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The American University in Cairo

School of Science and Engineering

Optimizing Rehabilitation and Maintenance of Hospitals

A Thesis Submitted to

Construction Engineering Department

In partial fulfillment of the requirements for the degree of

Master of Science

In

Construction Engineering

By

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Under the supervision of

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Finally, my deep appreciation and thanks for my parents and siblings for their incredible support and encouragement throughout my life.

ABSTRACT

Hospitals are one of the core elements of a health care system that provide medical service to the patients. Hospital facility management is a complex issue as it involves the management of several complex systems that have a direct impact on the delivery of health care issues. This research focuses on two vital aspects of hospital facility management, (1) level of service provided by the hospital and (2) technical aspects of mission critical hospital subsystems. This study proposes two models in order to maintain and improve the level of service delivered to the patients. The first model operates at the macro-level and undertakes the **Ne**twork-level **H**osp**i**tal **R**ehabilitation Trade off model (NEHIR). The model optimizes the scheduling of rehabilitation works through the use of genetic algorithm optimization engine. The model features through five modules, (1) Database module that stores the hospitals data, (2) Backward Markov chain module that estimates the transition probability matrix, (3) Deterioration prediction module that predict the future condition of the asset, (4) Rehabilitation Cost optimization and (5) Multi-objective rehabilitation schedule optimization that conducts a tradeoff between the modified rehabilitation cost and the number of unserved patients.

The second model operates at the micro-level and undertakes the **Ho**spital-level **Re**liability Centered **M**aintenance model (HOREM). The model optimizes the maintenance tasks for critical subsystems and optimize the allocation of maintenance budget among the hospital subsystems. HOREM model is consisted of five modules as follows, (1) Reliability Centered Maintenance module that was used to define the components, functions, functional failure, failure modes, failure consequence and maintenance type for subsystems components, (2) fuzzy logic system module for determining the probability of failure of different replacement/restoration intervals, (3) Monte-Carlo simulation module determining the probability of failure of different inspection intervals, (4) Multi-objective maintenance optimization module that tradeoff between the downtime and maintenance costs and (5) Systems Integration optimization module that optimize the top management maintenance budget on hospitals subsystems.

Two case studies were considered for verification and validation. The first case study is comprised of four hospitals was used for NEHIR model validation. The results of NEHIR model showed 8% decrease in number of unserved patients and 20% saving in rehabilitation costs. The second case study was one hospital that was used for validating HOREM model. The results of HOREM model showed 17% reduction in maintenance costs compared to traditional methods for the same downtime.

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LIST OF ACRONYMS

- AHU → Air Handling Unit
- AI → Artificial Intelligence
- ANNs → Artificial Neural Networks
- CCO → Curative Care Organization
- ERs → Emergency rooms
- FMEA → Failure Mode Effect Analysis
- FMECA → Failure Mode Effect Criticality Analysis
- FTA → Fault Tree Analysis
- GAs → Genetic Algorithms
- GDP → Gross Domestic Product
- HAI → Health Associated Infections
- HEPA → High-Efficiency Particulate Air
- HIO → Health Insurance Organization
- HOREM → Hospital-level Reliability Centered Maintenance
- HVAC → Heating, Ventilation and Air Conditioning
- ICUs → Intensive care units
- MOHP → Ministry of Health and Population
- NEHIR → Network-level Rehabilitation Trade-off
- OHI → Overall Hospital Index
- OHRM → Overall Hospital Rating Matrix
- ORs → Operating rooms

- P-F → Potential failure- Functional failure
- PM → Preventive Maintenance
- RC → Rehabilitation Costs
- RCM → Reliability Centered Maintenance
- RPN → Risk Priority Numbering
- RRs → Regular rooms
- THI → Teaching Hospitals & Institutes
- VIT → Vacuum Insulated Tank
- WHO → World Health Organization

LIST OF SYMBOLS

- AB_x → is the availability of beds per month for hospital x
- APH_x → is the average patients per month of hospital x
- APS_k → is the average patients served/hour for system k
- B_x → is the number of beds available in hospital x
- CR → is the crew rate in EGP/hour
- CS_i → is the condition state
- DC_i → is the degree of criticality for unit i
- DT → is the downtime listed in FMEA for failure modes
- DT_k → is the downtime in hours for system k
- D_x → is the duration of hospital x
- D_{xy} → is the duration covered in months at year y for hospital x
- IC_i → is the inspection cost for failure mode i
- ID → is the inspection duration in hours
- IHV_s → is the initial vacancy percentage of suspended/partially suspended hospital s
- IHV_x → is the initial vacancy of hospital x
- MC → is the material cost in EGP
- EDT → is the expected downtime in days
- MHV_x → is the modified vacancy percentage of hospital x
- MPH_x → is the maximum patients per month of hospital x
- MRC_x → is the modified rehabilitation cost for hospital x
- MR_x → is the modified rehabilitation strategy for hospital x

- n → number of years
- $NAPH_x$ → is the served patients per month during rehabilitation of hospital x
- $NSPH_x$ → is the total un-served patients during rehabilitation of hospital x
- OHR_i → is overall hospital rating percentage at a specific condition state
- $OHRM_a$ → is actual overall hospital rating matrix
- $OHRM_c$ → is the calculated overall hospital rating matrix
- $OHRM_i$ → is the initial overall hospital rating matrix
- $OHRM_{new}$ → is the new overall hospital rating matrix
- OL → Overlapping rate
- O_{xj} → is binary variable refers to rehabilitation of hospital x at time
- P → is the assumed transition matrix
- Pf → is the probability of failure "P (X<a)", is the inspection interval in days, X is minimum P-f interval (in case of condition based maintenance).
- PH_i → is the patients per hour for unit i
- P_{if} → is the percentage at a condition state i for an element f
- P_{mod} → is the modified transition matrix after adopting rehabilitation strategy
- Q_i → is the quantity to be renovated at condition state i
- r → inflation rate
- R → Rehabilitation strategy
- RCT_i → is the replacement costs for failure mode i
- RC_{xy} → is the rehabilitation cost for hospital x at year y
- RC_{xym} → is the rehabilitation cost for a hospital (x), at year (y) and month (m) at certain year

- R_s → is unit cost for the rehabilitation strategy
- SPH_x → is the new served patients by an operating hospital x
- SP_x → is the service suspension during rehabilitation of hospital x
- TMC → is the total maintenance costs
- TMRC → is the total modified rehabilitation cost for all hospitals
- TNSP → is the total number of un-served patients
- VB_t → is the total vacant beds in all hospitals
- W_f → is the weight of element f

1 INTRODUCTION

1.1 Background

Hospitals and health facilities are one of the most critical elements in society's infrastructure together with the other assets including roads and sewer networks (Griffin, 2006). Hospitals, which are usually funded by public sector are considered complex to manage, operate and maintain (Lavy and Shohet 2009). They deal with thousands of patients of different requirements. Moreover the presence of complex engineering services e.g. mechanical, electrical, medical gases…etc. that should deliver an un-interrupted high quality level of service. Furthermore, it includes different functional spaces like operating rooms (ORs), intensive care units (ICUs)…etc. (Ali and Hegazy, 2014). Consequently, hospitals maintenance is not an easy, straight forward task, due to the presence of diverse items that require different maintenance approaches that need to be considered in order to deliver the required level of service.

One of the main reasons for the decline in the healthcare service in many countries especially in the developing ones is the absence/low maintenance budgets hence inappropriate maintenance plans are adopted. In Egypt, Ministry of Health and Population (MOHP) is a major health service provider that owns a significant percentage from the 4506 facilities and 152,172 beds available in the country (WHO, 2006). Figure (1-1) shows the health facilities distribution across Egypt in 2005, 67% of the facilities are small units in rural areas, hospitals account for 14% while the clinics are the least with 2%. Figure (1-2) expresses the beds distribution across Egypt in 2005 respectively. The WHO reported that the average bed/1000 population in Egypt is 2.15 which is very low compared to central Europe which has an average bed/1000 population of 6.4 in 2005. The greatest bed/1000 population ratio was in Sinai due to the low population. Figure (1-3) shows the bed-population ratio through Egypt.

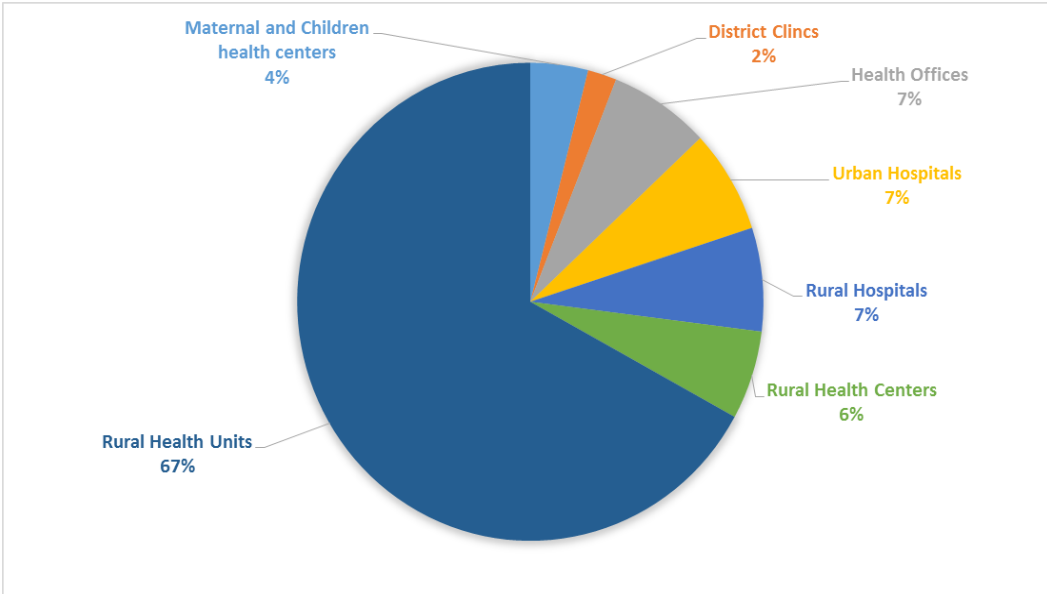

Figure 1-1: Health Facilities distribution in Egypt (WHO, 2006)

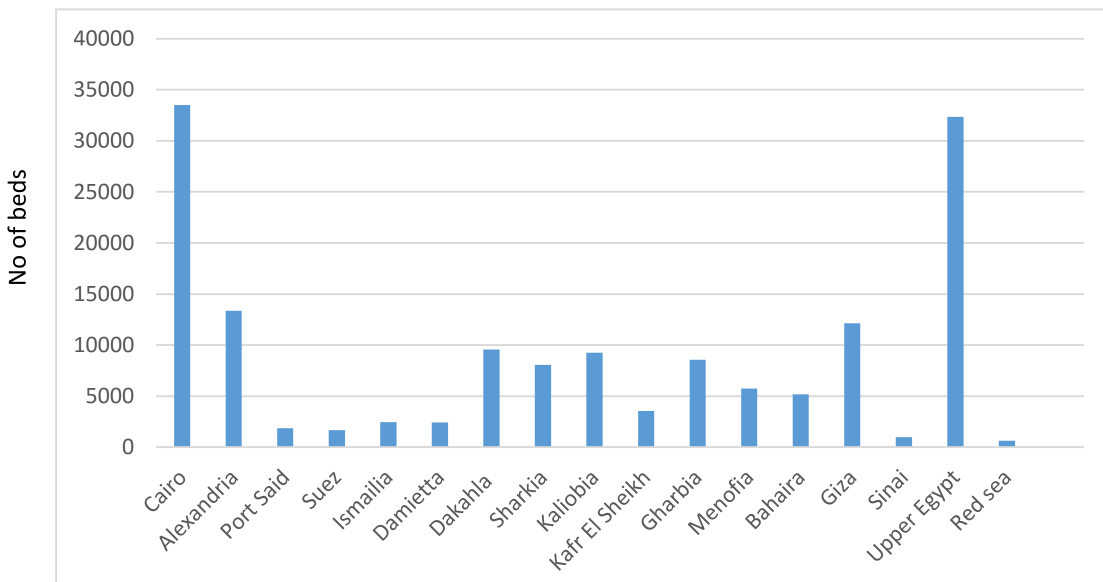

Figure 1-2: Beds Distribution across Egypt (WHO, 2006)

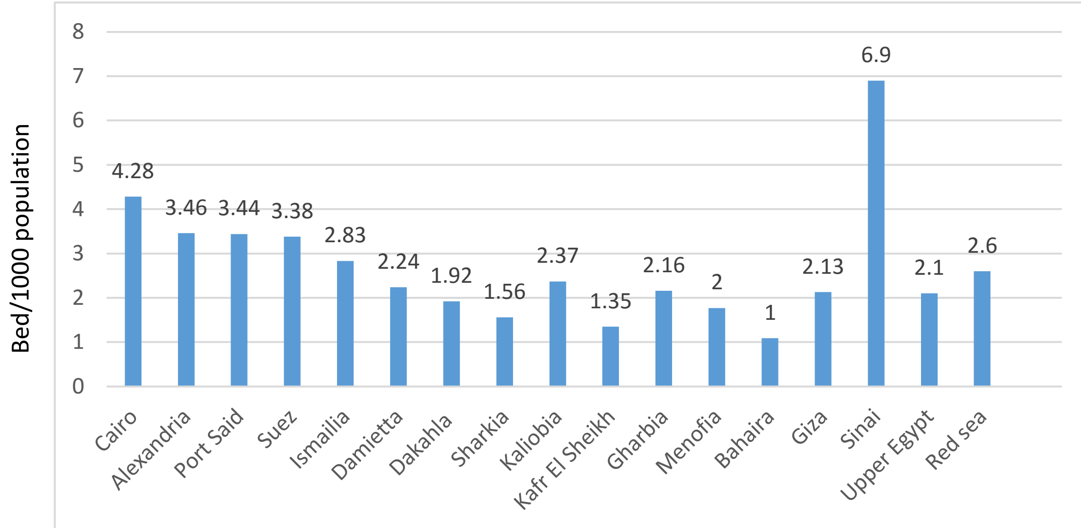

Figure 1-3: Bed/1000 population distribution across Egypt (WHO, 2006)

Regarding healthcare funding, the total public expenditure on health service in Egypt at 2005 was 3.7% of GDP which is low compared to other countries, only 19% of this budget is allocated to the health facilities. The total expenditure/capita was increased from $30 at 1990 to $192 at 2004. The sources of finance for healthcare system in Egypt are divided between public funding, donations and private sources, figure (1-4) shows different sources of finance for healthcare in Egypt in 2002 (WHO, 2006).

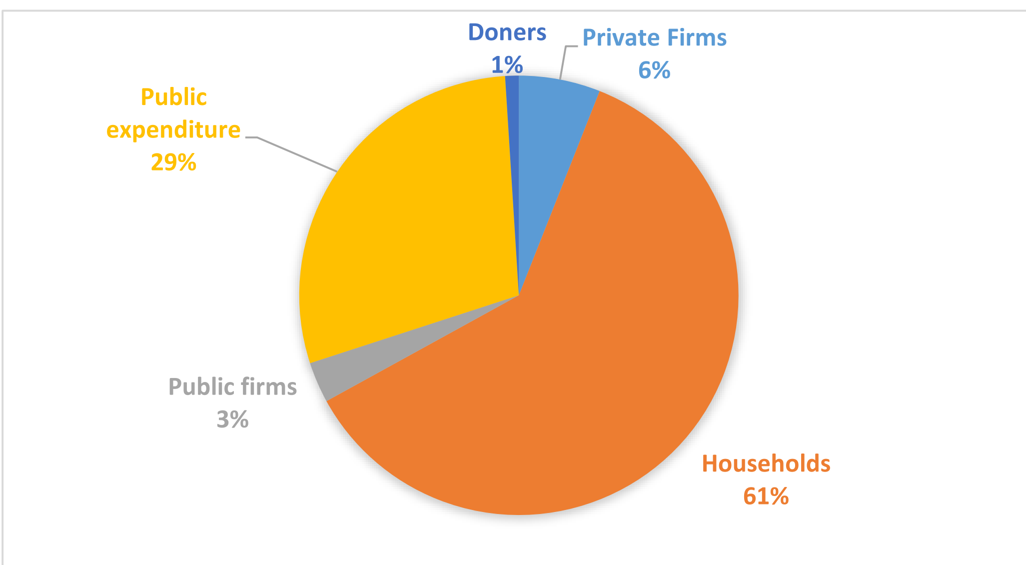

Figure 1-4: Sources of finance for Healthcare in Egypt (WHO, 2006)

As mentioned earlier, MOHP is main service provider in Egypt, however some other parties contribute in delivering healthcare service to the people. MOHP (public hospitals) owns 51% of beds available, followed by private hospitals (17.5%), university hospitals (17%) and the remaining are distributed between jails, companies, Health Insurance Organization (HIO), Curative Care Organization (CCO) and Teaching Hospitals & Institutes (THI). Figure (1-5) depicts service providers in Egypt and their contribution (WHO, 2006).

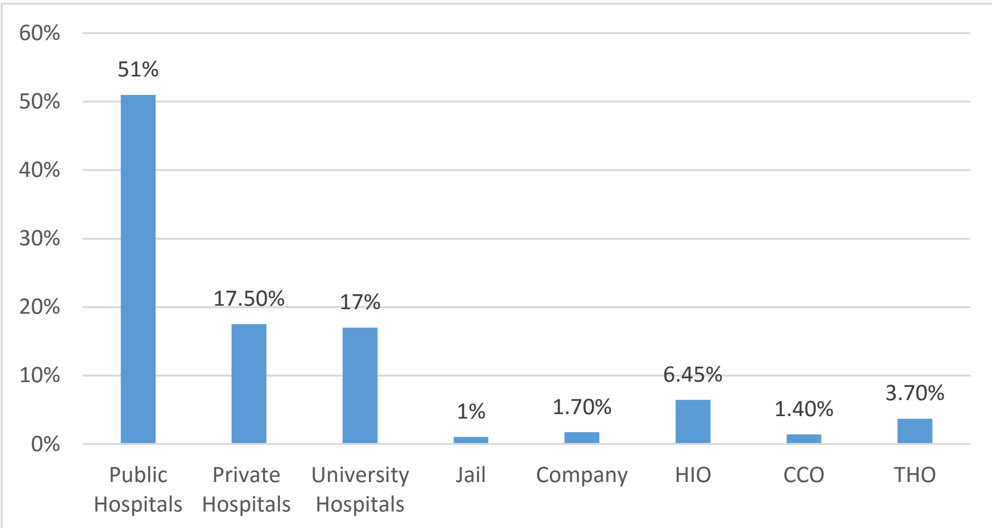

Figure 1-5: Service providers in Egypt in 2005 (WHO, 2006)

The WHO recommends the improvement of healthcare system through adopting efficient measures in financial resources allocation in order to elevate the service required by the people. Adopting efficient maintenance program is crucial in order to keep the current facilities, hence the government can spend on increasing the number of health facilities to meet growing population. Moreover it will assist in providing safe working environment to healthcare workforce (physicians, nurses…etc.), that leads to ensuring adequate level of service.

1.2 Problem Statement

Many hospitals were built several years ago. Due to the absence of regular inspection on hospitals structure, they are suffering from severe deterioration to the limit that some of these hospitals need to be demolished and re-constructed. For example, it was recommended to demolish a part of the National Cancer Institute in Cairo that was built 20 years ago as reported by (Al Masry al Youm, 2010). Other hospitals require rapid intervention by renovating and upgrading the structure in order to be able to provide safe environment to the patients and physicians.

Unfortunately, rehabilitation and upgrading is not an easy decision as it leads to partial or even full suspension of health service provided. Therefore a significant number of patients will not be served. The critical situation will arise if several hospitals in the same region or city are severely deteriorated and require intervention. On the other hand, postponing the rehabilitation will result in extra costs incurred as the structure is prone to further deterioration in addition to the increase in unit prices due to inflation issues. Consequently, it is crucial to carefully schedule the rehabilitation works of the hospitals taking into account total rehabilitation cost & the impact to healthcare system capacity.

Moreover, there are multiple systems within hospitals that work together on daily basis in order to provide service required to the patients e.g. HVAC systems, medical gas, elevators…etc. These systems need to provide un-interrupted service, else it might be a source of threat to the patients or it could decrease the level of service provided. In order to keep the service working 24/7 with no/minimal interruption, an efficient maintenance plan need to be adopted.

According to the British Standards Glossary of terms (3811:1993), maintenance "is the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function". There are several kinds of maintenance that includes corrective, preventive or predictive, the dilemma is which maintenance approach to be followed. Currently, corrective maintenance to some extent (run to failure) is the mostly used type of maintenance. This approach is appropriate if the consequence of failure is tolerable and of minimal/no impact on service which is not the case for hospitals. The result is a downtime & increased risk exposure to the patients and healthcare providers. The main reason for the absence and improper maintenance and inspection actions is the limited financial resources. Hence government need to employ cost effective strategies in order to maintain the current service provided within the budget available.

1.3 Research Objectives

The aim of this research is to address the problems that impact the service delivery in hospitals. Thus the main objectives of this research could be best summarized as follows:

- Study and analyze the current practice and the level of service-related issues in hospitals.
- Understand how various systems contribute to service delivered by hospitals
- Develop a model that conduct a tradeoff analysis between the number of unserved patients and the rehabilitation costs.
- Utilize the concept of Reliability Centered Maintenance in optimizing maintenance plans in order to minimize the downtime and maintenance cost.
- Verify and validate the models through actual case studies.

1.4 Research Scope

The scope of this research will be as follows:

1- The rehabilitation of hospital concrete structures as they have safety issues. Rehabilitation works of concrete structures will cause major/complete service suspension. Unlike other aspects that are important to be studied (not covered in this research) that include rehabilitation of hospital finishes that might result only in partial service suspension.

2- Hospitals include various systems that include firefighting, HVAC, electrical systems, medical gas systems (Enshassi and Shorafa, 2015). However, three systems were considered in this research which are medical gas system, HVAC systems and elevators due to the absence of reliable data on the other systems. Moreover, the selected systems represent (65-80%) of the total electromechanical costs as per expert views who were interviewed.

1.5 Methodology

1- The research considered the review of the literature in the following areas:

- Hospital facility management: review the previous research developed for managing hospitals and what did they consider, consequently the limitations that can be taken into account in developing our models.
- Deterioration models: methods of developing deterioration prediction for different assets and structures that includes deterministic models (regression analysis), stochastic models (Markov chains models) and artificial intelligence models (fuzzy logic systems and artificial neural networks). In addition, the most suitable approach to be used in our case.
- Deterioration causes: review the causes of deterioration and how they affect the structure in order to determine the repair methods.
- Hospital systems: review the different systems used in hospitals, their function and components and how the contribute to the service delivered to the patients.
- Maintenance types: review the different kinds of maintenance and how they are applied and when to be used. Maintenance strategies application differs between different components and failure modes.
- Optimization models: review different optimization techniques to decide on the most suitable one that can be applied to the models.

2- The research considered experts view to determine the functions, functional failures, failure modes, failure effects and failure consequence of all components of the hospital systems considered (HVAC, Elevators and medical gas system).

3- This research considered the experts view in deciding the p-f intervals for the failure modes that are not age related and their suitable probability distribution. In addition, expert views were considered in determining the factors that affect the performance of the items that fail by age.

4- Two models were developed to achieve the objectives mentioned, first model is NEHIR that considers the hospitals concrete structures and their different elements (beams, columns and slabs). Markov chains was used for future condition prediction, moreover genetic algorithms were used to optimize rehabilitation cost, number of unserved patients and provide rehabilitation schedule.

5- A Hospital-level Reliability Centered Maintenance model (HOREM) was developed that was dealing with hospital systems considered in this study (HVAC, medical gas and elevators). HOREM considered the use of Monte Carlo simulation and fuzzy logic system to determine the probability of failures associated with inspection intervals and replacement/restoration intervals respectively. Genetic algorithms were used to optimize maintenance plans and maintenance budget allocation.

6- A case study of several hospitals was considered to verify and validate the model demonstrate the results. Figure (1-6) illustrates the methodology to achieve the aforementioned objectives.

