selection of the parents
        [oldpop,fit]=selection (pool, fitpool,ngenitori);

        % Mutation
        newpop = mutation (oldpop,pm,ngen);
        oldpop = newpop;

        % Crossover
        newpop = crossover (oldpop,pc);
        oldpop = newpop;

        clear solamm;

        % Assessment of the admissible solutions (with at least 2
devices
        % considered)
        k = 1;
        for i = 1:size(oldpop,1)
            nfeat=sum(oldpop(i,:)); %number of devices in the current
solution
            if (nfeat>=nfeat_min) %check the admissible solution
                solamm(k,:)=oldpop(i,:);
                k=k+1;
            end
        end

        oldpop = solamm;

        fit=zeros(size(oldpop,1),1);

        %Calculation of the fitness of the new solutions
        for i = 1:size(oldpop,1)
            sol = oldpop(i,:);
            fit(i)= fitness (sol,w,p,budget);
        end

        % Merge of the new solutions with the initial ones
        pool1=[pool; oldpop];
        fitpool1=[fitpool; fit];

        % search for a new best solution
        ind=find(fitpool1==max(fitpool1));
        fit_best_temp=fitpool1(ind(1));

        % Check that the new best solution is better than the
previous one
        if fit_best_temp>fit_best
            fit_best=fit_best_temp;
            sol_best=pool1(ind(1),:);
        end

        % Extraction of the indeces of the solutions to be inserted
in the
```

```
        % new population
        indici= randsample(size(pool1,1),nind);

        clear pool
        clear fitpool

        % Selection of the solutions of the new population
        for i=1:length(indici)
            pool(i,:)=pool1(indici(i),:);
            fitpool(i,:)=fitpool1(indici(i),:);
        end
    end

    %saving of the best solution for each repetition
    solbest_fin(r,:)=sol_best;
    fitbest_fin(r)=fit_best;
end

%calculation of the total costs for each best solution
for i=1:20
costs(i)=sum(p.*solbest_fin(i,:)');
end