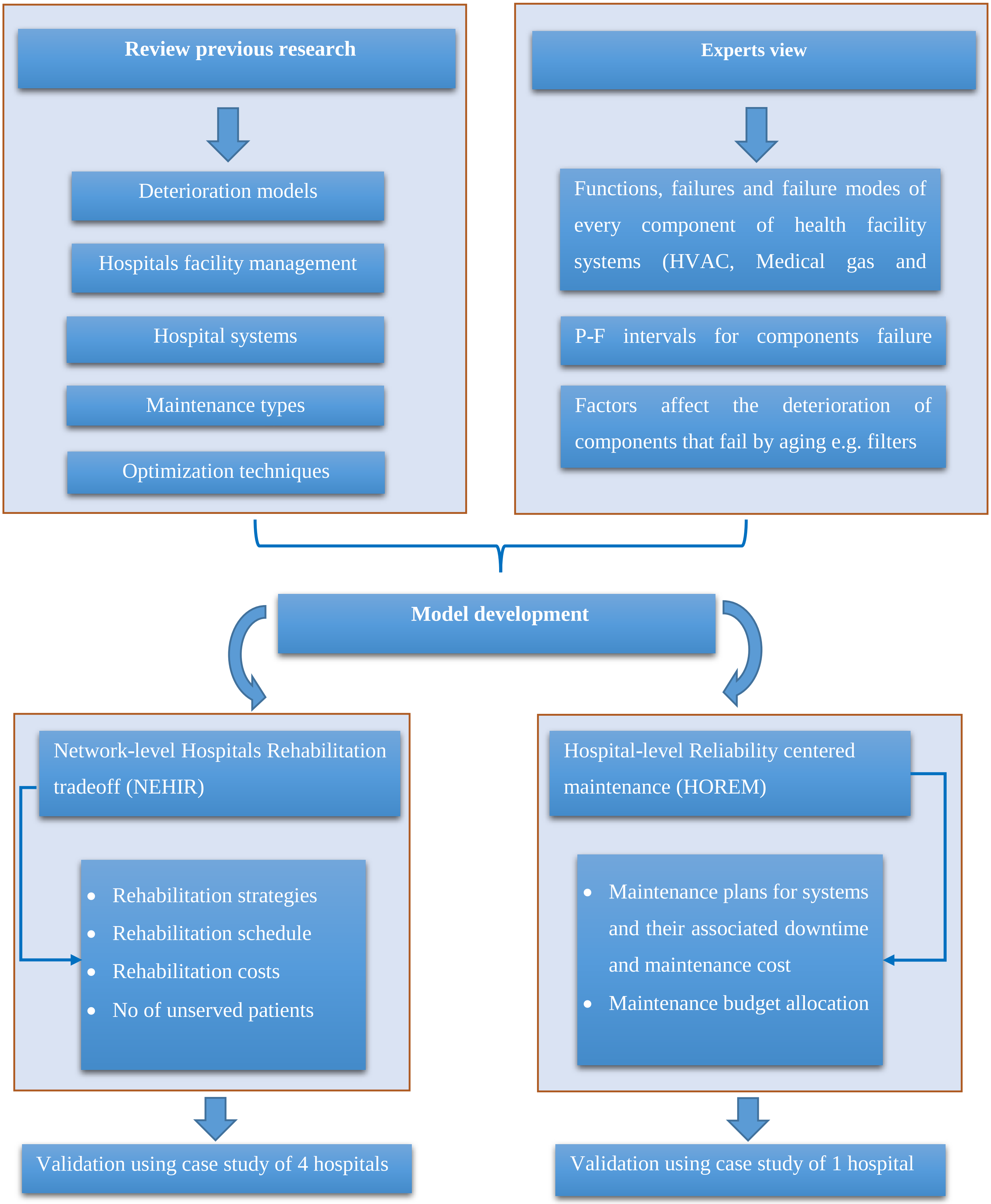

Figure 1-6: Research Methodology

1.6 Thesis Organization

The thesis is comprised of five chapters:

- **Chapter one (Introduction):** provides an overview of the current status of health facilities in Egypt, moreover it explains the research objective and methodology used in order to develop the proposed models.
- **Chapter two (Literature review):** introduces a detailed review for the previous research covering the dimensions and parameters that are beneficial for developing the models, this includes hospitals systems, deterioration models and maintenance approaches.
- **Chapter three (Research framework):** explains in details the proposed models that deal with hospital concrete structures and hospital systems.
- **Chapter four (Model Verification and Validation):** the chapter shows the results obtained from applying the models on actual case study.
- **Chapter five (Conclusion and recommendation for further research):** highlights the concluding remarks and subjects that can be considered for further improvements.

2 LITERATURE REVIEW

This chapter will highlight different methods for deterioration modeling, different optimization techniques, and types of maintenance, major hospital systems and previous studies done in heath facility management.

2.1 Deterioration of structures

In-order to manage hospital buildings effectively, it is crucial to understand causes of deterioration, types of deterioration prediction/modeling, condition rating & the effective rehabilitation and maintenance strategies that need to be adopted together with its cost. The following part is explaining the main causes of concrete building deterioration.

2.1.1 Causes of deterioration

2.1.1.1 Reinforcement corrosion

Corrosion of reinforcing steel is the leading cause of deterioration in concrete. When steel corrodes, the resulting rust occupies a greater volume than the steel. This expansion creates tensile stresses in the concrete, which can eventually cause cracking. For corrosion to occur, four elements must be present: (1) two metals on same location (2) at different energy levels, (3) an electrolyte, and (4) a metallic connection. In typical concrete structures, the rebar wires and chairs act as metallic connection while concrete paste act as the electrolyte. One of the main causes of reinforcement corrosion is the presence of chlorides. The chlorides dissolved in water together with the presence of oxygen can penetrate concrete through the cracks and corrode reinforcement. Some admixtures contain chlorides which is expose the steel reinforcement to corrosion. Water can be seeped to the concrete structure through improper plumbing creating an aggressive context around the reinforcement (PCA, 2002). Figure (2-1) depicts the reinforcement corrosion and figure (2-2) depicts the cracks due to corrosion.

Figure 2-1: Reinforcement corrosion (PCA, 2002)

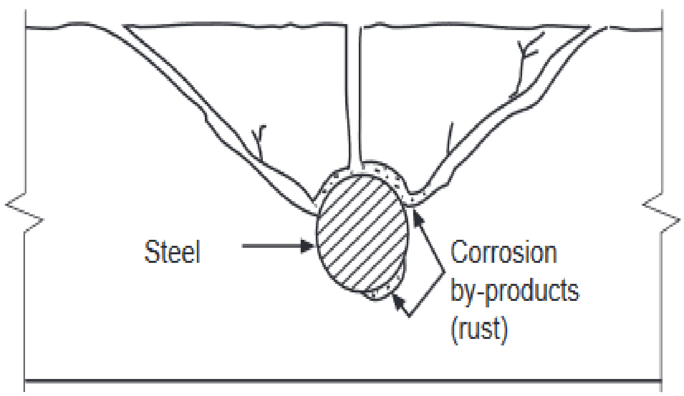

Figure 2-2: Concrete cracks due to reinforcement corrosion (PCA, 2002)

2.1.1.2 Chemical Attack

Chemicals like acids, alkalis and sulfates are forming danger context to concrete as it is normally cannot resist chemicals (in case of using Portland cement). Acids react with calcium hydroxide in concrete producing calcium compounds which is removed from the concrete creating voids that reduce the concrete strength (ACI 201, 1992).

Sulfates can attack concrete by reacting with hydrated compounds in the hardened cement. These reactions can induce sufficient pressure to disrupt the cement paste, resulting in loss of cohesion and strength (PCA, 2002).

2.1.1.3 Alkali – Aggregate reactivity

Caused by reactions between aggregate and alkali hydroxide in concrete leading to expansion and cracks. Alkali – aggregate reactivity could be either alkali-silica reactions or alkali – carbonate reactions. For alkali-silica reactions, the aggregates containing forms of silica will react with alkali hydroxide in concrete to form a gel which can swell by absorbing water causing expansion and damage to concrete. While the other type of reaction (alkali-carbonate reactivity) is taking place when alkali in cement reach with crystal in dolomite producing brucite which cause volumetric changes due to water absorption (PCA, 2002).

2.2 Hospital Elements and Divisions

A typical hospital is comprised of several divisions as follows:

- Administration division: that include the reception, waiting area and staff offices
- Outpatient's division: it serves the temporary patients such as clinics.
- Emergency division: provide treatment for patients without prior appointment in case of accidents.
- Diagnosis division: it includes laboratories and radiology.
- Medical treatment division: it includes operation units, intensive care units, maternity section, surgery, pediatrics and sterilization.
- Supporting departments: it includes food and catering services, laundry, security, storages and blood banks.
- Inpatients wards: that includes the regular rooms for the served patients and nurses rooms (PSSCIVE, 2014).

Figure (2-3) depicts a layout plan of a typical hospital at the ground floor. Ground floors in hospitals contain the administration, outpatient's services, radiology and kitchen. It is shown that emergency and clinics are close to exit doors and radiology.

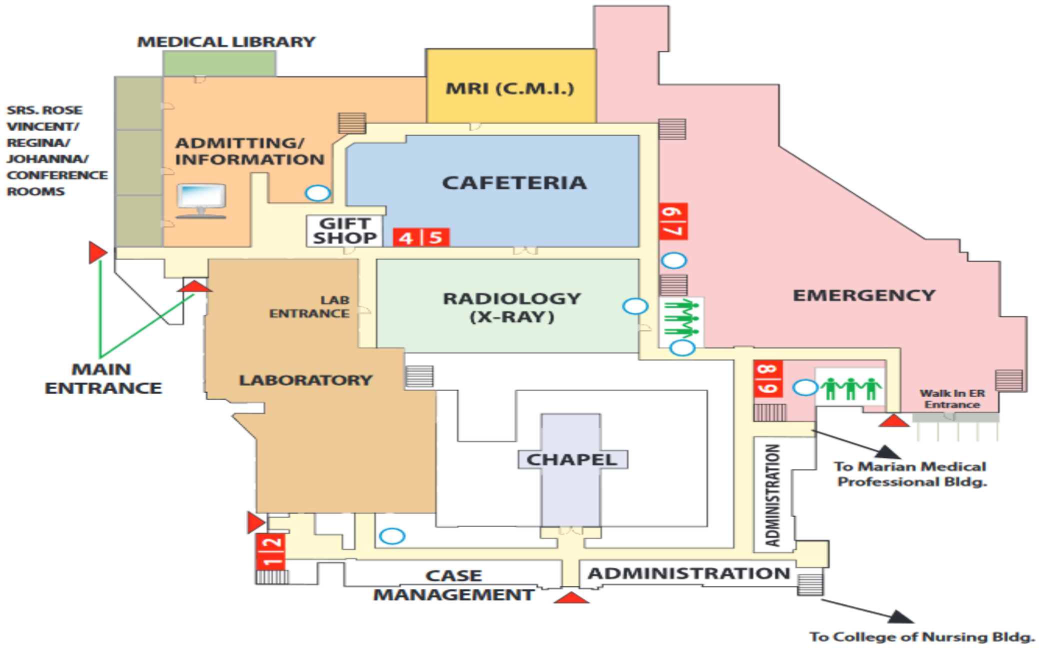

Figure 2-3: Ground floor layout for hospital (http://www.stemc.org/assets/Documents, 2013)

Figure (2-4) depicts a layout plan of a typical hospital at the upper floors. Upper floors in hospitals typically contain the other medical departments that include intensive care units surgery rooms and patients wards.

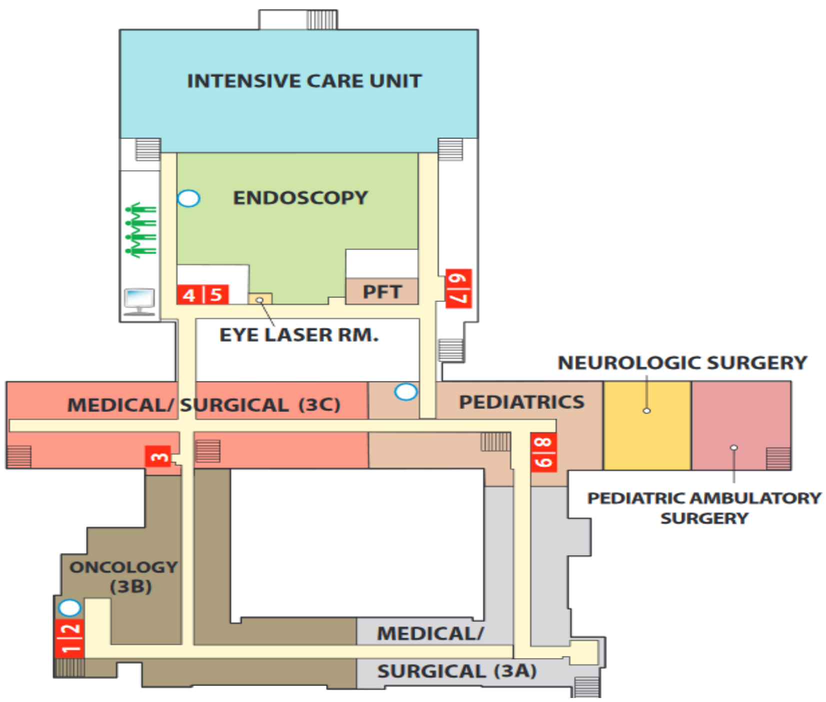

Figure 2-4: Upper floor layout for hospital (http://www.stemc.org/assets/Documents, 2013)

2.3 Hospital systems

Health facility are considered sophisticated and complex facility to manage due to the presence of several electromechanical and special systems that work together for delivering the service. MoyJr (1995) mentioned that to ensure health facility systems are working properly; an effective maintenance plan need to be adopted. This section will describe the systems included in this research.

2.3.1 Medical Gases

Medical gas systems are required to supply patients with oxygen, medical air and nitrous oxide. These gases flows through a huge central pipes network that have outlets in the patient's rooms, intensive care unit (ICU) and operations unit (Abu Al-Ainin, 2014).

2.3.1.1 Oxygen gas

Oxygen is primarily used in respiratory - therapy and anesthesia, Has the ability to support life and support combustion. Oxygen gas normally is supplied through liquid oxygen tanks and oxygen cylinders are available as a backup. Liquid oxygen gas tanks are less expensive than cylinders as they exist at cryogenic temperature of about (-181ºc) at atmospheric pressure, when warmed to ambient temperature the one liter will expand to fill x840 times its liquid volume (Abu Al-Ainin, 2014).

2.3.1.2 Nitrous Oxide

Exists in the normal conditions in atmosphere as a gas, its smell is somehow sweet itch, capable of producing the first and second stages in anaesthesia when inhaled, primarily used as an anaesthetic. Used commonly in operating rooms (ORs), and not further in the ICUs (Abu Al-Ainin, 2014).

2.3.1.3 Medical Air

Medical air is a normal air that is treated by using filters and dryer to provide normal respiration to the patients. Medical air is supplied by using medical air compressor plant.

2.3.2 Lift systems

Elevators are used for vertical transportation of people between different floors. In hospitals, elevator plays major role for patients especially for those who suffer from inabilities and require companion. Dimensions of elevators in hospitals should follow some standards that at least allow one stretcher with one companion. In addition, elevators should follow hygienic rules in terms of health and precautions should be taken towards anti-bacterial prevention, the interior space of elevator should be designed as stainless steel and lighting should be kept at a level that do not disturb the patient. Buttons are al low position unlike other elevators and wider doors are used (KONE Solutions, 2016).

2.3.3 HVAC systems

Chow and Yang (2003) believed that the presence of ventilation system in a hospital operating room and other rooms is crucial for human comfort and protecting the patient and surgical staff against hazardous emissions. In operating units, the role of HVAC system is critical and in order to reduce microbial exposure, the use of laminar flow ventilation is the engineering practice in those operating rooms designed for deep wound surgery. The supply air diffuser is located at the ceiling directly above the operation area, with the low-level exhaust outlets at the room periphery Chow and Yang (2003). Figure (2-5) depict a typical description of operating unit.

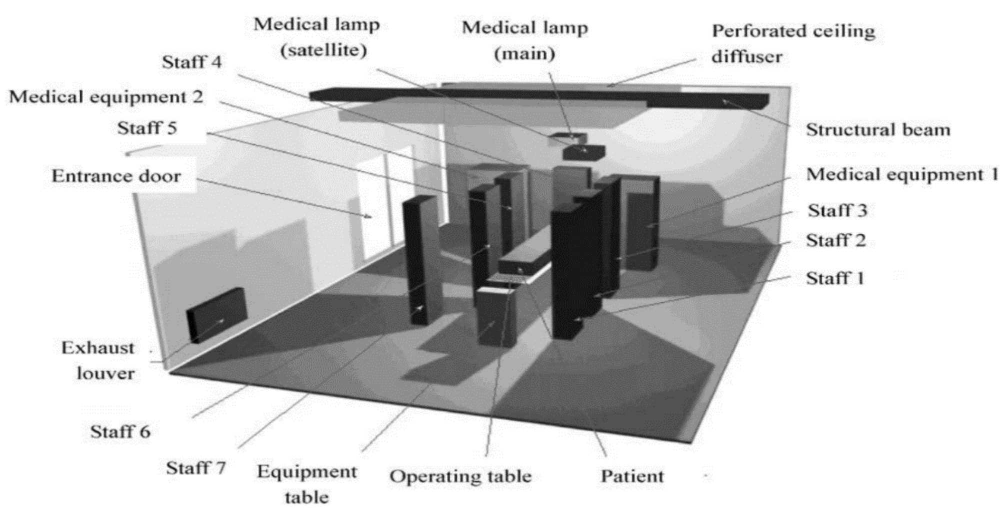

Figure 2-5: Operating Room Chow and Yang (2003)

2.4 Maintenance Types and Approaches

Maintenance is a procedure of "ensuring that physical assets continue to do what their users want them to do". Maintenance strategies have changed over the past decades due to changes in designs, required performance, and technology (Moubray, 1997).

2.4.1 Maintenance Strategies & History

2.4.1.1 First generation

At the first three decades on the twentieth century, the industry was not very highly mechanized, so downtime did not matter much. In other words scheduled maintenance plan is not required as the consequence was not significant. This strategy is called run to failure or corrective maintenance.

2.4.1.2 Second generation

In the mid of the twentieth century, strategies have changed due to the presence of significant of mechanization and a drop in manpower dependence. Hence equipment failures could and should be prevented, which led in turn to the concept of preventive maintenance (Moubray, 1997). Preventive maintenance assumes that parts are wearing out and failure is directly proportional to its age. Preventive maintenance is taking place by replacing or renew a certain item at fixed age intervals (NASA RCM, 2008). The main problem in this strategy is the ignorance of the actual condition of the item being replaced rather than the huge increase in maintenance cost relative to the operating costs (Moubray, 1997).

2.4.1.3 Third Generation

In the last three decades of the last century, managers viewed maintenance from a different perspective and new expectations & developments have raised. Figure (2-6) summarizes the three generations of maintenance and the expectations from maintenance application. In the third generation new maintenance techniques were developed (such as condition based maintenance or predictive maintenance), new decision support tools like failure modes and effects analyses & hazards analysis, in addition managers had a greater emphasis on reliability and maintainability.

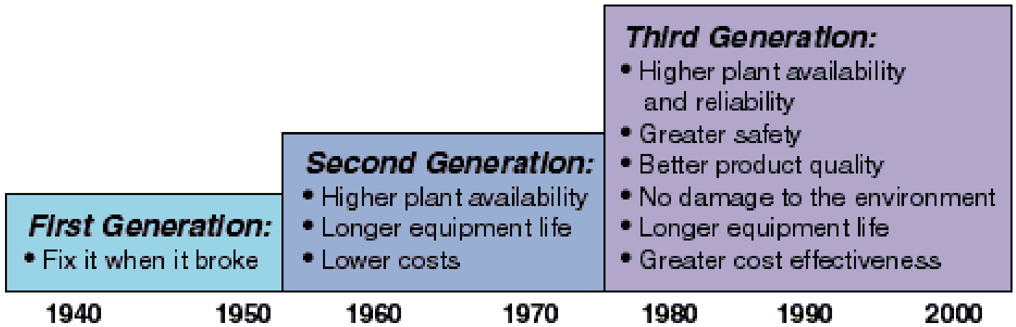

Figure 2-6: Different generations of maintenance (Moubray, 1997)

Consequently, it became crucial that asset managers need to select the most appropriate techniques to deal with each type of failure process in order to fulfill all the expectations of the owners of the assets, the users of the assets and of society as a whole.

2.4.2 Reliability Centered Maintenance

Reliability centered maintenance (RCM) is the modern strategy that can fulfill the aforementioned expectations of the asset manager. It integrates Preventive Maintenance (PM), Condition based maintenance & corrective maintenance (run to fail) to increase the probability that a component will function in the required manner over its design life-cycle with a minimum amount of maintenance and downtime (NASA RCM, 2008). According to Moubray (1997), RCM considers safety and environmental integrity, improve operating performance, longer useful life and more cost effectiveness.

In order to apply the RCM approach, several questions need to be answered:

1. What are the functions required by the asset in its present operating context?
2. What are the functional failures?
3. What are the failure modes (causes)?
4. What happens when each failure occurs?
5. What are the failure consequences?
6. What can be done to prevent or predict failure?
7. What should be done if suitable proactive task cannot be found (default actions)?

2.4.2.1 Function of the asset

Function is the intended purpose required by user, it is consisted of verb, object and desired performance standard e.g. to pump oil from point A to point B at minimum discharge of 800 liter/minute. There are two types of functions, primary function which is very easy to recognize as it expresses the user's objective. In other words it covers subjects like speed, discharge, capacity…etc. The other type is secondary function which satisfies other dimensions and parameters that include and not limited to efficiency, safety, environmental issues…etc. losing the secondary function has serious consequence thus it should be included in the maintenance plan. As shown in figure (2-7) performance standards of any asset is comprised of two elements, desired performance & built-in capability. As shown in figure (2-8) maintenance plan can restore the initial capability of the asset (maintainable asset) but cannot go beyond the initial capability (non-maintainable asset) (Moubray, 1997).

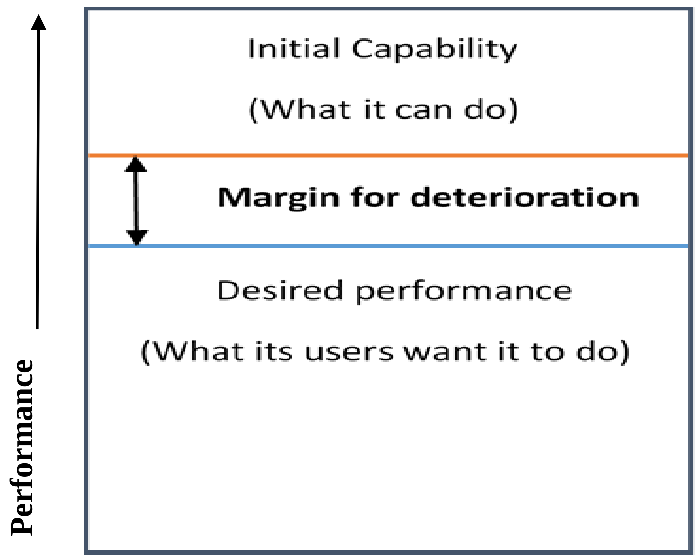

Figure 2-7: Performance standards for asset (Moubray, 1997)

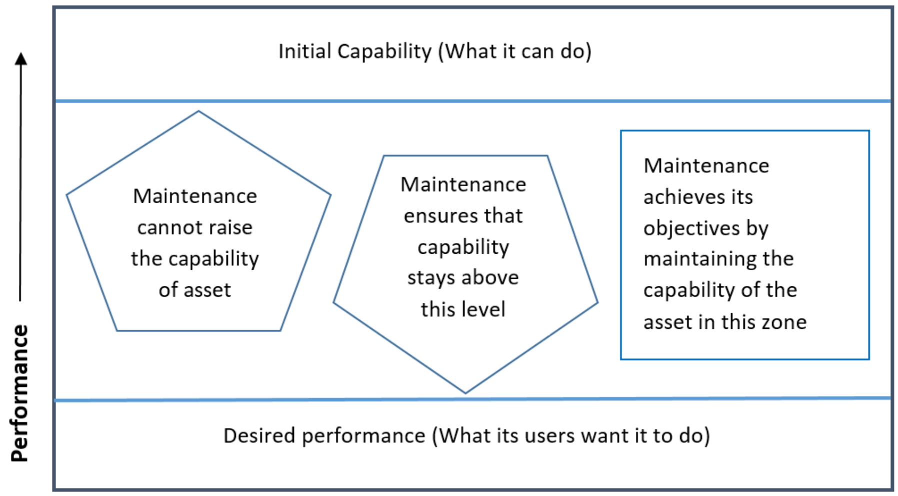

Figure 2-8: Maintainable asset (Moubray, 1997)

2.4.2.2 Functional Failure

As shown in figure (2-9), the functional failure is the inability of asset to fulfill the function to a standard of performance intended by the user. The failure could be partial as the item could perform function below the acceptable limit. The operating context is a governing element in determining the functional failure, in other words we should not generalize functional failures of components.

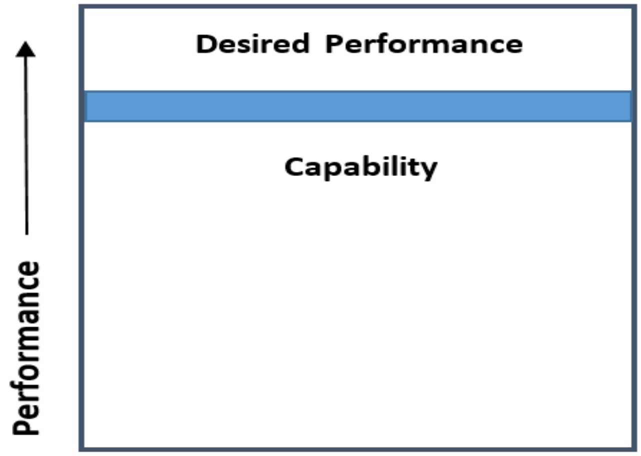

Figure 2-9: Functional failure of an asset (Moubray, 1997)

2.4.2.3 Failure Modes & Effects Analysis (FMEA)

Failure modes are events that cause functional failure for an asset. As a part of RCM, it is required to analyze the failure causes and their effects (FMEA analysis) in a proactive approach, in other words to expect and predict failures modes for every functional failures.

Moubray (1997) mentioned the categories of failure modes which are falling capability, initial incapability and increase in desired performance. Falling capability means that the component is unable to perform the function due to deterioration (erosion, wearing, fatigue, corrosion…etc.). Increase in desired performance means that the required performance became beyond the asset's envelope. This will result in assets will work until it is no longer able to deliver the function, or else the stresses increase until the asset deteriorate. While initial incapability means that the asset was not fulfilling the performance requirement of the owner.

The second step in FMEA analysis is listing the failure effects. Failure effects is answering the question "what happen when it fails". Failure effects are falling under two categories, the safety and environmental hazard (building collapse, growth of bacteria…etc.). The second category of failure effects is the secondary and production damage and this is measured by the downtime. Downtime of component is total time the asset is out of service from the moment it failed to the moment it is back. Figure (2-10) depict the components of downtime. FMEA analysis could be formed using manufacturer's manual, experts, users of equipment, historical records and equipment operators (Moubray, 1997).

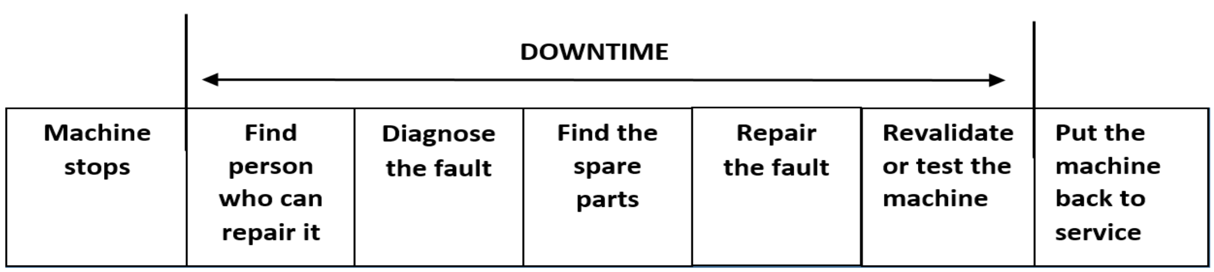

Figure 2-10: Downtime (Moubray, 1997)

2.4.2.4 Failure Consequence

Failure might affect the production, customer service, quality of product, or threat people's life or environment or it might have no effect. If failure has minor consequence, then no proactive maintenance need to be adopted. However, if the failure has major consequence then asset managers need to prevent or reduce the failure consequence, in other words the main objective of maintenance is not avoiding failure but avoiding the consequence or reducing its effect. There are three categories for failure consequence:

- Safety and environmental consequence: if it kills or hurt someone or it could breach any corporate, regional or national environmental standards.
- Operational/economic consequence: if it affects the production or operations (quality, operating cost, customer service, direct cost of repair…etc.)
- Non-operational consequence: neither safety nor production.

As per the RCM approach, if the consequence of failure has safety or/and environmental impact then the proactive maintenance approach is worth doing as long as it reduce the probability of failure to a tolerable level. Moreover, if the consequence of failure has operational impact, then a proactive maintenance is worth doing if the cost of the operational consequence is more than the cost of repairing/avoiding the failure. Furthermore, if the failure has non-operational consequence, then proactive maintenance is worth doing if it cost less than the cost of repairing of failure (Moubray, 1997).

2.4.2.5 Maintenance Approach

Proactive and default actions are the main two categories of maintenance. Proactive approach are a group of tasks that are implemented prior component failure. It could be either preventive (scheduled restoration or discard) or predictive (condition based maintenance). While default actions are tasks made for the components in a failed state. Figure (2-11) depict the maintenance strategies used in RCM.

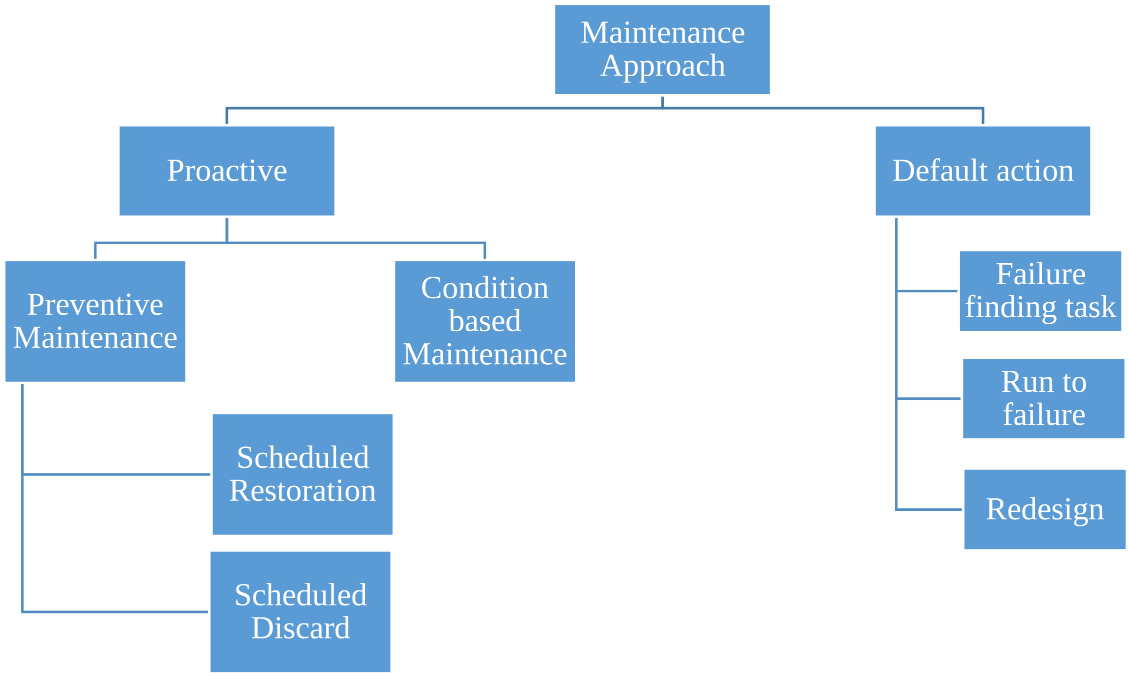

Figure 2-11: RCM Approach (Moubray, 1997)

Preventive maintenance is used if failure is age-related, at the beginning the component has high resistance to stress which declines be time at unknown rate. Age related failures are represented by three patterns of failure as shown in figure (2-12). Age-related failures are treated either by scheduled restoration which is "remanufacturing a single component or overhauling an entire assembly at or before a specified age limit regardless of its condition at that time". Scheduled restoration can take place through several means that includes cleaning and lubrication. Scheduled discard is "discarding an item at or before a specified age limit regardless of its condition at the time" (Moubray, 1997).

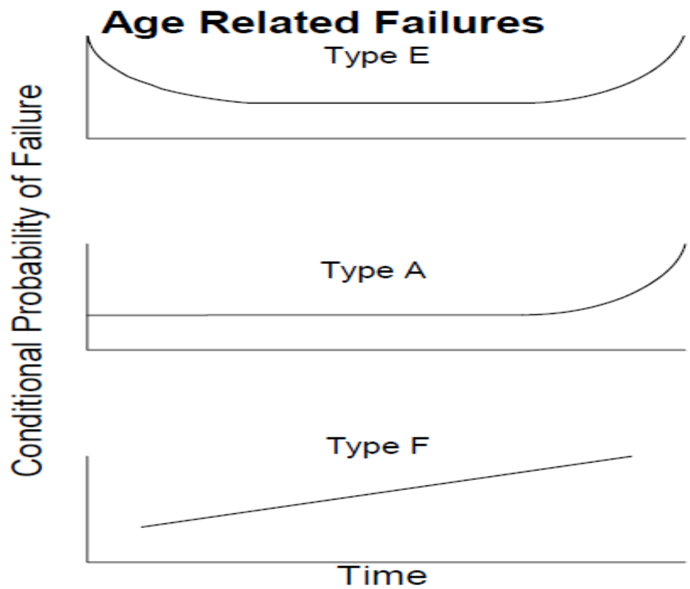

Figure 2-12: Age related failure patterns (Moubray, 1997)

If failures are not age-related (random failures), then the preventive maintenance is not feasible and thus managers resort to condition based maintenance. Figure (2-13) depict the patterns for non-age related failures. According to studies in US Navy, random failures are 77% to 92 % of the total failures (NASA RCM, 2008).

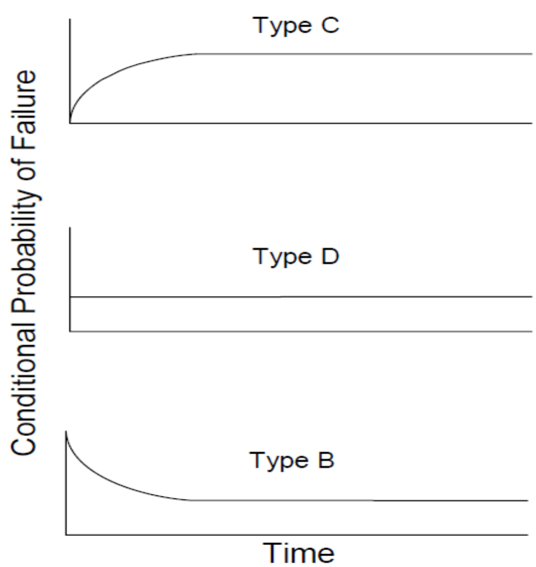

Figure 2-13: Non-age related failures pattern (Moubray, 1997)

Random failures are not age-related as mentioned, however they provide an alert that the components has started failing. If the item started to fail then it is impossible to prevent this failure. The objective of the condition based maintenance approach is to avoid production/service interruption as a result of failure. The warning point is called potential failure at which it starts deterioration and not related to age while point of failure is called functional failure, the time interval between the two points is called the p-f interval (Moubray, 1997).

Condition based maintenance aims to inspect the component at specific time interval such that it should be less than the p-f interval. In order to do this managers need to identify the condition monitoring techniques for detecting the potential failure effects and the p-f interval. The potential failure effects could be change in temperature, change in vibration, physical effects, chemical effects and particle effects. Condition monitoring devices could be used to detect those changes, however they might be quite expensive, in addition the device is capable to detect single potential failure effect e.g.(vibration analyzer cannot detect change in temperature). Hence, one the best resorts is the visual inspection as it is possible to detect several and many changes in the component. As for the p-f interval, it can be estimated based on judgment and experience of the right people like people who operate and maintain (Moubray, 1997). Figure (2-14) depicts the idea of the p-f interval with the level of performance of the asset.

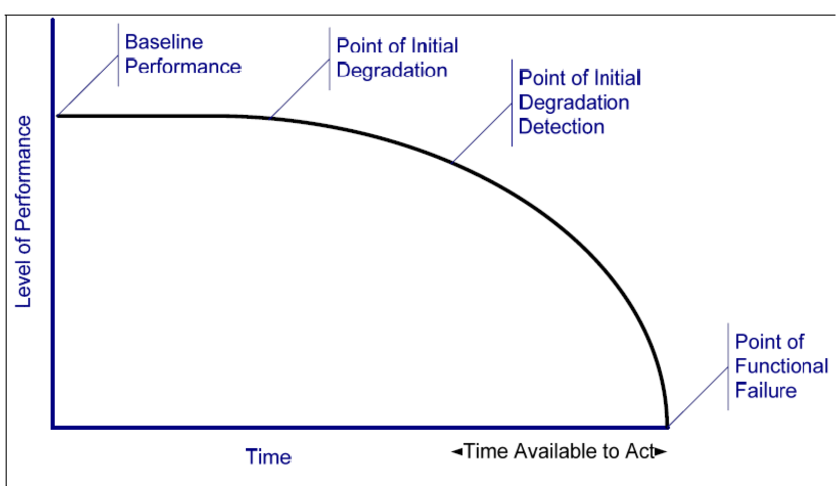

Figure 2-14: P-F Curve (Moubray, 1997)

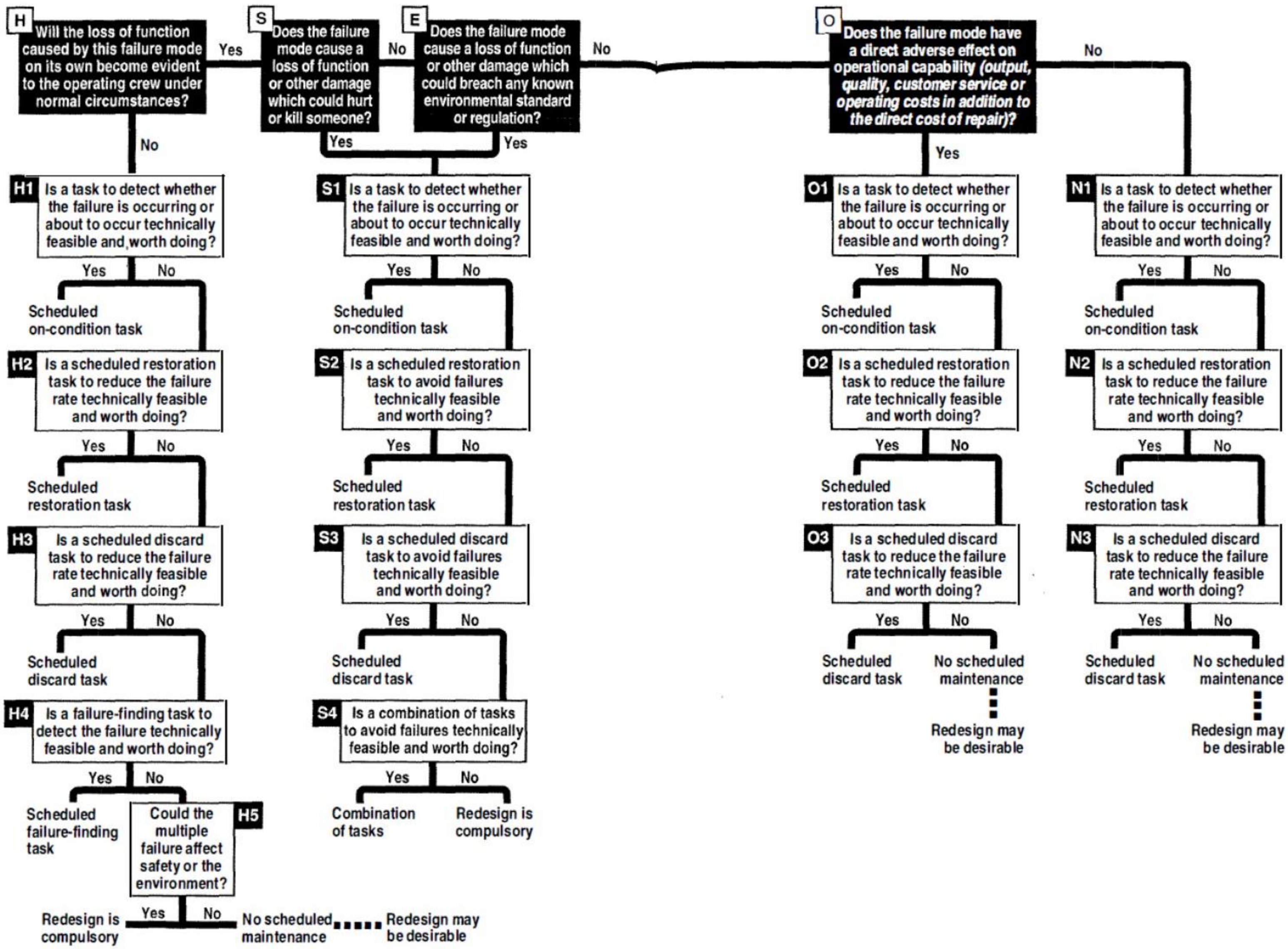

Figure 2-15: RCM Decision Tree (Moubray, 1997)

2.4.3 Applications of Maintenance techniques

Heo et al (2011) developed a genetic algorithm optimization model for determining maintenance strategy for electrical power station from a reliability centered perspective. The model included three deterioration states that is why a semi Markov module was used to model and predict the future condition of the asset. In addition, the decision variables were three maintenance strategies (no maintenance, weak and strong maintenance). The objective function was to optimize the total maintenance cost. The figure (2-16) summarizes the model's framework used.

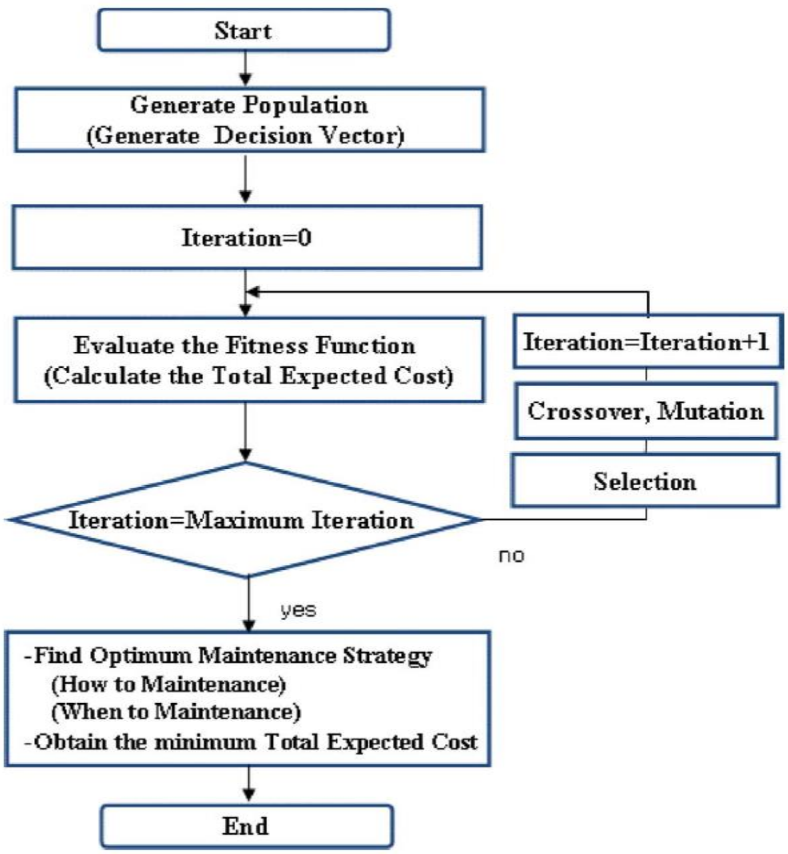

Figure 2-16: Model's framework, (Heo, et al , 2011)

Wu et al, (2012) developed a model for optimizing the condition based maintenance using artificial neural networks (ANNs) for health equipment. The ANNs was built using failure histories, the input was the age and the condition monitoring measurement at different inspections, while the output was the estimated life percentage. The error between ANNs output and actual life percentage was minimized to adjust the weight of the network. The Second step was to calculate expected maintenance cost and the optimal probability of failure. The last step was determining the maintenance strategy.

Yssaad et al (2014) developed a reliability centered maintenance framework for optimizing power distribution system. Failure mode and effect criticality analysis (FMECA) was used to evaluate and rate failure modes and effects. FMECA involves using of three parameters which are severity, occurrence and detectability, where each has a point scale. The product of the three parameters is called risk priority number (RPN), the greater the RPN the more critical the failure mode. Historical actuarial failure data was used to develop reliability analysis by using Weibull distribution to optimize the reliability and availability of components. The paramerters that need to be optimized are total mainteance cost, availabilty, reliability and mean time between failure

- Availabilty (A)= $\frac{MTBF}{MTBF+MTTR}$

  Where MTTR is mean time to repair, MTBF is mean time between failures

- Maintenace Cost = [Cm + Cf + Cs + Cu + Cp + Cd]+ICM

  where Cm is the cost of material, Cf is cost of facilities, Cs is cost of spare parts, Cu is unavailability cost, Cp is cost of personnel, Cd is cost of technical data and ICM is the indirect cost

- Reliability = $e^{-\lambda t}$

  where λ is failure rate

- Mean time between failure = $1/\lambda$

2.5 Optimization Techniques

There are various optimization methods can be used in approaching optimization problems. Traditional optimization techniques includes integer programming where decision variables can be integer only (Gao, 2004). Linear programming is another mathematical technique which provide the user with the best outcome where all functions and relationships are represented in a linear form (Hillier and Lieberman, 2001). In spite of the simplicity of these optimization techniques, they cannot be used with problems of large number of variables and non-linear objectives (Lovbjerg, 2002). Consequently, previous researchers suggested the use of evolutionary optimization techniques to overcome such problems (El Behairy, 2007). Genetic algorithms (GAs) are one of the famous evolutionary algorithms that have the ability to solve complex problems of many variables (Osman et al, 2003). They are search algorithms which are based on the mechanics of natural selection and genetics to search through decision space for optimal solutions (Goldberg, 1989). Genetic algorithms were used extensively by many researcher including Osman et al, (2003), Marzouk and Moselhi (2004), El Behairy (2007), Georgy and Basily (2008), in optimizing site layout planning, earth moving operations, bridges asset management and material delivery schedules respectively.

2.5.1 Optimization techniques in literature

Zhang (2006) developed an integer programming optimization model based on Markov chain for building facilities. The optimization module was used in order to optimize the management actions and budget allocations. The output of the model was annual management actions to take, annual budget allocation, the expected condition index (CI) values at the beginning of each year before and after management actions are taken, the expected annual performance levels; and sensitivity analysis and corresponding outputs to different budget scenarios for all the elements. The building network was based on UNIFORMAT II, the performance of building and its components will be represented by a condition index scale similar to the rating used by (Alberta Transportation, 2001). The condition index is a numerical indicator of the current state of infrastructure that is based on condition assessment. Management actions were applied to the building different elements that includes (1) no action (2) replacement (3) minor rehabilitation (4) major rehabilitation. Markov chains was used to predict condition of all elements in the building. The optimization engine will decide on the action plan (what to be repaired and to what extent?).

Abu-Samra et al, (2016) developed a genetic algorithm optimization model addressing the rehabilitation and maintenance policies for performance based contracts in roads. The model utilized regression analysis to model the asset deterioration and genetic algorithm optimization engine to optimize the maintenance and rehabilitation plan and minimize the life-cycle costs. The model was subject to a set of constraints (key performance indicators determined by the user) to achieve the user’s objective that includes alligator cracks, annual highway budget, surface rating and roughness index.