%File saving
save('ga8.mat','solbest_fin','nind','ngenitori','iter','pm','pc','fit
best_fin','costs')
```

أطر شاملة لدعم إتخاذ القرار فى إدارة الأجهزة الطبية

إعـــداد

المهندسة / نيڤين صالح خليل صالح

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عنـــوان الرسالــة :

أطر شاملة لدعم إتخاذ القرار فى إدارة الأجهزة الطبية

الكلمات الدالة : إدارة الأجهزة الطبية - آلية ترسيخ الجودة – الأولوية - الصيانة الوقائية - الإستبدال

ملخـــص البحـــث :
على مدار حياة الجهاز الطبى تحتاج المستشفيات أن تتخذ قرارات بشأن إدارة الأجهزة الطبية مستندة على مجموعة من المعايير المختلفة. تعد مراحل الحصول على الجهاز الطبى والصيانة الوقائية وعملية الإستبدال هى أهم مراحل حياة الأجهزة الطبية ولذلك يعتبر التخطيط الجيد لإدارة هذه المراحل هو مفتاح إدارة الأجهزة الطبية. فى هذه الدراسة تم التركيز على تطوير مجموعة من أطر العمل الخاصة بالحصول على الجهاز الطبى بالإضافة إلي الصيانة الوقائية والإستبدال مع الأخذ فى الإعتبار مجموعة من المعايير التى تؤثر على صناعة القرار لتحسين منظومة إدارة الأجهزة الطبية. فى هذه الدراسة تم إقتراح ألية ترسيخ الجودة كطريقة رئيسية تدور حولها الأطر الشاملة لإدارة هذه المراحل.

الملخص

على مدار حياة الجهاز الطبى تحتاج المستشفيات أن تأخذ قرارات لإدارة الأجهزة الطبية إستناداً على معلومات شاملة موثوقة . تعتبر طريقة جلب الجهاز الطبى والصيانة والإستبدال هى أهم مراحل إدارة الأجهزة الطبية. ووفقا لذلك فإن إعداد خطة جيدة لهذه المراحل تعتبر هى مفتاح إدارة الأجهزة الطبية. فى هذه الرسالة تم التركيز على تقديم إطار عمل لكل من جلب و صيانة وإستبدال الجهاز الطبى مع الأخذ فى الإعتبار مجموعة من المعايير التى تؤثر على إتخاذ القرار و ذلك لتحسين منظومة إدارة الأجهزة الطبية.

فى الأعمال السابقة, نستطيع أن نجد العديد من الطرق والأدوات التى تتناول إدارة الأجهزة الطبية فى مراحل مختلفة, ولكن مع القليل من الإهتمام بعمل إطار عمل شامل. تعتبر آلية ترسيخ الجودة واحدة من أدوات إدارة الجودة الشاملة والتى يمكن أن تستخدم لتحويل متطلبات العملاء إلى مستوى فنى مناسب أو مواصفات فنية. تستخدم هذه الطريقة بشكل أساسي فى التصنيع و مناطق الإنتاج. و بمراجعة الأعمال السابقة تكشف ان آلية ترسيخ الجودة نادراً ما تم إستخدامها فى إدارة الأجهزة الطبية بالرغم من مميزاتها المتعددة. فى هذه الدراسة, إقترحنا آلية ترسيخ الجودة كطريقة أساسية تتم حولها إنشاء مجموعة من ألأطر الشاملة لإدارة الأجهزة الطبية.

فى عملية جلب الأجهزة تم التركيز على عملية الشراء. وتعتبر إعطاء أولوية معقولة لطلب الشراء من بين الطلبات المقدمة واحدة من أهم التحديات التى تواجه شراء الأجهزة الطبية . فى هذه الرسالة تم عمل تكامل بين آلية ترسيخ الجودة و المنطق الضبابى لمحاولة حل هذه المشكلة إعتماداً على مجموعة من المعايير الفنية و الأمنية و المالية والتى تؤثر على شراء الأجهزة الطبية. بإستخدام هذا الإطار, تم تقسيم أولوية الشراء إلى خمسة فئات؛ مرتفع جداً, مرتفع, متوسط, منخفض, لا تقريبا. للتحقق من صحة النموذج المقترح تم تجميع عشرون طلب شراء من مستشفى عام مصرية وتم عمل مقارنة لأولويات هذه الطلبات. أوضحت النتائج مقدرة النموذج المقترح على تمييز الطلبات على حسب أولوية الشراء.

تعتبر الصيانة الوقائية هى القلب الوظيفى للهندسة الإكلينكية, ولذلك من الضرورى إعداد خطة تبدأ من عمل حصر جيد ومنظم للأجهزة. تم إقتراح إطار ثلاثى النطاق بإستخدام آلية ترسيخ الجودة كمفهوم جديد لتحديد أولوية الأجهزة التى تحتاج إلى صيانة وقائية. يتكون الإطار من نطاق المتطلبات , نطاق الوظيفة, ونطاق المفهوم. نطاق المتطلبات هو مصفوفة بيت الجودة . النطاق الثانى هو مصفوفة التصميم .و أخيراً النطاق الثالث هو مؤشر الأولوية والذى يحتوى على معايير حرجة لوضع أولوية للصيانة الوقائية مع توضيح أوزان هذه المعايير. وفقاً للدرجات النهائية للمعايير يتم تحديد أولوية الجهاز لعملية الصيانة الوقائية.