2.6 Deterioration modelling

Deterioration prediction is a significant stage in whole life cycle of building management process (Edirisinghe et al, 2010). The models used for prediction of deterioration trend can be classified in three categories, deterministic models, stochastic models and artificial intelligence models (Tran, 2007).

2.6.1 Deterministic deterioration models

Deterministic models describe a mathematical relationship between input and output parameters of an asset system in which a good correlation can be derived from the parameters. Deterministic deterioration models could be linear or non-linear & could be developed using regression analysis, curve-fitting method, and straight-line extrapolation. However, the deterministic approach is often not applicable to complex asset systems in which many variables are available (Morcous et al. 2002).

2.6.2 Stochastic models

Stochastic models are used in applications in engineering and other applied sciences. Srinivasan and Mehta (1978) have explained the principals of stochastic models. The use of stochastic models has contributed significantly to the field of modelling infrastructure deterioration because of the high uncertainty involved in the deterioration process and thus it overcomes the limitation of deterministic models. Markov chain are one of the widely used stochastic method in asset management (El-Behairy, 2007).

Markov chain is comprised of three elements, the first element is the decision time which is the point of time when decisions are made that depend on period span considered (1 month, 3 months, 1 year…etc.). The second element is the action sets where the element of the asset occupies condition state. The third element is the transition probability matrix which state the probability by which an element will remain in its condition state and the probability that an element move to the next condition state within certain time interval (Zhang, 2006). According to Benjamin and Cornell (1970), Markov chain is a memory-less in other words future behavior depends only on the current state, and not the past history.

$$P = \begin{pmatrix} 0.95 & 0.05 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.93 & 0.07 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.91 & 0.09 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.88 & 0.12 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.83 & 0.17 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Figure 2-17: Transition matrix example (Zhang et al, 2005)

2.6.2.1 Stochastic Models application

Several studies used Markov chains in modelling deterioration of concrete buildings. Keshavarzrad et al (2014) developed an integrated asset management plan for buildings. The study derived building component deterioration curves and useful lives and percentage change in conditions. Five scale condition rating was developed to assess the asset condition, where condition 1-2 is 100%-55% of the remaining useful life of building (43 years), condition 2-3 = 55%-37% of remaining useful life, condition 3-4 = 37%-25% of remaining useful life condition 4-5 = %11-%25 of remaining useful life. Figure (2-18) depicts the condition rating scale.

Condition 1	Very good
Condition 2	Good
Condition 3	Moderate
Condition 4	Poor
Condotion5	Very poor

Figure 2-18: Condition rating used by (Keshavarzrad et al, 2014)

A transition probability matrix was developed and calibrated using the data of assets as shown in figure (2-19). Deterioration curves were then developed for 320 building using the transition matrix by multiplying the initial condition (1 0 0 0 0) by the transition matrix. Figure (2-20) shows an example for deterioration curve developed by the model.

0.9483	0.0517	0	0	0
0	0.871	0.129	0	0
0	0	0.806	0.194	0
0	0	0	0.834	0.166
0	0	0	0	1

Figure 2-19: Transition Matrix (Keshavarzrad et al, 2014)

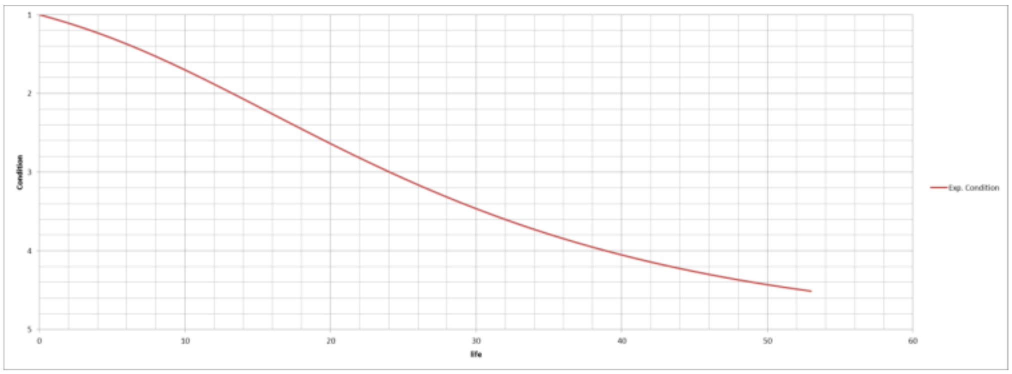

Figure 2-20: Deterioration Curve (Keshavarzrad et al, 2014)

Kirkham and Boussabaine (2005) proposed a stochastic approach to the forecasting of the residual service life of hospital buildings. The results from their proposed model, based upon a combination of weighted average techniques and a Markov property; the minimum of exponentials, were compared with those obtained by means of existing deterministic methods and revealed an average percentage difference of 56.26%.

Morcous et al, (2003) discussed the application of Markov deterioration models to identify environmental categories for bridge decks in Canada. The study considered several transition matrix as shown in figure (2-21) in order to express different climatic conditions. It was concluded that the categories used to describe the various possible environments for a bridge element are neither accurately defined nor explicitly linked to the external factors affecting the element deterioration.

	1	2	3	4	5
1	0.98	0.02	0	0	0
2	0	0.97	0.03	0	0
3	0	0	0.97	0.03	0
4	0	0	0	0.96	0.04
5	0	0	0	0	1

Benign environment

	1	2	3	4	5
1	0.95	0.05	0	0	0
2	0	0.94	0.06	0	0
3	0	0	0.94	0.06	0
4	0	0	0	0.92	0.08
5	0	0	0	0	1

Low environment

	1	2	3	4	5
1	0.93	0.07	0	0	0
2	0	0.92	0.08	0	0
3	0	0	0.91	0.09	0
4	0	0	0	0.90	0.10
5	0	0	0	0	1

Moderate environment

	1	2	3	4	5
1	0.87	0.13	0	0	0
2	0	0.86	0.14	0	0
3	0	0	0.85	0.15	0
4	0	0	0	0.83	0.17
5	0	0	0	0	1

Severe environment

Figure 2-21: Transition Matrices for Climatic conditions Morcous et al, (2003)

2.6.3 Artificial Intelligence Deterioration Models

Artificial intelligence (AI) includes case based reasoning, artificial neural networks (ANNs) and fuzzy logic systems. According to El-Behairy (2007) ANN is a convenient tool for developing deterioration models.

2.6.3.1 Artificial Neural Networks

Normally ANN is comprised of input layer, output layer and one or more hidden layer. Each layer consist of a number of neurons which is connected to each other by weights. Learning process takes place by adjusting the weights in an attempt to reduce the difference between the actual and desired output (Negnevisky, 2002). Figure (2-22) depicts a typical ANN diagram.

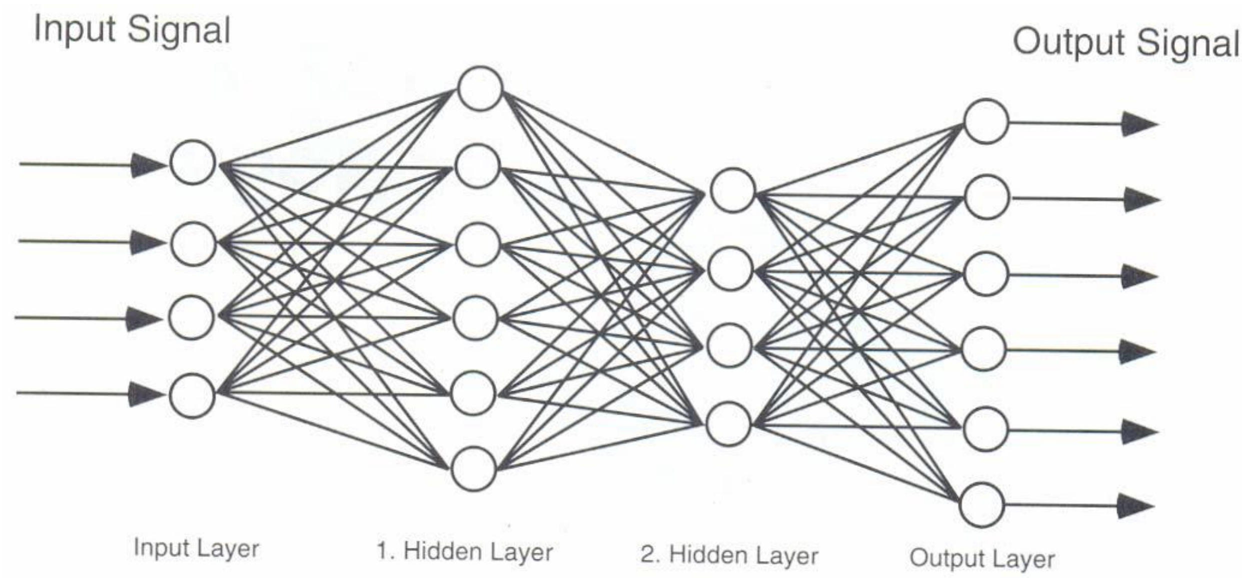

Figure 2-22: Typical ANNs diagram (Von Altrock, 1995)

2.6.3.2 ANNs application

Sobanjo (1997) developed a model for predicting deterioration using ANN. A multi-layer ANN was employed to relate the age of the bridge superstructure to its condition rating. The inspection records for 50 bridge superstructures were used for training and testing purposes where 75% (training), while the remaining data were used for testing. The network used in this study is depicted in figure (2-23).

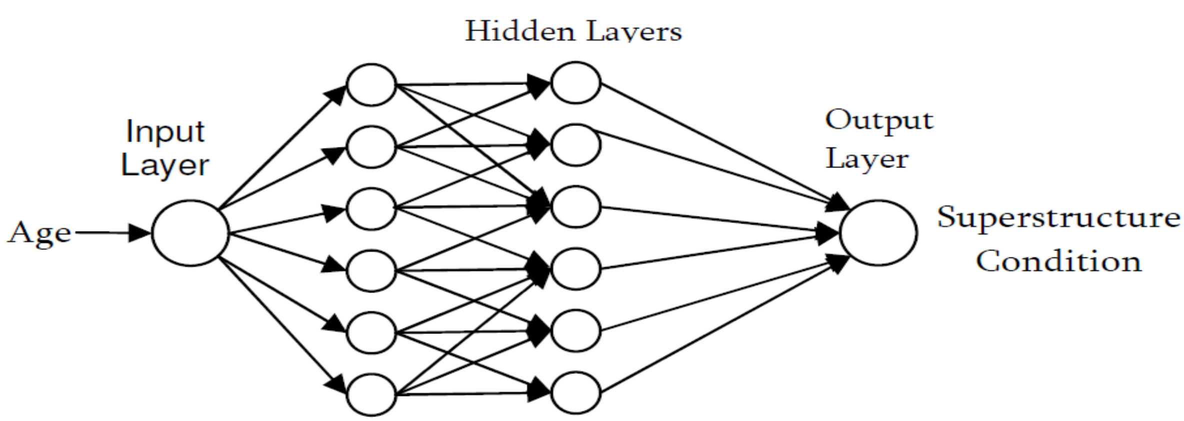

Figure 2-23: Multi-layer Neural Networks (Sobanjo, 1997)

2.6.3.3 Fuzzy Logic Systems

Fuzzy sets were developed by Zadeh (1965) to account for the uncertainties in defining issues unlike conventional sets. In fuzzy sets, each element has a degree of membership that ranges between zero and one, this is opposite to the conventional sets where the element should have a full membership to be considered as a part of a set. In fuzzy logic systems, memberships can take various shapes, however trapezoidal and triangular are widely used ones (Dubois and Prade 1988; Chen and Hwang 1992). Figure (2-24) depicts a trapezoidal membership function.

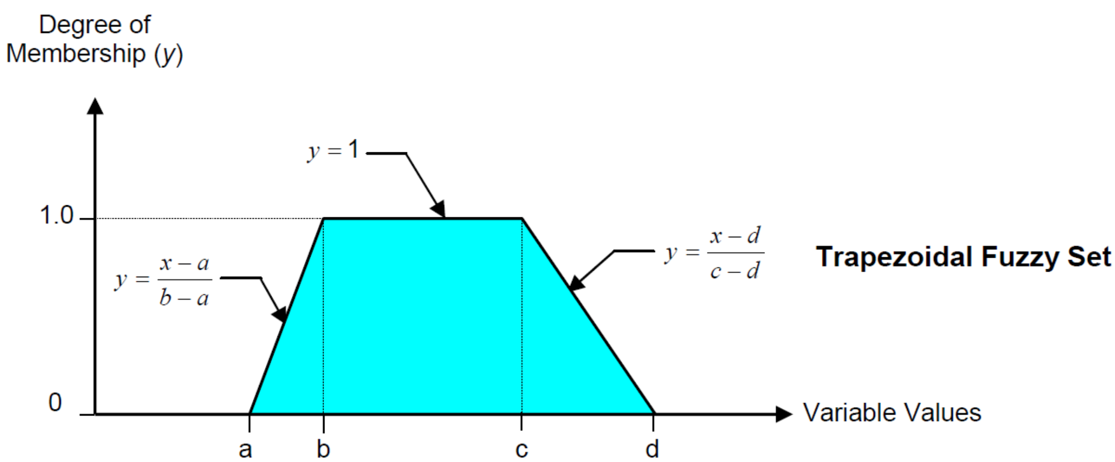

Figure 2-24: Trapezoidal shape (Dubois and Prade 1988; Chen and Hwang 1992).

Figure (2-25) depicts fuzzy logic architecture. In fuzzy expert systems, crisp set of input data are gathered and converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. This step is known as fuzzification. Afterwards, an inference is made based on a set of rules. Lastly, the resulting fuzzy output is mapped to a crisp output using the membership functions, in the defuzzfication step (Negnevisky, 2002).

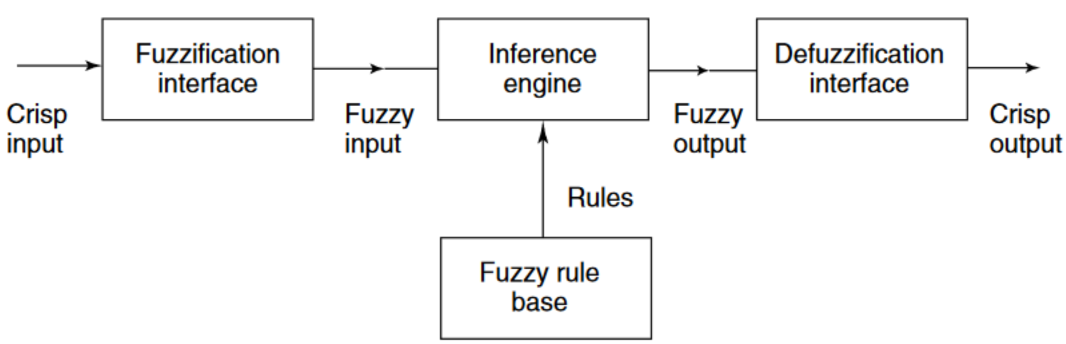

Figure 2-25: Fuzzy logic architecture (Abraham, 2005)

2.6.3.4 Fuzzy logic systems application

Liang et al (2001), developed a fuzzy model for evaluating the damage state of existing reinforced concrete bridges. The input is consisted of three factors (crack width, steel corrosion and outward appearance) while the output was damage grade of the item. The study concluded that the model may also be used as a design reference for service life in future bridge building.

2.7 Hospital Facility Management in Previous research

Lavy and Shohet (2007) developed an object oriented decision support system model for health care facility management that is based on heuristic databases and case based reasoning. The model was consisted of 3 modules which are the input module, reasoning evaluator and predictor phase and output interface. The input interface is subdivided into two phases, phase 1 includes the general data about the facility such as type of facility, environment, availability of labor, and designation of areas within the facility, while phase 2 includes the specific data for each building such as actual and required service life of buildings, actual and required performance for systems and components, actual levels of risk, and maintenance policies. Figure (2-26) shows the architecture of the input interface used.

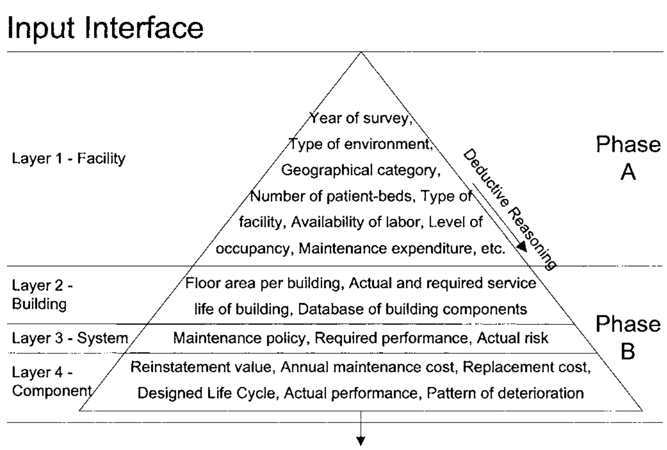

Figure 2-26: Input interface (Lavy and Shohet (2007))

Phase 1 included one layer (general data), while phase 2 included 3 layers for building, system and component. The second module (reasoning evaluator and predictor phase) is comprised of three layers which are facility parameters, actual indicators and prediction indicators. Lavy and Shohet (2007) have focused in his research two main items which are the structure performance predictor and facility coefficient. Lavy and Shohet (2007) assumed that the pattern of deterioration for the concrete structure components is subdivided into the following two intervals, the first interval is from (0-15 years) where the structure is deteriorating linearly from 100 to 95 points. The second interval is between 15 to 72 years where the performance is deteriorating exponentially from 95 to 60 points as shown in the figure (2-27), then the performance indicator is calculated and hence the future performance can be forecasted. The facility coefficient was developed in order to estimate the annual maintenance resources for the healthcare facility. The coefficient expressed the resources required for adopting a pure preventive maintenance which is compared with resources required for a hospital or health facility under standard service condition. The research concluded that healthcare management is quite complicated and difficult since it is required to satisfy the user's requirement like the patients and medical staff by selecting combinations of maintenance policies, in addition, it is required to work within strict budgets.

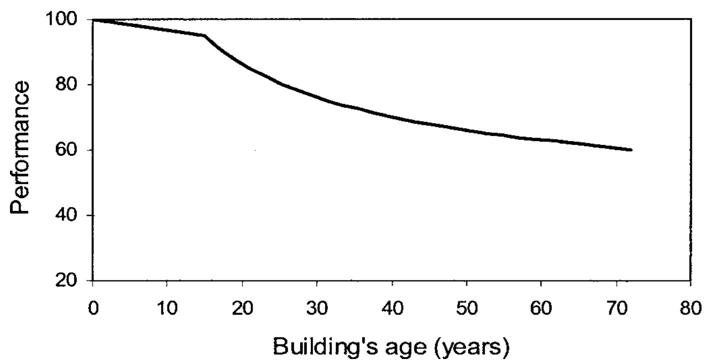

Figure 2-27: Concrete structure deterioration (Lavy and Shohet, 2007)

Liyanage et al (2008) categorized facility management in healthcare to hard and soft facility management where hard is related to management & maintenance of the facility while soft facility management is related to services like cleaning, security and waste management. The author developed a performance framework for cleaning services in an attempt to control & prevent the healthcare associated infections (HAI). The framework was developed on four stages, the first stage was reviewing the literature and perform interviews with experts in the area of HAI.

The second stage was performing a quantitative semi structured interviews and the third stage was employing a questionnaire survey, while the fourth stage is developing the performance management framework. The resulted framework as shown in the figure (2-28) is consisted of three sections, the first was performance indicators & goals, the second section is setting up the performance measures for monitoring the progress , the third and the last section was control and improving the overall performance and practice. It was concluded that performance meaning and its way of measurement was not really understood, moreover a significant care must be given to the soft facility management as it contributes in maintaining the quality of care delivered to the patients.

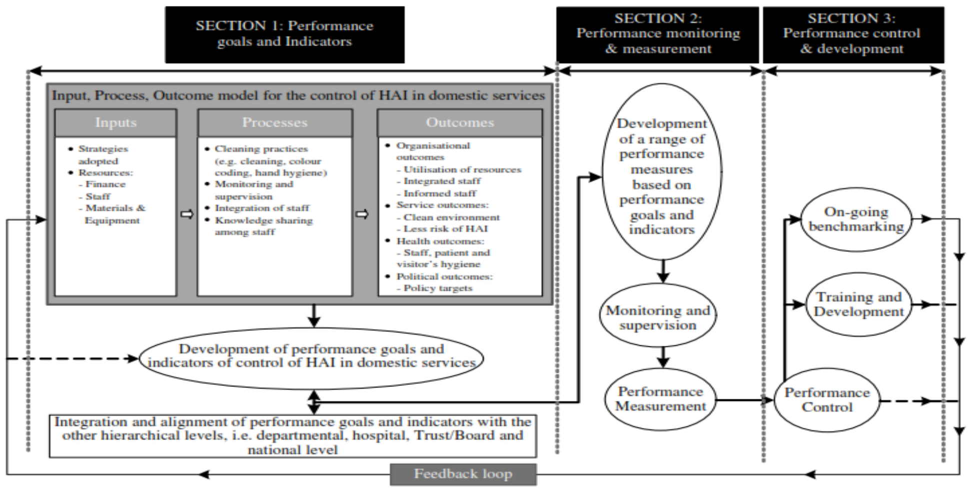

Figure 2-28: Proposed framework (Liyanage et al (2008))

Lucas et al (2013) developed a BIM model was developed to capture the information needed through the healthcare facility lifecycle from the concept and design phase to the construction & operation phase. The model will be used to support facility management response to emergency situations within a healthcare environment. The first step in this model was developing case scenarios where the Failure Mode & Effect Analysis (FMEA) and Fault Tree Analysis (FTA) to document HVAC malfunctioning case in operating room. FMEA was used to define the functional failures for components and the failure modes (causes) and failure effect, then the detectability and likelihood were determined and hence the action required to reduce the occurrence of failure. FTA was used to define the root causes for the failure which was "Water incursion over operating room" and prevention method was suggested to the potential for each root cause. The second step was information analysis where the faults from the FMEA and FTA were used to develop use case flows, the use case flow depict how to respond when emergency occur and the interactions between healthcare staff, figure (2-29) depicts the framework used in this research. The final step is product model and ontology development which is used to sort & store information, while the ontology will assist in querying & filtering data.

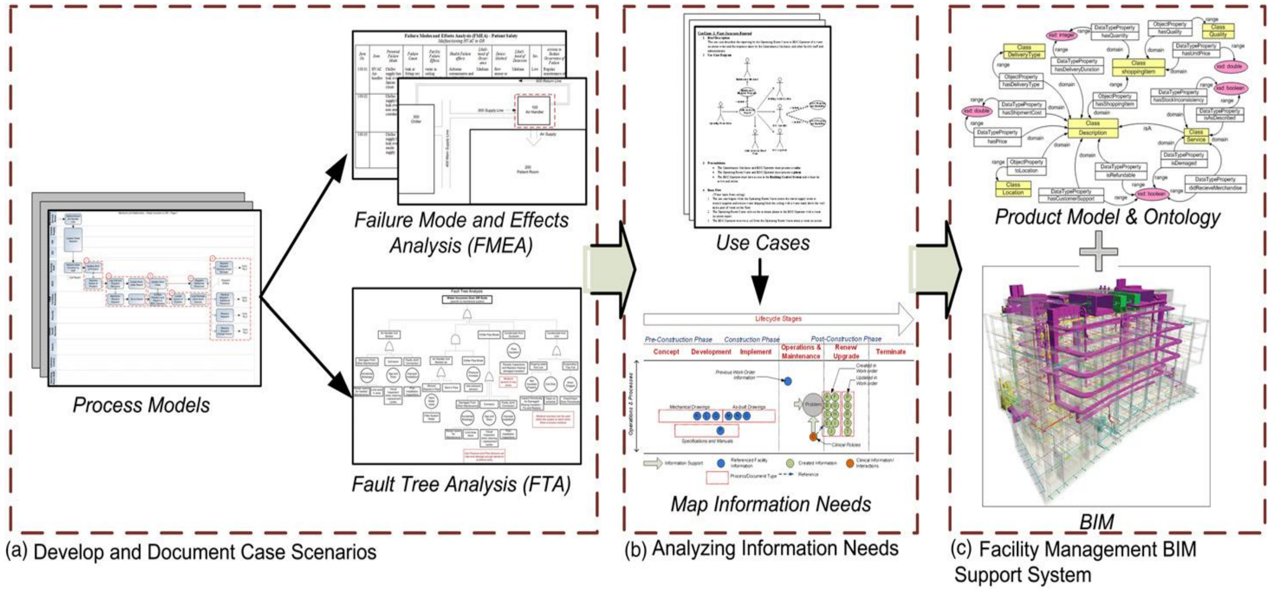

Figure 2-29: Model framework (Lucas et al, 2013)

2.8 Research Gaps

- Adopting preventive maintenance approach is not accurate for all the cases since it consider that all components are failing by aging (age-related failures), however many failure modes are not age related. Studies done by U.S Navy in 1982 indicates that 77% to 92% of failures are random (NASA RCM, 2008). This research will consider the review of different types of maintenance and the most suitable approach to be applied in this study.
- Previous research did not consider the use of RCM in developing maintenance plans for hospital systems.
- Moreover previous research considered maintenance management plans for different systems, however, they did not mention the relation between service delivery and maintenance plans. In addition, there was no consideration for integrating these systems in the same facility. Furthermore, using actuarial failure data is not an accurate method for developing maintenance plans regardless that it is quite difficult to gather these data with its operating context and the working environment, a point of view reveals that the components of significant operating or safety consequence are not left to fail as the owners prefer to prevent their failure. Consequently, the available data are representing components with minor failure consequence (Moubray, 1997).

3 RESEARCH FRAMEWORK

3.1 Introduction

This chapter presents the proposed framework for improving the service delivery in hospitals through adopting effective management plans. In this chapter, we are dealing with two frameworks, the first one is Network-level Hospitals Rehabilitation Tradeoff (NEHIR) as shown in figure (3-1) that focuses on optimization of rehabilitation of the deteriorated hospital concrete structures that deals with two objectives; (1) minimize rehabilitation cost (2) minimize unserved patients. The model is using genetic algorithms and Markov chains to achieve the aforementioned objectives. The second model is the Hospital-level Reliability Centered Maintenance based model (HOREM) that deals with optimizing maintenance plans for hospital systems that work on day to day basis and impact the service delivery. The model utilizes reliability centered maintenance approach (RCM), Monte Carlo simulation, optimization & fuzzy logic systems. The model is dealing with two main objectives; (1) minimize expected downtime and (2) minimize maintenance cost, then the model will use genetic algorithm in optimizing the allocation of maintenance budget among systems. The service delivery is being measured by number of patients served. In other words if a system of high impact on service delivery has stopped working, then the service will be suspended hence no patients will be served. If a hospital is being rehabilitated, then the service delivered will be partially or fully suspended, hence number of patients served are affected.

3.2 Network-level Hospitals Rehabilitation Tradeoff (NEHIR)

The model of is comprised of five modules:

- Database Module
- Backward Markov
- Deterioration prediction module
- Rehabilitation cost (RC) optimization
- Multi-objective optimization for rehabilitation schedule

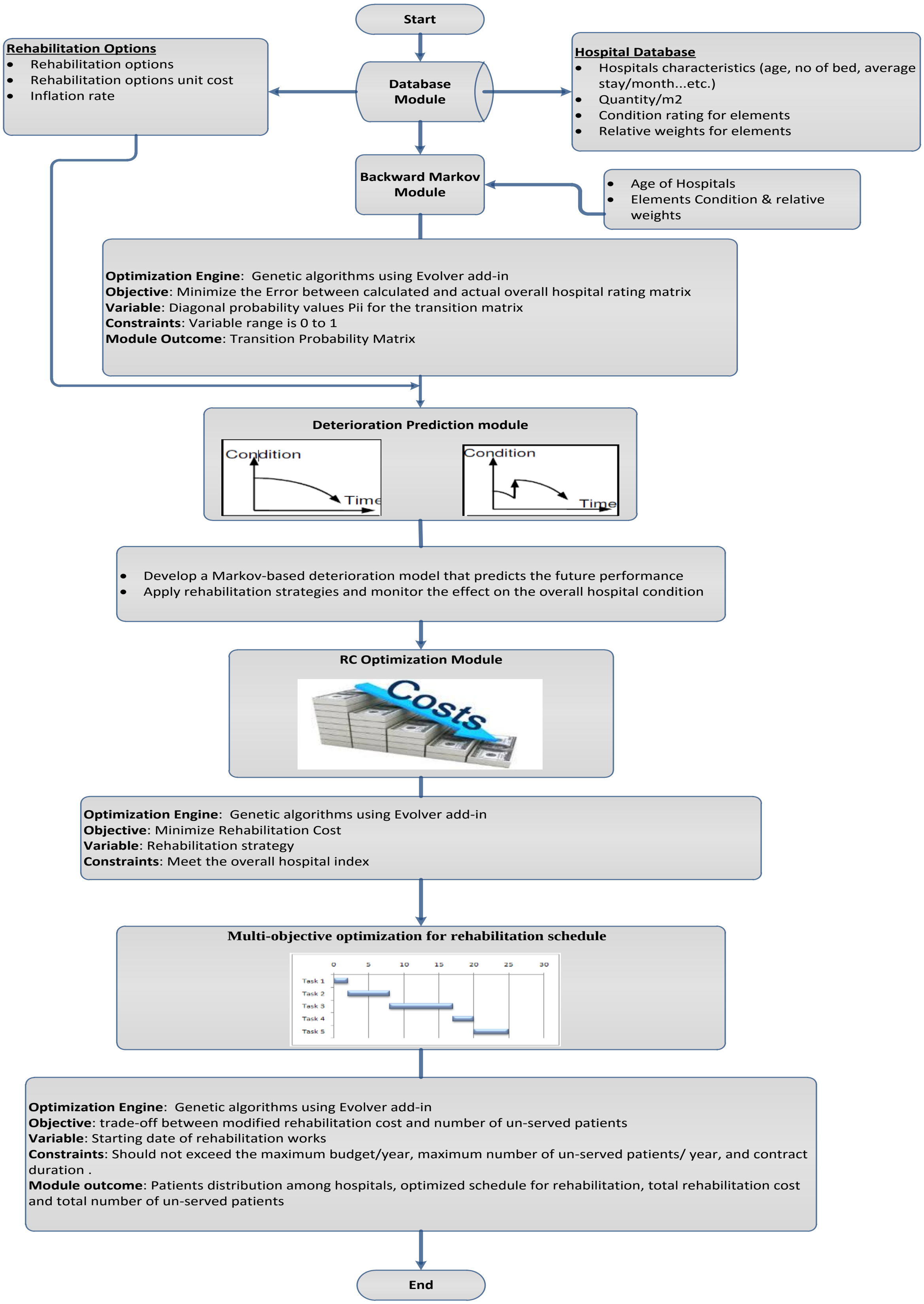

Figure 3-1: NEHIR Framework

3.2.1 Database Module

The module stores the data that includes hospitals characteristics data such as (age, no of beds, average occupation, average stay/month, percentage of service suspension and concrete quantity). In addition it includes all condition-related information for different elements (slabs, columns and beams) along with their relative weights. Furthermore, the module contains the rehabilitation options and their unit cost and inflation rate. Those rehabilitation options were provided by the experts along with their effects on the condition state. Each one of these options is applied at specific condition state. The strategies considered are (S1) reinforcement cleaning, (S2) partial concrete replacement and reinforcement, and (S3) full concrete replacement and reinforcement. Reinforcement cleaning involves removing of corrosion from reinforcement bars in order to improve bonding with concrete. Reinforcement cleaning is sufficient if there is no significant loss in the bar cross section (Nemati, 2006). As per the expert views, reinforcement cleaning is applicable if the loss in bar's diameter is not exceeding 20%.

In addition, partial and/or full concrete replacement are also commonly used methods for concrete repair for improving the concrete strength (Soudki, 2010). As per the expert views partial concrete replacement is applicable if the corrosion in steel reinforcement is less than 50% of reinforcement bar diameter. However, full concrete replacement is applicable if the corrosion is exceeding 50%. Table (3-1) shows the rehabilitation options and their application and how it could improve the condition rating according to expert views.

Table 3-1: Rehabilitation Options

Rehabilitation Code	**Rehabilitation Option**	**Condition state application**	**Resulted Condition state**	**Cost/m^2**
S1	Reinforcement cleaning	C3	C1	EGP 450
S2	Partial concrete replacement and reinforcement	C4	C1	EGP 900
S3	Full concrete replacement and reinforcement	C5	C1	EGP 1700

3.2.2 Backward Markov module

The module is responsible for deriving a proper transition matrix to be used for deterioration prediction and rehabilitation strategies. The module considers the individual rating for slabs, beams, columns and weights, in order to come up with the overall hospitals rating matrix (OHRM) and overall hospital index (OHI).

3.2.2.1 Overall Hospital Index (OHI) Calculation

A five scale condition state was considered to demonstrate the condition rating for the different building elements and the overall hospital rating where the user estimate the percentage at each condition state according to experts inspection for the building. Equation (3.1) shows the calculation for the overall hospital rating that will be applied for all the elements (slab, columns and beams) and for the five condition states. Equation (3.2) shows the overall hospital index calculation. Table (3-2) depicts the condition rating scale used in NEHIR model.

Table 3-2: Condition Rating Scale

Condition state rate	**1**	**2**	**3**	**4**	**5**
Description	V. Good	Good	Average	Poor	V. Poor

$$OHR_i = \frac{\sum_{f=1}^{e} P_{if} \ x \ W_f}{W_T} \qquad (3.1)$$

Where;

OHR_i is overall hospital rating percentage at a condition state i

e is the total number of elements

P_{if} is the percentage at a condition state i for an element f

W_f is the weight of element f

W_T is the total relative weight of elements.

Table 3-3: Overall Hospital Rating Matrix (OHRM)

Condition state rate	**1**	**2**	**3**	**4**	**5**
Description	V. Good	Good	Average	Poor	V. Poor
Percentage	OHR_1 %	OHR_2 %	OHR_3 %	OHR_4 %	OHR_5 %

$$OHI = \sum_{i=1}^{c} OHR_i \times CS_i \qquad (3.2)$$

Where;

i is condition state counter

c is total number of condition states

OHR_i is overall hospital rating percentage at a specific condition state i

CS_i is the condition state rate

OHI is the overall hospital index

3.2.2.2 Transition Probability matrix

A transition matrix (5 x 5) was used for condition prediction. The transition matrix shows the probabilities of moving from one condition state to another at one year. The transition matrix assumes that within a time interval (one year) the hospital might remain in its state or deteriorate to the next condition state. In other words at the same row there are two probability values and the summation must be one. Figure (3-2) depicts an example of transition matrix.

$$P = \begin{bmatrix} \text{Condition} & 1 & 2 & 3 & 4 & 5 \\ 1 & P11 & P12 & 0 & 0 & 0 \\ 2 & 0 & P22 & P23 & 0 & 0 \\ 3 & 0 & 0 & P33 & P34 & 0 \\ 4 & 0 & 0 & 0 & P44 & P45 \\ 5 & 0 & 0 & 0 & 0 & P55 \end{bmatrix}$$

Figure 3-2: Transition matrix

In order to derive the transition matrix, the initial overall hospital rating matrix ($OHRM_i$) is assumed which is shown below:

Table 3-4: Initial overall hospital rating matrix

Condition state	1	2	3	4	5
Percentage	1	0	0	0	0

The actual overall hospital rating matrix ($OHRM_a$) is based on the element's condition rating as determined through the condition assessment:

Table 3-5: Actual overall hospital rating matrix

Condition state	1	2	3	4	5
Percentage	OHR_1 %	OHR_2 %	OHR_3%	OHR_4 %	OHR_5%

The calculated overall hospital rating matrix ($OHRM_c$) is calculated using the following equation:

$$OHRM_c = P^{n} \times OHRM_i \tag{3.3}$$

Where;

$OHRM_c$ is the calculated overall hospital rating matrix,

$OHRM_i$ is the initial overall hospital rating matrix

P is the assumed transition matrix

n is the age in years.

The last step is minimizing the difference between the $OHRM_c$ & $OHRM_a$ through using optimization engine.

$$\text{Error} = \sum_{x=1}^{c} \left| (OHRM_a)_x - (OHRM_c)_x \right| \tag{3.4}$$

Where;

x is the condition state counter

c is the total number of condition states.

3.2.2.3 Optimization Engine

The optimization engine was used to minimize error in equation (3.4) in order to achieve the transition matrix required. According to Behairy (2007), simple linear programming did not provide the most optimum solution, hence genetic algorithm was proposed to solve this problem due to its non-linearity. Figure (3-3) depicts decision variables in optimization module.

Objective function: minimize the Error (equation 3.4)

Variables: probabilities at the condition states (highlighted in transition matrix)

Constraints: Total values in one is 100%

Results: the approximate transition matrix that can be used for condition prediction.

P=

Condition	1	2	3	4	5
1	P11	P12	0	0	0
2	0	P22	P23	0	0
3	0	0	P33	P34	0
4	0	0	0	P44	P45
5	0	0	0	0	P55

Figure 3-3: Decision variables for transition matrix

3.2.3 Deterioration Prediction Module

Deterioration model was developed based on Markov chains in order to estimate and predict the future decline in overall hospital condition. In addition, the module will monitor the effect of applying the rehabilitation strategy on improving the overall hospital condition. Deterioration prediction module use the transition probability matrix and the overall hospital rating matrices of hospitals calculated from the Backward Markov module.

3.2.4 Rehabilitation Cost (RC) Optimization module

This module was employed to provide the optimum rehabilitation strategy. This module and the Rehabilitation schedule optimization module work together in order to optimize the total rehabilitation cost and un-served patients. In this model the maximum overall rehabilitation duration for all hospitals is six years (seventy two months). i.e. (within 6 years all hospitals should be rehabilitated). This means that there are six chances for implementing a rehabilitation for the hospital (either rehabilitate at year 1 or year 2 or year 3…..etc.). In other words, this module will provide six different rehabilitation strategies with their associated rehabilitation cost.

The transition matrix is modified based on the rehabilitation strategy shown in figure (3-5) that is adopted in order to elevate the asset performance and capability. In NEHIR model, the rehabilitation strategy is the percentage to be rehabilitated at every condition state, this strategy will affect the transition matrix as shown in figure (3-6). The decision variable is set to be the rehabilitation strategy, the constraint is the overall hospital index (OHI) which determined by the decision maker and objective function is the RC. Genetic algorithms were used in optimizing the rehabilitation cost as they are beneficial for complex and multivariable problems, in addition they are suitable for determining the best rehabilitation strategies (El Behairy, 2007).

<u>Transition probability matrix for deterioration:</u>

$$P_{old}=\begin{bmatrix} \text{Condition} & 1 & 2 & 3 & 4 & 5 \\ 1 & P11 & P12 & 0 & 0 & 0 \\ 2 & 0 & P22 & P23 & 0 & 0 \\ 3 & 0 & 0 & P33 & P34 & 0 \\ 4 & 0 & 0 & 0 & P44 & P45 \\ 5 & 0 & 0 & 0 & 0 & P55 \end{bmatrix}$$

Figure 3-4: Old Transition Matrix

- **<u>The rehabilitation strategy:</u>**

$$R=\begin{bmatrix} \text{Condition} & \% \\ 1 & 0\% \\ 2 & 0\% \\ 3 & X_1\% \\ 4 & X_2\% \\ 5 & X_3\% \end{bmatrix}$$

Figure 3-5: Rehabilitation Strategy

- **<u>Transition probability matrix for deterioration and rehabilitation:</u>**

$$P_{mod}=\begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ P11 & P12 & 0 & 0 & 0 \\ 0 & P22 & P23 & 0 & 0 \\ X_1\% & 0 & (1-X_1\%)*P33 & (1-X_1\%)*P34 & 0 \\ X_2\% & 0 & 0 & (1-X_2\%)*P44 & (1-X_2\%)*P45 \\ X_3\% & 0 & 0 & 0 & (1-X_3\%)*P55 \end{bmatrix}$$

Figure 3-6: Modified Transition Matrix

- **<u>The new overall hospital rating matrix:</u>**

$$OHRM_{new}=(P_{mod})^n \text{ x } OHRM_{old} \qquad (3.5)$$

Where;

$OHRM_{new}$ is the new overall hospital rating matrix

P_{mod} is the modified transition matrix after adopting rehabilitation strategy n is the number of years

$OHRM_{old}$ is the old overall hospital rating.

- **<u>Rehabilitation Cost Calculation (RC)</u>**:

$$Q_i = (OHR_{old})_i \times Q_t \qquad (3.6)$$

Where;

Q_i is the quantity to be renovated at condition state i

$(OHR_{old})_i$ is the new overall hospital rating matrix.

Q_t is the total quantity of hospital in m^2

$$RC_{x,y} = \sum_{i=1}^{c} Q_i \times R \times Rs \times (1+r)^n \qquad (3.7)$$

Where;

$RC_{x,y}$ is the rehabilitation cost for hospital x at year y

i is the condition state counter

c is total number of condition states

r is inflation rate

n is number of years

Rs is unit cost for the rehabilitation strategy

R is percentage to be rehabilitated at condition state i

As aforementioned, NEHIR model will provide six rehabilitation strategies and their associated RC for each hospital. The model will assume that rehabilitation will be performed at the year of inspection, consequently the level of deterioration is not changed and the cost of rehabilitation is remaining the same. However if the rehabilitation was postponed to the next year, the RC will rise due to inflation issues in addition the further increase in deterioration. This issue will be handled by the scheduling optimization module as it considers a crucial dimension which is the service suspension that leads to a drop in the number of served patients. Table (3-6) depicts rehabilitation cost optimization formulation.

Table 3-6: Summary for optimization formulation used in RC module

Rehabilitation Cost Optimization Module	
Objective	Minimize $RC_{x,y} = \sum_{i=1}^{c} Q_i$ x Rs x R x $(1 + r)^n$
Variables	Rehabilitation strategy "R"
Constraints	Overall Hospital Index (OHI)
Results	Six rehabilitation strategies and their associated rehabilitation costs for all hospitals

3.2.5 Multi-objective optimization for rehabilitation schedule Module

The results obtained from RC optimization module are six rehabilitation strategies and their associated cost for hospitals. Data included in the database (contract duration of rehabilitation, no of beds, average stay/month, average occupation and service suspension during rehabilitation) are being used in order to provide a tradeoff between the number un-served patients and the total rehabilitation costs.

3.2.5.1 Modified Rehabilitation Cost

A schedule of 6 years (72 months) was performed which will be used by the optimization engine to determine the starting date for hospital rehabilitation. Each date will be given an integer number e.g. Jan-2014 is represented by 1, hence the finishing date will be calculated based on equation (3.8)

$$\text{Finishing Date} = \text{Starting Date} + \text{Duration} \qquad (3.8)$$

The decision variable in this model is the starting date represented by the integer numbering which is selected by the optimization engine. Once it is selected a binary numbers are generated covering the time interval between the starting dates and finishing dates. In others words if the hospital is rehabilitated then its binary number is 1 else its 0. Therefore the model was subject to a constraint that the summation of binary number ($O_{x,j}$) should be equal to contract duration determined by the decision maker (D_x).

$$D_x = \sum_{j=1}^{72} O_{xj} \tag{3.9}$$

Where;

D_x is the duration of hospital x

$O_{x,j}$ is binary variable refers to rehabilitation of hospital x at time j

- **<u>The rehabilitation cost per month is calculated based on this equation</u>**:

$$RC_{xym} = \frac{RC_{x,y}}{D_x} \tag{3.10}$$

Where;

RC_{xym} is the rehabilitation cost for a hospital (x), at year (y) and month (m) at certain year

D_x is the contract duration in months for rehabilitation determined by the decision maker for hospital (x).

- **<u>The modified rehabilitation cost for a hospital;</u>**

$$MRC_x = \sum_{j=1}^{72} RC_{xym} \tag{3.11}$$

Where;

MRC_x is the modified rehabilitation cost for hospital x

- **<u>The total modified rehabilitation costs for all hospitals (TMRC);</u>**

$$TMRC = \sum_{x=1}^{h} \sum_{j=1}^{72} RC_{xym} \tag{3.12}$$

Where;

TMRC is the total modified rehabilitation cost for all hospitals

x is hospital counter

h is total number of hospital

j is a time counter

- **The modified rehabilitation strategy:**

$$MR_x = \sum_{y=1}^{6} (R_{xy} \text{ x } \frac{D_{xy}}{D_x}) \quad (3.13)$$

Where;

MR_x is the modified rehabilitation strategy for hospital x

R_{xy} is rehabilitation strategy for hospital x at year y

D_{xy} is the duration covered in months at year y for hospital x

3.2.5.2 Patients Distribution

The second objective that was considered is the total number of un-served patients. In this model the optimization engine works on providing the modified rehabilitation cost (MRC) and the associated un-served patients through scheduling the rehabilitation works for the hospitals. The model calculates the overlapping ratio (OL) in scheduling the rehabilitation works for hospitals. The higher the OL the more the un-served patients. This module uses the following parameters for each hospital, (1) the number of beds, (2) average stay, (3) average occupation, and (4) service suspension percentage during rehabilitation for each hospital. The following equations shows the steps of calculating the number of un-served patients.

- **Availability of beds per month**

$$AB_x = 30 \,/\, AS_x \quad (3.14)$$

Where;

AB_x is the availability of beds per month for hospital x

AS_x is the patient's average stay in days for hospital x

- **Average patients per month for hospital**

$$APH_x = OR_x\% \text{ x } B_x \text{ x } AB_x \quad (3.15)$$

Where;

APH_x is the average patients per month of hospital x

OR% is the average occupation rate of hospital x

B_x is the number of beds available in hospital x

- **Maximum patients per month for hospital**

$$MPH_x = B_x \text{ x } AB_x \tag{3.16}$$

Where;

MPH_x is the maximum patients per month of hospital x

- **Initial hospital vacancy**

$$IHV_X = \frac{MPHx - APHx}{VB_t} \tag{3.17}$$

Where;

IHV_x is the initial vacancy of hospital x

VB_t is the total vacant beds in all hospitals

- **If the hospital is rehabilitated then the new average patients served per month is calculated**

$$NAPH_X = (1\text{-}SP_x) \text{ x } APH \tag{3.18}$$

Where;

$NAPH_X$ is the served patients per month during rehabilitation of hospital x

SP_x is the service suspension during rehabilitation of hospital x

- **Total un-served patients during rehabilitation**

$$NSPH_X = \sum_{x=1}^{h}(APH_x - NAPH_x) \tag{3.19}$$

Where;

$NSPH_x$ is the total un-served patients during rehabilitation of hospital x

h is the total number of hospitals

Under normal circumstances, when all hospitals are operating, they are having a number of vacant beds which are expressed by the initial vacancy percentage (IHV_X). However if a hospital is being fully or partially out of service, the vacancy percentage will change simply because the total number of vacant beds in all hospitals have reduced. The un-served patients of this hospital are distributed among the other operating hospitals based on the new vacancy percentage. Consequently, the number of served patients for the remaining operating hospitals will increase to accommodate the un-served patients from the hospitals that are being out of service, this is should not violate the maximum capacity of hospital (MPH_x). Otherwise, the new served patients of the operating hospitals is equal to the maximum capacity.

- **<u>The modified vacancy percentage for a hospital;</u>**

$$MHV_X = \frac{IHVx}{(1 - IHV_S)} \tag{3.20}$$

Where;

MHV_x is the modified vacancy percentage of hospital x

IHV_S is the initial vacancy percentage of suspended/partially suspended hospital s

- **<u>The new served patients for hospital during service suspension in other hospitals;</u>**

$$SPH_x = (APH_x + (MHV_x \text{ x } NSPH_x)) <= MPH_x \quad OR \quad SPH_x = MPH_x \tag{3.21}$$

Where;

SPH_x is the new served patients by an operating hospital x, in addition to its contribution in accommodating the un-served patients from other hospitals

- **<u>The total non-served patients per month</u>**

$$TNSP = \sum_{x=1}^{h} APH_x - SPH_x \tag{3.22}$$

Where;

TNSP is the total number of un-served patients

h is the total number of hospital

x is hospital counter

- **<u>The overlapping rate in rehabilitation schedule</u>**

$$OL\% = \frac{Overlapping\ time}{Total\ rehabilitation\ time\ for\ all\ hospitals} \quad (3.23)$$

Table (3-7) summarizes the formulation of the multi-objective optimization for rehabilitation schedule.