تم إختبار الموديل المقترح على بيانات مجمعة من200 جهاز طبى ل 70 نوع من الأجهزة الطبية تخص 32 قسم طبى من الأقسام المختلفة فى إثنين من المستشفيات الإيطالية بمقاطعة بيومنت على مدار عام 2012. بناءاً على هذا الموديل تم تقسم الصيانة الوقائية من حيث الأولوية إلى خمسة فئات , مرتفع جداً, مرتفع, متوسط, منخفض, أدنى. وفقاً للنتائج النهائية تم تقسيم أجهزة التحقيق من حيث أولوية الصيانةإلى 15% مرتفع جداً, 19% مرتفع , 30% متوسط, 27% منخفض, و فقط 9% تحتاج أدنى مستوى من الصيانة. إستناداً إلى هذه النتائج تم إعتماد الخطة من مسئول قسم الهندسة الإكلينكية للمستشفتين.

بما أن الصيانة الوقائية غالية فمن الضرورى والحتمى تحديد أوقات إجراء الصيانة. يعتبرتحديد الصيانة الوقائية المثلى من المشاكل القديمة التى تم الإستفاضة فى دراستها. تكمن المشكلة هنا فى أن معظم النماذج المقترحة إن لم يكن كلها تعتمد على تقنين الفترات الزمنية للصيانة وعدد مرات الصيانة بغض النظر عن تقنين تسلسل الأجهزة نفسها لعملية الصيانة آخذة فى الإعتبار أولوية الأجهزة للصيانة الوقائية. ولهذا تقدم هذه الدراسة حل لهذه المشكلة عن طريق إيجاد التسلسل الأمثل للأجهزة بإستخدام لوغاريتمات مستعمرة النمل المثلى . تم إقتراح إصدارين من اللوغاريتمات وذلك لزيادة تعقيد النموذج خطوة بخطوة. كلا الإصدارين بدأوا من قائمة واحدة بها الأجهزة على حسب الأولوية و أختلفوا فى الدالة الإرشادية . النموذج الأول أخذ فى الإعتبار فقط أولوية الجهاز للصيانة بينما مكان تواجد الجهازقد أخذ فى الإعتبار للنموذج الثانى . تم تطبيق هذه النماذج على 182 جهاز وقد أظهرت النتائج فاعلية هذا اللوغارتمات لهذه النوعية من المشاكل.

يعد إستبدال الأجهزة الطبية من المسائل المعقدة والتى يمكن أن ينتج عنها بعض المشاكل. فى هذه الدراسة تم إقتراح آلية ترسيخ الجودة للتعامل مع هذه المرحلة الحرجة بإستخدام مجموعة من العوامل التى تؤثر بشكل مباشر أو غير مباشر على قرار الإستبدال. فى هذا النموذج خرج آلية ترسيخ الجودة هو قائمة من الأجهزة التى تعكس مدى الإحتياج للإستبدال. علاوة على ذلك الأجهزة التى تحتاج للإستبدال تم عمل تقنين لها بإستخدام اللوغاريتمات الجينى مع الأخذ فى الإعتبار الميزانية المتاحة وذلك للوصول إلى الحد الأقصى من الأجهزة التى تحتاج إلى إستبدال . تم تقييم النموذج المقترح عن طريق بيانات مجمعة من 60 جهاز طبى فى مستشفى عامة مصرية. وقد أظهرت النتائج مدى قوة النموذج حيث انه إستطاع بنجاح أن يميز أولوية الإستبدال عن طريق تقسيم الأجهزة إلى أربع فئات , مرتفع جداً , مرتفع, متوسط, عير محتاج, بالإضافة إلى أنه فى نفس الوقت حدد الحد الأقصى من الأجهزة التى تحتاج إستبدال معتبراً الميزانية المتاحة.

ختاماً يمكن القول بأن آلية ترسيخ الجودة أثبتت نجاحها كطريقة يمكن إستخدامها بشكل جيد فى عمل أطر شاملة لإدارة الأجهزة الطبية والتى يمكن أن تكون أداة إرشاد لقسم الهندسة الإكلينكية فى إتخاذ القرارات.

تتكون هذه الرسالة من سبعة فصول يمكن توضيحها كالتالى :

. **الفصل الأول:** يوضح مقدمة عامة عن الموضوع مع توضيح المشاكل والأهداف من هذا البحث.

الفصل الثانى: يقدم نبذة مختصرة عن إدارة الأجهزة الطبية تتضمن المفهوم , المراحل, الطرق , و المعايير المتبعة .

الفصل الثالث: يقدم الطرق المستخدمة فى هذه الرسالة مع شرح توضيحى لكل طريقة على حدة إستناداً على الأعمال السابقة.

الفصل الرابع: يتناول هذا الفصل عملية شراء الأجهزة الطبية وكيفية إعطاء أولوية مناسبة للأجهزة يتم فيها تناول الأعمال السابقة و تقديم الموديل المقترح وعرض النتائج التى تم التوصل إليها.

الفصل الخامس: فى هذا الفصل تم التعامل مع مرحلة الصيانة الوقائية للأجهزة الطبية. فى البداية تم عرض لبعض النماذج السابقة التى تناولت هذا الموضوع بعد ذلك تم تقديم النماذج المقترحة لتحديد أولوية الأجهزة وتحديد التسلسل الأمثل للأجهزة على حسب الأولوية الناتجة ثم بعد ذلك تم عرض النتائج التى تم التوصل إليها.

الفصل السادس: يقدم هذا الفصل مشكلة الإستبدال الأمثل للأجهزة الطبية والطرق السابقة التى تناولتها وكيفية علاج هذه المشكلة عن طريق إقتراح نموذج جديد يحدد أولوية الأجهزة ثم بعد ذلك يتم تقنين هذه القائمة من الأجهزة على حسب الميزانية المتاحة للإستبدال . أيضا تم عرض النتائج التى تم التوصل إليها فى هذا الفصل.

الفصل السابع : يعرض الإستنتاجات التى تم التوصل إليها عن طريق إستخدام هذه الحلول المقترحة لتلك المشاكل التى تواجه إدارة الأجهزة الطبية مع تقديم توصيات مستقبلية لهذه النماذج و المقترحات.