Table 3-7: Summary for Optimization formulation

Multi-objective rehabilitation schedule optimization	
Objective 1	Minimize TNSP = $\sum_{x=1}^{h} APH_x - SPH_x$
Objective 2	Minimize TMRC = $\sum_{x=1}^{h} \sum_{j=1}^{72} RC_{xym}$
Variables	Starting dates of rehabilitation works (1-72)
Constraints	• Maximum budget per year • $D_x = \sum_{j=1}^{72} O_{x,j}$ • Maximum number of un-served patients/year
Results	• Schedule for rehabilitation • Total rehabilitation costs • Total non-served patients • Modified rehabilitation strategies • Patients distribution

3.3 Hospital-level Reliability Centered Maintenance model (HOREM)

Figure (3-7) depicts the model's framework that deals with hospital systems. It utilizes reliability centered maintenance (RCM), Monte-Carlo simulation, optimization and fuzzy logic systems. This model was applied on three major systems that impact the service delivery in hospitals which are HVAC system, Medical gas system and Elevators (Enshassi and Shorafa, 2015). RCM was selected in this study as it integrates different types of maintenance types and it defines when and how to use every type through using RCM decision tree (figure 2-15). Moreover, it has been used by many organizations including NASA to develop maintenance plan for their equipment and assets (NASA RCM, 2008). RCM is an effective maintenance approach as it increase equipment availability and reliability while minimizing life-cycle costs (NASA RCM, 2008). In this study, RCM was used to breakdown the systems to components and identify their functions, functional failures, failure modes, failure effects and their consequences. According to the RCM diagram, the maintenance approach (condition based maintenance, preventive and corrective maintenance) could be selected. RCM will provide a plan for inspection interval, inspection cost and replacement schedules. However decision makers may not be able to provide the required budget to apply the full plan as required by RCM. Experts were asked to estimate a range of the possible p-f intervals as they are uncertain to some extent, thus Monte-Carlo simulation was used. Considering the minimum p-f interval means very low probability of failure (very low probability of downtime) but high maintenance costs and the vice versa.

Fuzzy logic was used to model the preventive maintenance plan by providing the expected probability of failure associated with every replacement/restoration interval. The reason for using fuzzy logic system is the difficulty of obtaining failure data that could be used in modeling preventive maintenance and defining optimum replacement/restoration schedule for equipment components. Experts view were considered to define the factors that affect performance and deterioration of components that fails by aging (fuzzy input variables and their ranges). In addition, there feedback was considered in developing fuzzy rules. Genetic algorithms were required to provide a tradeoff between the expected downtime and maintenance costs, in other words the decision maker will be provided by the downtime associated with budget selected. A second step optimization was used to integrate all systems together, the main target for this is to allocate the budget allowed on these different systems based on their impact on the service delivery.

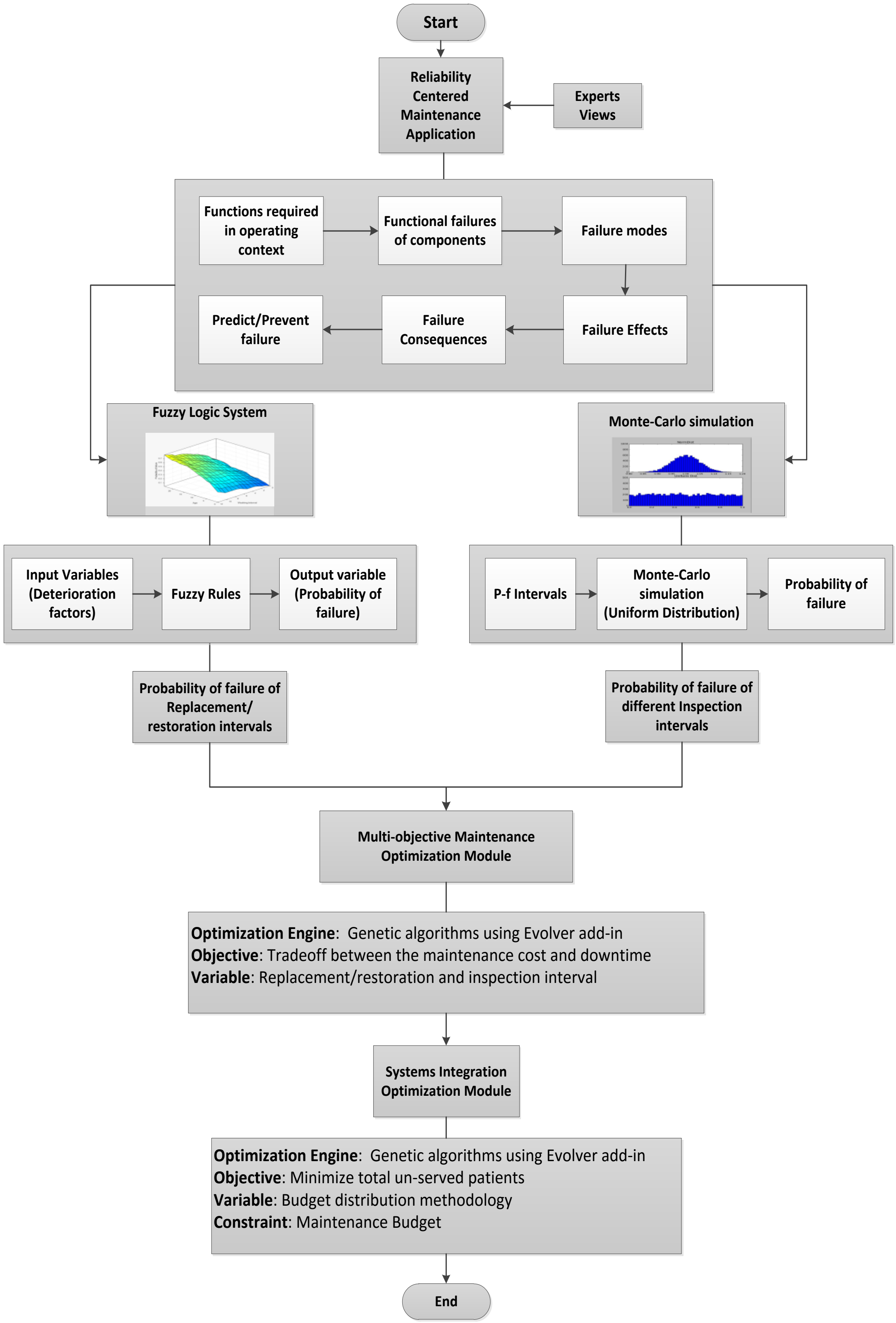

Figure 3-7: HOREM model framework

3.3.1 Reliability Centered Maintenance Application

As mentioned previously, RCM approach was used to develop a maintenance plan for hospital systems in order to maintain service delivered to the patients and to keep the environment safe and suitable for the others to deliver their duties in appropriate manners. The seven questions of RCM were applied on three systems (HVAC, Medical gas and Elevators) that have a significant impact on the service delivery. The seven questions that are applied are as follows:

1. What are the functions required by the asset in its present operating context?
2. What are the functional failures?
3. What are the failure modes?
4. What happens when each failure occurs?
5. What are the failure consequences?
6. What can be done to prevent or predict failure?
7. What should be done if suitable proactive task cannot be found (default actions)?

As explained in section 2.4.2, the second step after answering the first five questions that were considered in the FMEA analysis is applying the RCM decision diagram in figure (2-15) in order to answer the remaining questions. RCM decision diagram provides the manager with the suitable maintenance approach.

In order to do this, interviews were made with some experts personally in these fields in order to build this model. Interviews are one of the common methods for data gathering (Campbell, 2013). The questions were semi-structured where it was prepared in the light of the RCM questions. The questions that were asked to the experts are attached in Appendix (A). Table (3-8) depicts experts' details and their fields. The answers are then compiled and used to develop FMEA, the maintenance approaches, p-f intervals and fuzzy logic parameters. A common feedback was given by experts regarding the questions as they consider it lengthy and time consuming which is one of the limitations of RCM.

Table 3-8: Experts details

Experts	Field	Title	Experience/years	Firm
1	HVAC	Consultant/owner	25	Consulting
2	HVAC	Designer	10	Consulting
3	HVAC	Installation Engineer	5	Contractor
4	HVAC	Project Manager	15	Contractor
5	HVAC	Project Manager	12	Contractor
6	Medical gas	Installation Engineer	6	Contractor
7	Medical gas	Inspection Engineer	5	Consulting
8	Medical gas	Project Manager	15	Contractor
9	Medical Gas	Manager	20	Contractor
10	Elevators	Senior Designer	12	Contractor
11	Elevators	Maintenance Engineer	7	Contractor
12	Elevators	Project Engineer	11	Contractor
13	Elevators	Installation Engineer	7	Contractor

3.3.1.1 Primary HVAC System

Primary HVAC systems are the ones installed in operating units and intensive care units differs from the ones installed in other rooms. Operating rooms and intensive care units specifications requires an anti-bacterial environment hence special filters and exhaust systems are installed to provide a clean air from bacteria and send off the exhaled air that contain microbes and anesthetic gases outside the room, consequently 100% fresh air HVAC system is a must.. Figure (3-8) shows the components of HVAC systems. Table (3-9) shows the FMEA developed for primary HVAC.

3.3.1.1.1 Components of HVAC in ORs & ICUs considered in FMEA

- Pre-filters : It removes coarse contaminates from air allowed to the AHU
- Secondary filter: The filter removes fine particles
- Fan coil
  - Cooling coil: To cool the air supplied to the desired temperature
  - Freon Pipe: To carry the Freon gas from the compressor to the coil
- Blower
  - Fan belt: Transfer energy to fan impeller
  - Shaft: Transfer energy to the blower via drive belts
  - Ball Bearing: Support blower shaft
  - Impellers: Provide required air flow and discharge pressure
- HEPA filter: To trap microbes and bacteria from entering the operations
- Return system
  - Drive belt: Transfer energy to fan impeller
  - Shaft: Transfer energy to the blower via drive belts
  - Ball Bearing: Support blower shaft
  - Impellers: Provide required air flow and discharge pressure

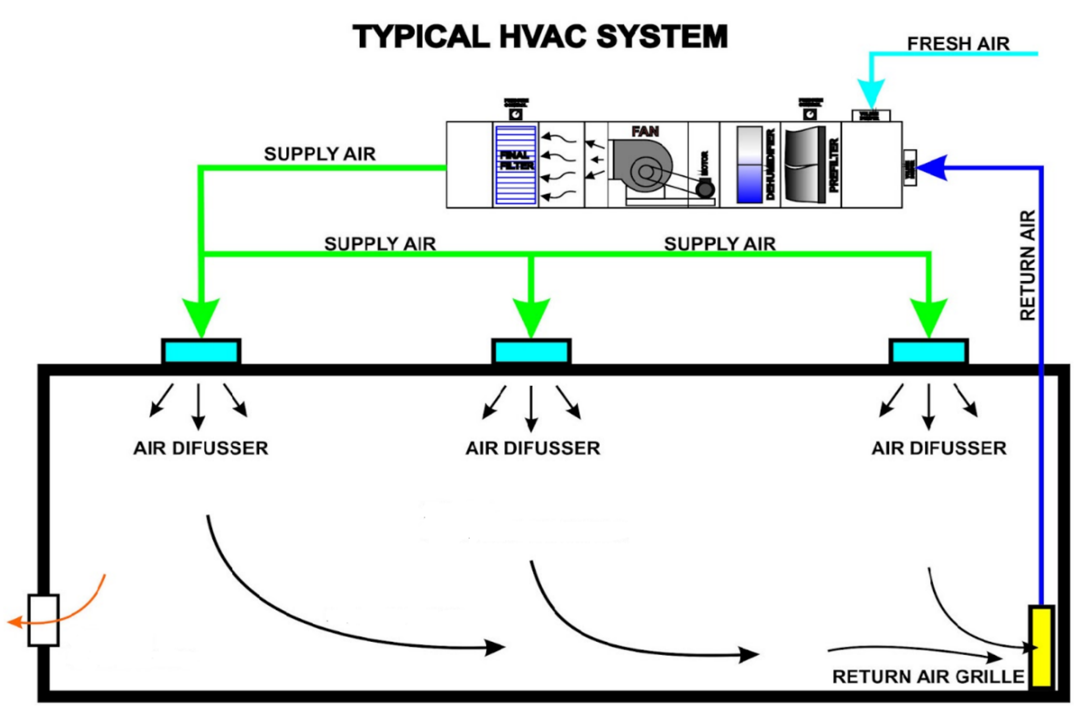

Figure 3-8: HVAC System (hvac4food.blogspot.com, November 2016)

Table 3-9: FMEA for primary HVAC system

Name		Function		Functional Failure		Failure Mode		Failure Effect	Failure Consequence
1	Pre-filter	1	To remove coarse contaminates from air allowed to the AHU	A	Failure to remove contaminates	1	Saturated filter	• Air supply reduction to the HVAC system • Downtime= 2 hours	Operational Consequence
						2	Ripped or torn filter	• Contaminates will collected at the second filter which might be failed. This will allow contaminates to be accessed to the room in case of improper installation of HEPA filter. • Downtime= 2 hours	Safety consequence
2	Secondary filter	1	The filter removes fine particles	A	Failure to remove particles from the supplied air	1	Saturated filter	• Reduction in airflow supplied • Downtown= 2 hours	Operational Consequence
						2	Ripped or torn filter	• Air supplied to the space will contain Unhealthy & particles • Downtime= 2 hours	Safety consequence
3	Fan coil		Provide the required cooling capacity		Listed below		Listed below	Listed below	

3.1	Cooling coil	1	Cooling the air supplied to the desired temperature	A	Cooling coil failed to provide the required cooling capacity	1	Cooling coil is ruptured	• Air is not cooled • Downtime= 10 days •	Operational Consequence
3.2	Freon pipe	1	To carry the Freon gas from the compressor to the coil	B	Failed to transfer the Freon gas	1	Leakage in Freon gas pipe	• Freon gas leaks • Air is not cooled • Downtime= 1day •	Operational Consequence
4	Blower		To supply the required capacity (CFM) of air to the fan coil.		Failed to supply the required capacity of air.		Listed below	• Listed below	
4.1	Fan belt	1	Transfer energy to fan impeller	A	Failed to transfer the energy to the fan impeller	1	Defective fan belt (worn or cracked)	• Air flow reduction • Vibration and noise increase • Downtime= 4 hours	Operational Consequence
4.2	Shaft	1	Transfer energy to the blower via drive belts	B	Failed to provide the energy required for the blower	1	Bent shaft	• Airflow reduction • Vibration • Downtime = 3 days	Operational Consequence
4.3	Ball bearing	1	Support blower shaft	C	Failure to support blower shaft	1	Improper lubrication	• Increased temperature • Noise problem • Airflow reduction • Downtime= 1 day	Operational Consequence
						2	Fatigue	• Increased temperature • Noise problem • Downtime= 1 day • Airflow reduction	Operational Consequence

4.4	Impellers	1	Provide required air flow and discharge pressure	D	Failure to provide required air flow	1	Fatigue	• Noise & vibration problem • Airflow reduction • Downtime = 5 days • The whole blower is changed	Operational Consequence
5	HEPA Filter	1	To trap microbes and bacteria from entering the operations	A	Failed to purify the supplied air from the pathogens	1	Filter leaks	• Pathogens are allowed to the space. • Downtime= 2 hours • Leak detection devices.	Safety Consequence
6	Exhaust		To take air outside the room		Failed to take air outside room		Listed below	• Listed below	
6.1	Drive belt	1	Transfer energy to fan impeller	A	Failed to transfer the energy to the fan impeller	1	Defective fan belt (worn or cracked)	• Failed to take the air to the outside atmosphere • Downtime= 4 hours	Safety Consequence
6.2	Shaft	1	Transfer energy to the blower via drive belts	B	Failed to provide the energy required for the blower	1	Bent shaft	• Failed to take the air to the outside atmosphere • Downtime = 3 days	Safety Consequence
6.3	Ball bearing	1	Support blower shaft	C	Failure to support blower shaft	1	Fatigue	• Failed to return the air to the outside atmosphere • Increased temperature • Noise problem • Downtime= 1 day • Airflow reduction	Safety Consequence

6.4	Impellers	1	Provide required air flow and discharge pressure	D	Failure to provide required air flow	1	Fatigue	• Failed to take the air to the outside atmosphere • Noise & vibration problem • Airflow reduction • Downtime = 5 days • The whole blower is changed	Safety Consequence

3.3.1.1.2 Maintenance Approach

The following table (3-10) depicts the maintenance approach selected, task duration, task cost and task description for primary HVAC.

Table 3-10: Maintenance approach of HVAC system of ORs and ICUs

Failure Mode	Maintenance Approach	Task duration	Task Cost	Task description
Ripped/torn filters	**Predictive Maintenance**	1 hr.	**EGP 150/hr**	**Inspection**
Cooling coil rupture		3 hr.		
Leakage of Freon pipe		2 hr.		
Defective fan belt		2 hr.		
Bending of shaft		2 hr.		
Bearings fatigue		2 hr.		
Improper lubrication of bearings		1 hr.		
Impellers fatigue		2 hr.		
HEPA filter leaks		1.5 hr.		
Pre-filter saturation	Scheduled Restoration	1 hr.		Filter Washing
Secondary filter saturation	Scheduled Discard	1 hr.	150/hr + EGP 1000	Filter Replacement

3.3.1.2 Secondary HVAC system

HVAC systems used in other rooms (regular rooms- emergency rooms) are used not just for creating comfort to the occupants and patients but it assists in maintaining a healthy environment for recovery and healing process. Table (3-11) shows FMEA for secondary HVAC.

Table 3-11: FMEA for Secondary HVAC system

Name		Function		Functional Failure		Failure Mode		Failure Effect	Failure Consequence
1	Pre-filter	1	To remove coarse contaminates from air allowed to the AHU	A	Failure to remove contaminates	1	Saturated filter	• Air supply reduction to the HVAC system • Downtime= 2 hours	Operational Consequence
						2	Ripped or torn filter	• Contaminates will collected at the second filter which might be failed. • Downtime= 2 hours	Safety consequence
2	Secondary Filter	1	The filter removes fine particles	A	Failure to remove particles from the supplied air	1	Saturated filter	• Reduction in airflow supplied • Downtown= 2 hours	Operational Consequence
						2	Ripped or torn filter	• Air supplied to the space will contain Unhealthy & particles • Downtime= 2 hours	Safety consequence
3	Fan coil		Provide the required cooling capacity		Listed below		Listed below	Listed below	
3.1	Cooling coil	1	Cooling the air supplied to the desired temperature	A	Cooling coil failed to provide the required cooling capacity	1	Cooling coil is ruptured	• Air is not cooled • Downtime= 10 days	Operational Consequence
3.2	Freon pipe	1	To carry the Freon gas from the compressor to the coil	A	Failed to transfer the Freon gas	1	Leakage in Freon gas pipe	• Freon gas leaks • Air is not cooled • Downtime= 1day	Operational Consequence

4	Blower		To supply the required capacity (CFM) of air to the fan coil.		Failed to supply the required capacity of air.		Listed below	• Listed below	
4.1	Fan belt	1	Transfer energy to fan impeller	A	Failed to transfer the energy to the fan impeller	1	Defective fan belt (worn or cracked)	• Air flow reduction • Vibration and noise increase • Downtime= 4 hours • Vibration analysis, visual inspection	Operational Consequence
4.2	Shaft	1	Transfer energy to the blower via drive belts	A	Failed to provide the energy required for the blower	1	Bent shaft	• Airflow reduction • Vibration • Downtime = 3 days	Operational Consequence
4.3	Ball bearing	1	Support blower shaft	A	Failure to support blower shaft	1	Fatigue	• Increased temperature • Noise problem • Downtime= 1 day • Airflow reduction	Operational Consequence
4.4	Impellers	1	Provide required air flow and discharge pressure	A	Failure to provide required air flow	1	Fatigue	• Noise & vibration problem • Airflow reduction Downtime = 5 days • The whole blower is changed	Operational Consequence

3.3.1.2.1 Maintenance Approach

The following table (3-12) depicts the maintenance approach selected, task duration, task cost and task description for secondary HVAC.

Table 3-12: Maintenance approach of secondary HVAC system

Failure Code	Maintenance Approach	Task duration	Task Cost	Task description
Torn/ripped filter	Predictive Maintenance	1 hr.	EGP 150/hr	Inspection
Cooling coil rupture		3 hr.		
Leakage of Freon pipe		2 hr.		
Defective fan belt		2 hr.		
Bending of shaft		2 hr.		
Improper lubrication of bearings		1 hr.		
Bearings fatigue		2 hr.		
Impellers fatigue		2 hr.		
Pre-filter Saturation	Scheduled Restoration	1 hr.		Filter Washing
Secondary filter saturation	Scheduled Discard	1 hr.	150/hr + EGP 1000	Filter Replacement

3.3.1.3 Medical Gas system

The medical gases used in a hospital are life-supporting element that gives direct influence in maintaining the life of a patient, therefore it is a must to ensure a stable supply of medical gases. Figure (3-9) depicts the typical components of medical air plant. Table (3-13) shows the FMEA for medical gas system.

3.3.1.3.1 Components of Medical Gas system considered in FMEA

- **Liquid Oxygen Supply**
  - **Vacuum Insulated Tanks:** To keep liquid oxygen inside the tank at low temperature -180 ^{0}C
  - **Evaporator**: Convert the liquid oxygen gaseous state.
  - **Control Valves**: To prevent oxygen backflow
  - **Safety Valve**: To discharge oxygen gas to the atmosphere when pressure build up automatically.
  - **Super-heater:** To heat the oxygen gas before serving to patients
  - **Regulators**: To regulate pressure of oxygen gas prior delivery to patients
- **Medical Air Plant**
  - **Inlet Filter**: To remove coarse contaminates from air allowed to the system
  - **Carbon Filter**: To allow air supply with minimal hydrocarbons
  - **Bacterial Filter**: To allow air supply with minimal Bacteria
  - **Relief Valve**: To discharge medical air to the atmosphere when pressure build up automatically.
  - **Air Receiver Tank**: To store air that will be supplied to the patients
  - **Dryer**: To remove water from air supplied to patients
  - **Pressure reducer**: To reduce pressure of air prior delivery to patients

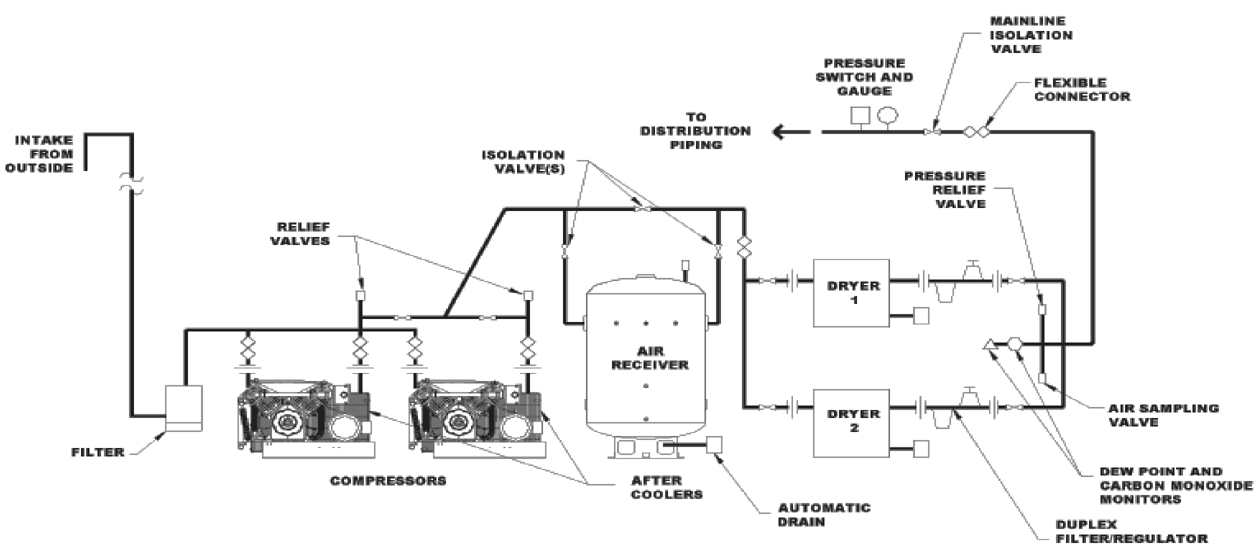

Figure 3-9: Medical air compressor plant (http://bestprocessequipment.com, November, 2016)

Table 3-13: FMEA for Medical gas system

Name		Function		Functional Failure		Failure Mode		Failure Effect	Failure Consequence
1	Liquid Oxygen Supply		To Supply oxygen gas to the patients		Listed Below		Listed Below	Listed Below	
1.1	Vacuum insulated tank	1	To keep liquid oxygen inside the tank at low temperature -180 C	A	Failed to maintain the temperature which keep oxygen at liquid state.	1	Cracks at the outer & inner surface of the tank	• Air is allowed to pass replacing vacuum reducing the insulating capabilities of the tank • Inner surface will be exposed to damage • Downtime = 7 days	Safety Consequence
1.2	Evaporator	1	Convert the liquid oxygen gaseous state.	A	Failed to convert the liquid gas	1	Cracks that leads to liquid oxygen leaks	• Liquid oxygen will not be converted to gas, hence oxygen gas is not produced • Noise is produced • Downtime= 10 days	Safety Consequence
1.3	Control valve	1	To prevent oxygen backflow	A	Failed to prevent oxygen backflow	1	Valve wearing	• Oxygen gas cannot be supplied & leaking may occur • Noise is produced • Downtime= 3 days	Safety Consequence

1.4	Safety Valve	1	To discharge oxygen gas to the atmosphere when pressure build up automatically.	A	Failed to maintain oxygen gas	1	Spring failure	• Oxygen will not be stored and discharged to outside atmosphere • Sound and noise is produced • Downtime = 3 day	Safety Consequence
1.5	Super heater		To heat the oxygen gas before serving to patients	A	Failed to heat oxygen gas	1	Coil cracks leading to leaks	• Liquid oxygen cannot be delivered and service will be suspended • Downtime = 20 days	Safety Consequence
1.6	Regulator		To regulate pressure of oxygen gas prior delivery to patients	A	Failed to regulate oxygen gas pressure	1	High flow-rate than the valves capacity leading to wearing	• Pressure will not be regulated to suit patients need • Noise and heat • Downtime= 10 days	Safety Consequence
2	Medical Air Plant		To deliver pure air Good. Moderate from Unhealthy and microbes.	A	Listed below		Listed below	• Listed below	
2.1	Inlet filter		To remove coarse contaminates from air allowed to the system	A	Failure to remove contaminates	1	Saturated filter	• Air supply reduction • Downtime= 10 days • Pressure drop indicates failure	Safety Consequence

2.2	Carbon Filter		To allow air supply with minimal hydrocarbons	A	Failed to allow air supply with minimal hydrocarbon	1	Saturated Filter	• Air supply reduction • Downtime= 10 days • Pressure drop indicates failure	Safety Consequence
2.3	Bacterial filter		To allow air supply with minimal Bacteria	A	Failed to allow air supply with minimal bacteria	1	Saturated filter	• Air supply reduction • Downtime = 10 days • Pressure drop indicates failure	Safety Consequence
2.4	Relief Valve		To discharge medical air to the atmosphere when pressure build up automatically.	A	Failed to maintain air inside in the system	1	Spring failure	• The valve is opened • Noise is produced • Downtime= 3 day	Safety Consequence
2.5	Air Receiver tank		To store air that will be supplied to the patients	A	Failed to store air	1	Automatic drain failure	• Air tank cannot store air • Downtime = 2 days	Safety Consequence
2.6	Dryer		To remove water from air supplied to patients	A	Failed to remove water from air	1	Coil leaks due to crack	• Air will contain water vapor • Downtime = 20 days	Safety Consequence
2.7	Pressure reducer		To reduce pressure of air prior delivery to patients	A	Failed to regulate air pressure	1	High flow-rate than the valves capacity leading to wearing	• Pressure will not be regulated to suit patients need • Noise and heat • Downtime= 10 days	Safety Consequence

3.3.1.3.2 Maintenance Approach

The following table (3-14) depicts the maintenance approach selected, task duration, task cost and task description for medical gas system.

Table 3-14: Maintenance approach for Medical Gas systems

Failure Code	Maintenance Approach	Task duration	Task Cost	Task description
VIT crack	Predictive Maintenance	4 hr.	EGP 250/hr	Inspection
Evaporator crack		2 hr.		
Control Valves wearing		2 hr.		
Safety Valve failure		2 hr.		
Super-heater crack		4 hr.		
Regulators high flow rate		1 hr.		
Inlet Filter saturation		1 hr.		
Carbon Filter saturation		1 hr.		
Bacterial Filter saturation		1 hr.		
Relief Valve spring's failure		2 hr.		
Tanks drain		2 hr.		
Dryer coil's crack		2 hr.		
High flow rate of reducer		1 hr.		

3.3.1.4 Elevator systems

Elevators are used to for vertical transportation for patients and workers in hospital. Figure (3-10) depicts a description for elevator system. Table (3-15) shows the FMEA for elevator system.

3.3.1.4.1 Components of Elevator system considered in FMEA

- Guideways: To control geometric position of the cab
- Sheaves: To transfer energy to cab
- Wire Rope: To provide support to the system
- Clutch: To control speed of elevator

- Elevator Brakes: To provide safety stop
- Bearings: To provide geometric alignment to elevator

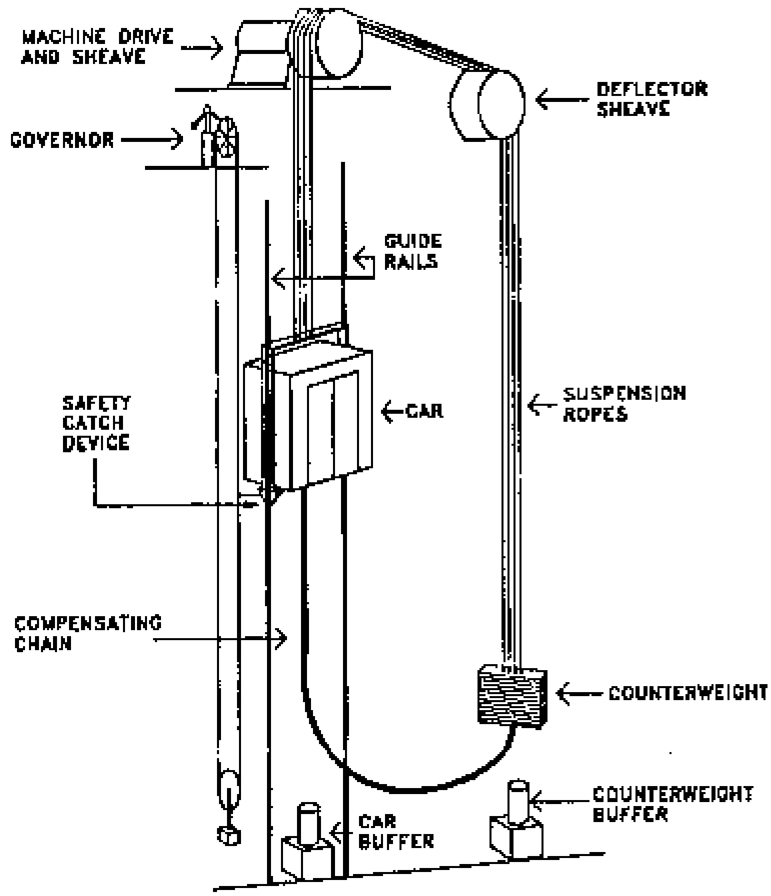

Figure 3-10: Elevator system (http://arlweb.msha.gov, November 2016)

Table 3-15: FMEA for Elevators

Name		Function		Functional Failure		Failure Mode		Failure Effect	Failure consequence
A	Elevator system	1	To safely provide vertical transportation of people.		Failed to transport people		Listed below	Listed below	
1	Guideways	1	To control geometric position of the cab	A	Failed to control geometric position of the cab	1	Fasteners failure	• Unsafe elevator • Limited vertical access • Overcrowd of other elevators • Downtime= 5 days	Safety Consequence
2	Sheaves	1	To transfer energy to cab	A	Failed to work on transferring energy to cab	1	Wear due to friction	• Unsafe elevator • Limited vertical access • Overcrowd of other elevators • Downtime= 2 days	Safety Consequence
3	Wire Rope	1	To provide support to the system	A	Failed to provide support to system	1	Parting of wire rope	• Unsafe elevator • Limited vertical access • Overcrowd of other elevators • Downtime= 7 days	Safety Consequence
4	Clutch	1	To control speed of elevator	A	Failed to control speed of elevator	1	Wearing clutch due to friction	• Unsafe elevator • Limited vertical access • Overcrowd of other elevators	Safety Consequence

								• Downtime= 2 days	
5	Elevator Brakes	1	To provide safety stop	A	Failed to provide safety stop	1	Frictional wear	• Unsafe elevator • Limited vertical access • Overcrowd of other elevators • Downtime = 5 days	Safety Consequence
6	Bearings	1	To provide geometric alignment to elevator	A	Failed to provide geometric alignment to elevator	1	Improper lubrication	• Unsafe elevator • Limited vertical access • Overcrowd of other elevators • Downtime = 1 day	Safety Consequence

3.3.1.4.2 Maintenance Approach

The following table (3-16) depicts the maintenance approach selected, task duration, task cost and task description for elevators.

Table 3-16: Maintenance Approach for elevator

Failure mode	Maintenance Approach	Task duration	Task Cost	Task description
Guideways fastener failure	**Predictive Maintenance**	**2 hours**	**EGP 120/hr**	**Inspection**
Sheaves wear				
Wire parting				
Clutch wearing				
Brakes frictional wear				
Bearing improper lubrication				

3.3.2 Monte-Carlo Simulation & Fuzzy logic system Module

This module considers the use of Monte-Carlo and fuzzy logic systems to provide the user with the possible solutions and the expected probability of failure. Mainly two approaches were selected for dealing with different failures, scheduled restoration/discard (preventive maintenance) and predictive maintenance (condition based maintenance). If a certain failure mode requires a scheduled maintenance (preventive maintenance) or requires a condition based maintenance, this entails a fixed interval replacement/restoration or inspection over the entire period respectively. This might not be applicable due to budget constraints, in addition exceeding the replacement, restoration and inspection time intervals will leads to higher the probability of failure. Consequently, Monte-Carlo simulation was used for the failure modes that require condition based maintenance (regular inspections). As mentioned in the literature review section, the inspection intervals should not exceed the expected p-f interval. Experts were asked to provide p-f intervals for every failure mode and an approximate probability distribution that could represent it. Uniform distribution was selected by the experts to represent the p-f intervals for providing range of solutions. Uniform distribution consideration is being supported by the random failure patterns (figure 2-13) as the major part of the useful life of the component is behaving uniformly with age. Probability of failure increases by considering long inspection intervals and vice versa. On the other hand, fuzzy logic system was used to represent the deterioration factors of the failure modes that requires preventive maintenance. As result of RCM application, two failure modes required preventive maintenance which are pre-filter and secondary filter saturation. As mentioned earlier, experts provided the guideline for the input and output variables (age, working hours, washing intervals and probability of failure) and fuzzy rules, except for the location variable which was considered from Saddek et al (2014) who models the air quality using fuzzy logic system. Saddek et al (2014) have used six input variables (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy and hazardous). However in this model for simplicity, the variables were grouped into three (good.moderate, moderately acceptable, and unhealthy).

3.3.2.1 Fuzzy Logic System models

3.3.2.1.1 Fuzzy Logic system for Preventive Maintenance for Pre-filter Saturation

a- <u>Input Variables</u>

- Washing interval
- Location
- Age
- Working hours

b- <u>Output Variables</u>

- Probability of failure

c- <u>Membership functions for washing interval</u>

Table (3-17) and figure (3-11) depict the membership function used for washing intervals of pre-filter.

Table 3-17: Membership function for washing interval

1-Washing Interval		
Variable	**Membership Type**	**Parameter (months)**
Short	Triangular	(0 0 2)
Moderate Short	Triangular	(0 2 4)
Moderate	Triangular	(2 4 6)

Moderate Long	Triangular	(4 6 8)
Long	Triangular	(6 8 10)
Longer	Triangular	(8 10 11)
V.Long	Triangular	(10 11 12)
Extreme	Triangular	(11 12 12)

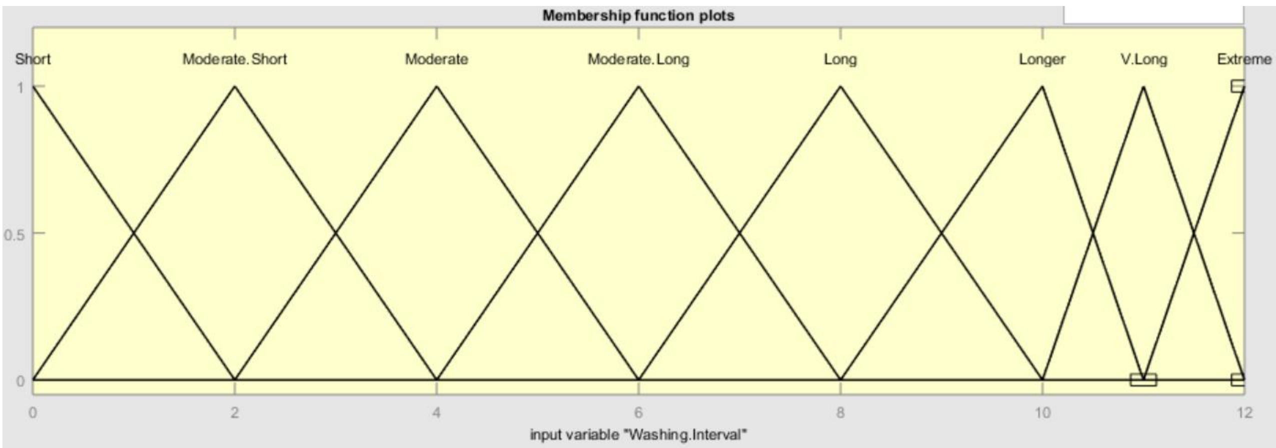

Figure 3-11: Membership function for washing interval

d- <u>Membership functions for working hours</u>

Table (3-18) and figure (3-12) depict the membership function used for working hours

Table 3-18: Membership function for Working hours

2-Working Hours		
Variable	**Membership Type**	**Parameter (hours)**
Short	Triangular	(0 0 8)
Moderate Short	Triangular	(0 8 15)
Moderate	Triangular	(8 15 22)
Long	Triangular	(15 24 24)

Figure 3-12: Membership function for Working hours

e- <u>Membership functions for location</u>

Table (3-19) and figure (3-13) depict the membership function used for location.

Table 3-19: Membership function for location

2-Location		
Variable	**Membership Type**	**Parameter (Air quality index)**
Good. Moderate	Triangular	(0 0 120)
Moderately Acceptable	Triangular	(80 150 220)
Unhealthy	Triangular	(180,500 500)

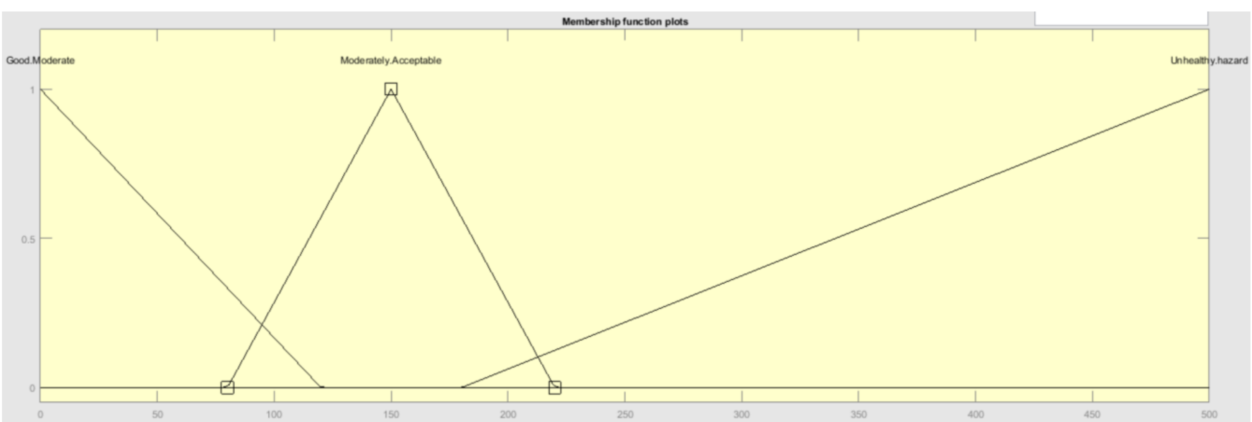

Figure 3-13: Membership function for Location

f- Membership functions for age

Table (3-20) and figure (3-14) show membership function for age.

Table 3-20: Membership function for Age

4- Age		
Variable	**Membership Type**	**Parameter (Air quality index)**
Extreme New	Triangular	(0 0 3)
V.New	Triangular	(0 3 6)
New	Triangular	(3 6 9)
Moderate New	Triangular	(6 9 12)
Moderate	Triangular	(9 12 15)
Moderate Old	Triangular	(12 15 18)
Old	Triangular	(15 18 21)
V.Old	Triangular	(18 21 24)
Extreme Old	Triangular	(21 24 24)

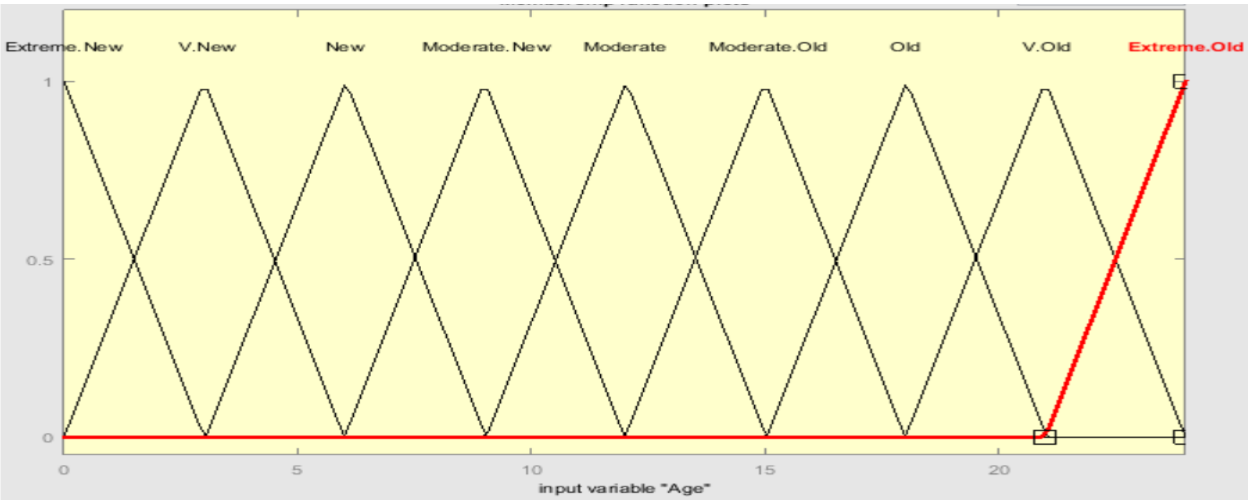

Figure 3-14: Membership function for Age

g- Membership functions for output (probability of failure)

Table (3-21) and figure (3-15) show the membership function for the output variable (probability of failure).

Table 3-21: Membership function for the output

5- Probability of failure		
Variable	**Membership Type**	**Parameter (%)**
Negligible	Triangular	(0 0 0.075)
V. Extreme Lowest	Triangular	(0 0.075 0.15)
Extreme. Lowest	Triangular	(0.075 0.15 0.225)
Lowest	Triangular	(0.15 0.225 0.3)
Lower	Triangular	(0.225 0.3 0.375)
Low	Triangular	(0.3 0.375 0.45)
Moderate. Low	Triangular	(0.375 0.45 0.525)
Moderate	Triangular	(0.45 0.525 0.6)
Moderate. High	Triangular	(0.525 0.6 0.675)
High	Triangular	(0.6 0.675 0.75)
Higher	Triangular	(0.675 0.75 0.825)
Highest	Triangular	(0.75 0.825 0.9)
Extreme. Highest	Triangular	(0.825 0.9 0.975)
V. Extreme Highest	Triangular	(0.9 1 1)

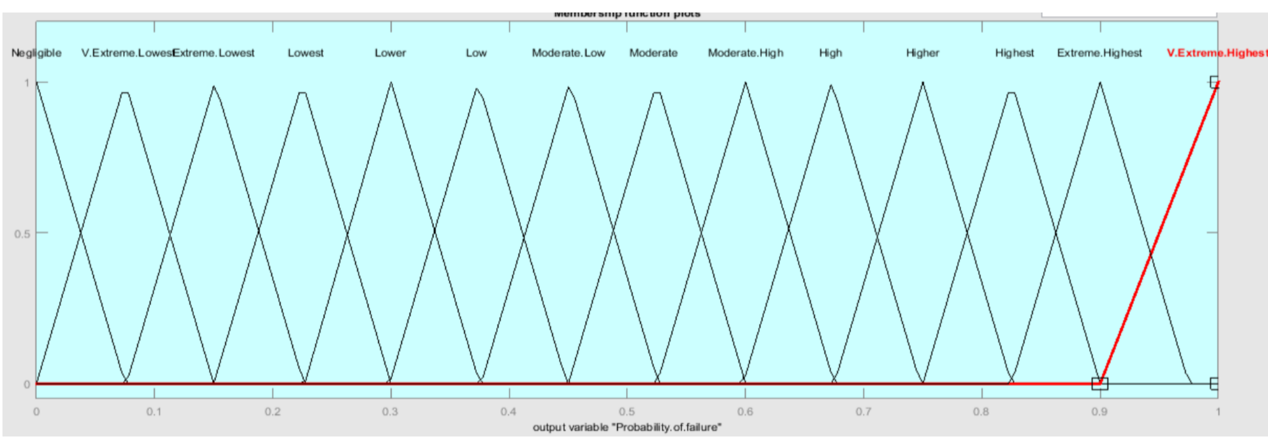

Figure 3-15: Membership function for Output

3.3.2.1.2 Fuzzy Logic system for secondary-filter saturation

a- <u>Input Variables</u>

- Age

- Working hours
- Location

b- <u>Output Variables</u>

- Probability of failure

c- <u>Membership function for age</u>

Table (3-22) and figure (3-16) depict the membership function used for age of secondary filter.

Table 3-22: Membership function for Age

1- Age		
Variable	**Membership Type**	**Parameter (months)**
Short	Trapezoidal	(0 0 5 6)
Moderate. Short	Triangular	(5 6 7)
Moderate	Triangular	(6 7 8)
Moderate. Long	Triangular	(7 8 9)
Long	Triangular	(8 9 10)
Longer	Triangular	(9 10 11)
V. Long	Triangular	(10 11 12)
Extreme	Triangular	(11 12 12)

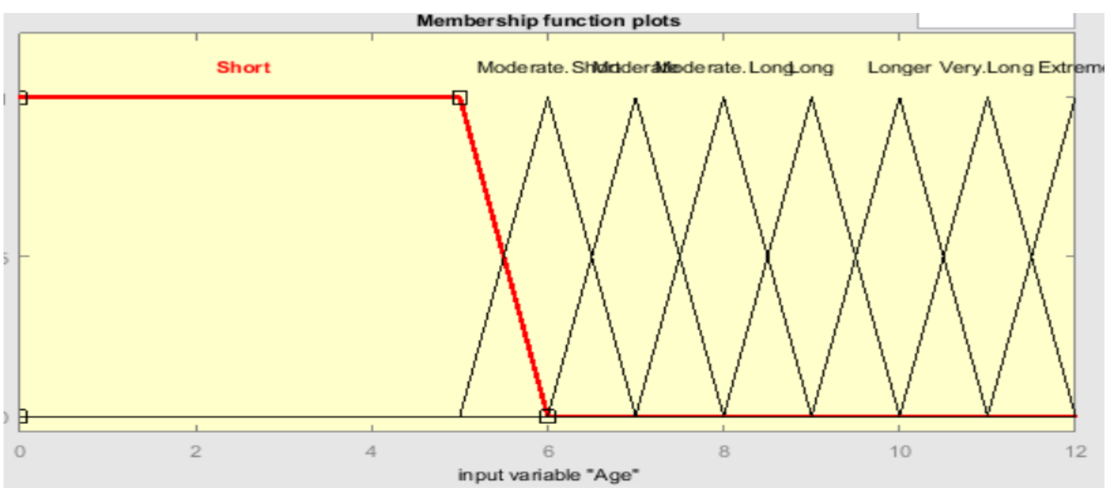

Figure 3-16: Membership function for Age

d- Membership function for working hours

Table (3-23) and figure (3-17) depict the membership function used for working hours.

Table 3-23: Membership function for Working hours

2-Working Hours		
Variable	**Membership Type**	**Parameter (hours)**
Short	Triangular	(0 0 8)
Moderate Short	Triangular	(0 8 15)
Moderate	Triangular	(8 15 22)
Long	Triangular	(15 24 24)

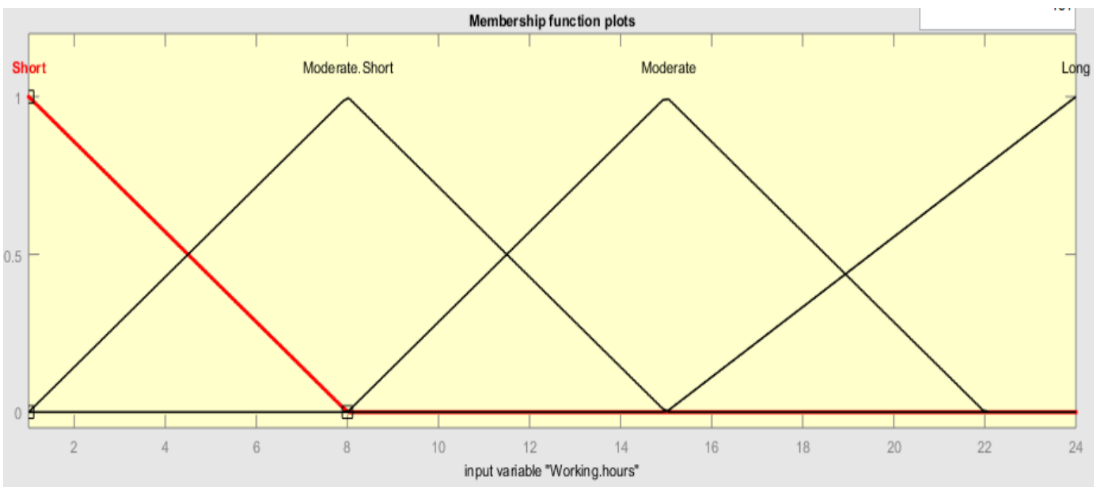

Figure 3-17: Membership function for Working hours

e- Membership function for location

Table (3-24) and figure (3-18) show the membership function for location.

Table 3-24: Membership function for location

2-Location		
Variable	**Membership Type**	**Parameter (Air quality index)**
Good. Moderate	Triangular	(0 0 120)
Moderately Acceptable	Triangular	(80 150 220)
Unhealthy	Triangular	(180 500 500)

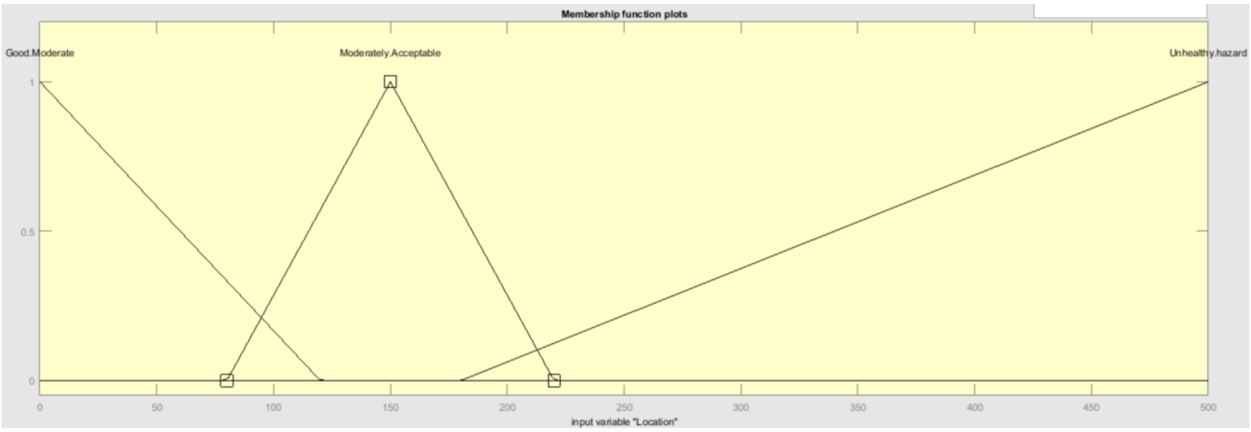

Figure 3-18: Membership function for Location

f- <u>Membership function for output (probability of failure)</u>

Figure (3-19) shows the membership function for the output variable (probability of failure).

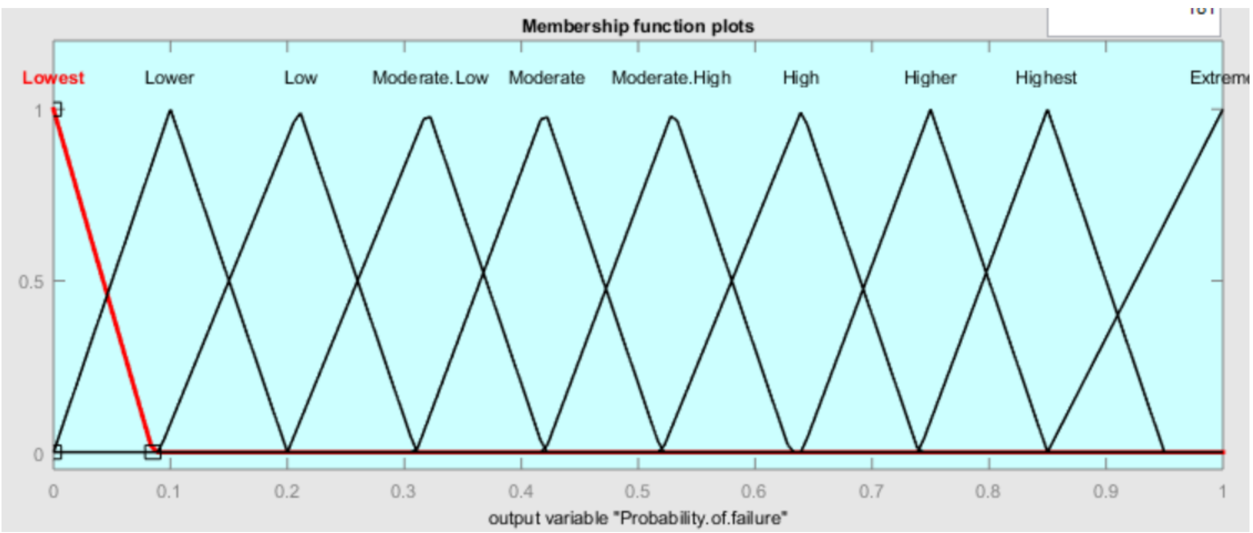

Figure 3-19: Membership function for output (Secondary filter)

3.3.2.1.3 Fuzzy Rules

Fuzzy rules were set under the guide of experts and the centroid of area method was used for defuzzfication. An extract of the fuzzy rules used are shown in the Appendix (B).

3.3.2.2 Monte-Carlo simulation

3.3.2.2.1 Condition based maintenance for HVAC failure modes

Table (3-25) depicts the failure modes of HVAC system components that require a condition-based maintenance together with the minimum and maximum p-f intervals.

Table 3-25: P-F intervals for HVAC failure modes

Item	Mini P-f Interval/day	Maxi P-f Interval/day	Distribution
Torn Pre-Filter	5	10	**Uniform distribution**
Torn Secondary Filter	5	10	
Coil leaks	60	90	
Freon gas pipe leaks	30	60	
Defective fan belt	20	45	
Shaft bending	30	60	
Ball bearing fatigue	60	90	
Impellers fatigue	60	90	
HEPA Filter leaks	10	25	
Bearings improper lubrication	15	30	

3.3.2.2.2 Condition based maintenance for Medical gas failure modes

Table (3-26) depicts the failure modes of medical gas system components that require a condition-based maintenance together with the minimum and maximum p-f intervals.

Table 3-26: P-f interval for medical gas system

Item	Mini P-f Interval/day	Maxi P-f Interval/day	Distribution
VIT Cracks	120	210	
Evaporator Cracks	90	120	
Control valve Wearing	30	60	
Safety spring failure	30	60	
Cooling coil leaks	15	30	
Regulator failure	30	60	
Saturated inlet filter	120	150	

Saturated carbon filter	120	180	**Uniform distribution**
Saturated bacterial filter	90	120	
Relief valve spring failure	30	60	
Automatic drain failure	10	30	
Coil Leaks	90	120	
Reducer failure	30	60	

3.3.2.2.3 Condition based maintenance for Elevator failure modes

Table (3-27) depicts the failure modes of elevator components that require a condition-based maintenance together with the minimum and maximum p-f intervals.

Table 3-27: P-f intervals for elevator

Failure mode	**Mini P-f interval/day**	**Maxi P-f interval/day**	**Distribution**
Fasteners failure of Guideways	90	120	**Uniform distribution**
Sheaves wear due to friction	10	20	
Parting of wire rope	60	120	
Brakes frictional wear	7	15	
Improper lubrication	15	30	
Clutch wearing	120	150	

3.3.3 Multi-objective Maintenance Optimization module

Decision variables: Replacement, inspection and restoration intervals

Objectives: Maintenance Cost & Expected Downtime (EDT)

$$\text{TMC} = \sum_{i=1}^{m} IC_i + RCT_i \qquad (3.24)$$

Where;

TMC is the total maintenance costs

IC_i is the inspection cost for failure mode i

RCT_i is the replacement costs for failure mode i

m is the total number of failure modes

$$RCT = MC \text{ x } \frac{12 \text{ months}}{\text{Replacement interval}} \quad (3.25)$$

$$IC = \frac{365 \text{ days}}{\text{Inspection interval}} \text{ x IDx CR} \quad (3.26)$$

Where;

ID is the inspection duration in hours

CR is the crew rate in EGP/hour

MC is the material cost in EGP

$$EDT = Pf \text{ x } DT \quad (3.27)$$

Where;

EDT is the Expected Downtime in hours

DT is the downtime listed in FMEA for failure modes

Pf is the probability of failure "P (X<a)", a is the inspection interval in days, X is minimum P-f interval (in case of condition based maintenance).

Or Pf is the probability failure provided by the fuzzy logic system given certain operating context (working hours, location, age …etc.) (In case of preventive maintenance).

3.3.4 Systems Integration Optimization Engine

The solutions generated in the optimization engine will provide an estimate for the minimum and maximum budget required for maintenance and the associated expected downtime (EDT). This module works on distributing the global available budget determined by the higher management on the hospital different systems based on their impact to the service delivered.

In this context, four types of typical units in a hospital were considered, which are intensive care units, regular rooms, emergency rooms and operation units. The user will have to enter the average patients per month for each type of unit, hence, patients per hour could be calculated. In addition the degree of criticality (the contribution of the system to the service delivery) of every system to each unit was considered as shown in table (3-28). Where 1 means that the system is a critical for the unit in order to deliver an adequate service, 0.5 means that the system is partially critical to the unit and 0 means not applicable or not important e.g. emergency rooms most probably are available in ground floor, consequently elevator system are not important factor for it to provide the required service.

Table 3-28: Degree of criticality

Rating	Degree of criticality
0	Non critical
0.5	Partially critical
1	Critical

The average patients served/hour by every system is calculated as follows:

$$APS_k = \sum_{i=1}^{u} (DC_i \, x PH_i) \qquad (3.28)$$

Where;

APS_k is the average patients served/hour for system k

DC_i is the degree of criticality for unit i

PH_i is the patients per hour for unit i

u is the total number of units

As mentioned the optimization module will provide several solutions (maintenance cost and the associated expected downtime), hence the total number of un-served patients will be calculated using the downtime resulted as shown in equation (3.29). Optimization engine was required to optimize the allocation of maintenance budget among different systems. Genetic algorithms were used as it is suitable for problems of combinatorial nature. The decision variable is the percentage of the budget allocated and decided by the user and the objective is to minimize total un-served patients from all systems as shown in equation (3.29).

$$\text{Total un-served patients} = \sum_{k=1}^{s}(\text{DT}_k \text{ x } \text{APS}_\text{k}) \tag{3.29}$$

Where;

DT_k is the downtime in hours for system k

s is the total number of systems considered.

4 MODELS VERIFICATION AND VALIDATION

4.1 NEHIR Model verification and validation

Four hospitals located in one of the cities in Upper Egypt were considered to verify and validate the model. The hospitals were suffering from deterioration due to aging and environmental circumstances. These publically owned hospitals were categorized as economic health facilities, in other words the patients were not paying the actual value for the service they obtain. This means that these hospitals were not having an adequate financial resources to improve their performance and thus improve the level of service provided. It was decided to rehabilitate the hospitals and bring new systems as some these hospitals were suffering from the absence of some of them like HVAC, fire-fighting…etc. In addition, it was planned to convert the hospitals from economic to partial economic, in other words the government will not fully subsidize the service in an attempt to save and provide a convenient financial resources to maintain the hospitals and maintain the level of service.

Table (4-1) shows the characteristics of hospitals entered by the user that include age, area, number of floors, no of beds quantity, average occupation, average stay, service suspension and inflation rate. Tables (4-2) shows the individual rating for hospital 1 based on assessments of experts. The individual rating of hospitals 2,3 and 4 are shown in Appendix (C).

Table (4-3), shows the weights taken based on the experts opinion whom performed the condition assessment. Table (4-4) depicts the overall hospital rating matrix (OHRM). Table (4-5) depicts the OHI for hospitals.

Table 4-1: Hospital characteristics data

Items	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Age (years)	35	33	20	30
Area m^2	5200	3300	2900	3800
No of floors	5	4	4	4
No of beds	340	160	100	150
Quantity m^2	33800	17160	15080	19760
Average Occupation	70%	80%	90%	85%
Average Stay/ days	10	10	10	10
Service suspension	100%	100%	55%	100%
Inflation rate	8%			
Duration (months)	11	9	6	8

Table 4-2: Hospital 1 (Individual rating matrix)

Hospital 1			
Condition	Slab	Beams	Columns
1	8%	8%	15%
2	12%	15%	20%
3	25%	17%	10%
4	20%	25%	25%
5	35%	35%	30%

Table 4-3: Relative weights

Item	Weight%
Slab	50%
Beams	30%
Columns	20%
Sum	100%

Table 4-4: Overall Hospital Rating Matrix

Condition State	1	2	3	4	5
Hospital 1	10.50%	13.50%	18.50%	22.50%	35.00%
Hospital 2	15.36%	13.21%	20.43%	20.71%	30.29%
Hospital 3	21.79%	15.00%	21.43%	17.50%	24.29%
Hospital 4	15.88%	13.90%	20.12%	20.24%	29.86%

Table 4-5: The Overall Hospital Index (OHI)

Hospital	Overall Hospital Index
Hospital 1	3.58
Hospital 2	3.37
Hospital 3	3.08
Hospital 4	3.34

4.1.1 Backward Markov

These data entered will be stored in the database to be used by backward Markov and the optimization modules. The Overall Hospital Rating Matrix (OHRM) was used together with the age of hospitals to develop a transition matrix. Equation (3.3) in section 3.2.2 shows the calculation procedure for the $OHRM_c$ (calculated Overall Hospital Rating Matrix). The objective function was to minimize the error as stated in equation (3.4) of the same section. Decision variable was the diagonal probability conditions as shown in figure (3-3). The genetic algorithm optimization using Evolver add-in package to get the transition matrix as shown in table (4-6). The resulted transition matrix will be used in the rehabilitation cost optimization module.

Table 4-6: Resulted Transition Matrix

TPM	1	2	3	4	5
1	92.6%	7.4%	0.0%	0.0%	0.0%
2	0.0%	90.6%	9.4%	0.0%	0.0%
3	0.0%	0.0%	87.3%	12.7%	0.0%
4	0.0%	0.0%	0.0%	90.0%	10.0%
5	0.0%	0.0%	0.0%	0.0%	100.0%

4.1.2 RC Optimization module

Genetic algorithm was used to optimize the rehabilitation cost for all hospitals. Table (4-7) depicts the optimization parameters. The module has provided six rehabilitation strategies for all hospitals starting from year 2014 till year 2019. Table (4-8) summarize the results obtained for hospital (1) from optimization engine. In 2014, it was decided to rehabilitate 89% of components that require (reinforcement cleaning) and the same percentage for (partial concrete replacement and reinforcement) and 32% for (full concrete replacement and reinforcement). In 2015 the rehabilitation costs increased as more deterioration occurs, in addition the effect of inflation took place. The adopted rehabilitation strategy was more as it was decided to repair 92% for (reinforcement cleaning) and 94 % for (partial concrete replacement and reinforcement) and 33% for (full concrete replacement and reinforcement). In 2016 the cost increases due to the same reasons mentioned above, however the percentage rehabilitated in (reinforcement cleaning) and (partial concrete replacement and reinforcement) was less than the previous year. However, the percentage rehabilitated for (full concrete replacement and reinforcement) was more by 4% to be 36.5% as the unit cost for (full concrete replacement and reinforcement) is more expensive than the other options. The results of the other hospitals are available in Appendix (D). The crossover and mutation threshold was 90% and 10% respectively. The population number was 100 and the optimization engine will stop if the maximum change is not exceeding 0.01% for 500 trials.

Table 4-7: Rehabilitation cost optimization parameter

Rehabilitation Cost Optimization Module	
Objective	Minimize $RC_{x,y} = \sum_{i=1}^{c} Q_i$ x Rs x R x $(1+r)^n$
Variables	Rehabilitation Strategy “R”
Constraints	Overall Hospital Index (OHI) = 2.4
Results	6 rehabilitation strategies and their associated rehabilitation costs for all hospitals

Table 4-8: Rehabilitation Strategy for Hospital 1

Hospital 1	2014	2015	2016	2017	2018	2019
Reinforcement cleaning	89.57%	91.86%	90.81%	89.77%	89.94%	84.40%
Partial concrete replacement and reinforcement	89.45%	94.28%	92.11%	89.94%	90.00%	89.62%
Full concrete replacement and reinforcement	32.62%	33.18%	36.45%	39.71%	41.60%	44.08%
Rehabilitation Cost (EGP)	15,981,868	16,911,624	18,273,468.99	19,635,313	20,874,841	22,249,134

4.1.3 Multi-objective optimization for rehabilitation schedule

After obtaining results of the rehabilitation strategies for each hospital. This module will schedule the rehabilitation of different hospitals. Consequently, it will provide the number of un-served patients and modified rehabilitation cost. Genetic algorithms were used in optimizing schedule for rehabilitation, the cross-over and mutation thresholds were 90% and 10% respectively, population number was 100 chromosomes and termination condition is achieving 500 trials with maximum change 0.01%. Table (4-9) depicts the rehabilitation scheduling optimization formulation. Pareto frontier was used to represent the optimal solutions, Pareto optimality is used for accounting multi-objective optimization (Marzouk and Moselhi, 2004). Figure (4-1) depicts the results obtained from the module with the Pareto frontier showing the optimal solutions. NEHIR model provided 200 solutions where 9 solutions formed the Pareto frontier representing the most feasible solutions among the others. The modified rehabilitation cost is affected mainly by the decision time simply because deciding to repair later will end up with higher costs due to inflation and increase in deterioration and vice versa. Moreover, the model was subject to a sum per year (EGP 20,000,000) and a maximum un-served patients per year (5000) which was also affecting the modified rehabilitation cost. On the other hand early or late rehabilitation decision was not having a direct impact on the number of un-served patients. However, they are affected by the number of hospitals rehabilitated at a certain time interval, which is represented by the overlapping percentage. Table (4-10) depicts the feasible solution details regarding cost and number of unserved patients.

Table 4-9: Scheduling optimization formulation

Optimization Parameters	
Objective 1	Minimize TNSP = $\sum_{x=1}^{h} APH_x - SPH_x$
Objective 2	Minimize TMRC = $\sum_{x=1}^{h} \sum_{j=1}^{72} RC_{xym}$
Variables	Starting dates of rehabilitation works (1-72)
Constraints	• Maximum budget per year = EGP 20,000,000 • Maximum un-served patients/year < 5000 persons

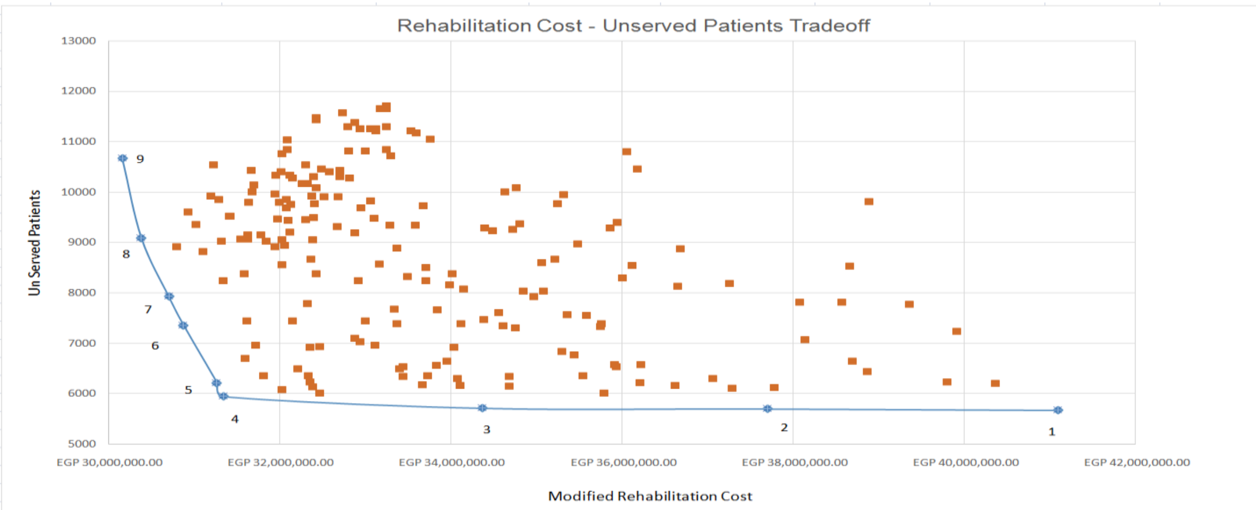

Figure 4-1: Pareto frontier for modified rehabilitation cost and un-served patients

Table 4-10: Pareto frontier points

ID	Un-Served Patients	Modified Rehabilitation Cost (EGP)	Total Rehabilitation Duration/days	Overlapping %
1	5671	EGP 41,091,146.84	1020	0%
2	5701	EGP 37,705,679.97	1765	1.70%
3	5711	EGP 34,372,560.84	1339	2.24%
4	5946	EGP 31,344,383.25	1065	5.63%
5	6216	EGP 31,267,543.16	1037	17%
6	7359	EGP 31,098,233.69	884	20%
7	7926	EGP 30,709,131.45	1550	21.3%
8	9084	EGP 30,385,162.33	1065	22.6%
9	10671	EGP 30,164,810.77	580	87.9%

4.1.3.1.1 Case one (Total un-served Patients = 5946, OHI =2.4)

In this part, point 4 in table (4-10) was selected to demonstrate the capabilities of the model. Figure (4-2) shows the schedule resulted for hospitals rehabilitation. Table (4-11) depicts the rehabilitation strategies and the associated rehabilitation cost for every hospital. Table (4-12) depicts the patients distribution among hospitals during rehabilitation.

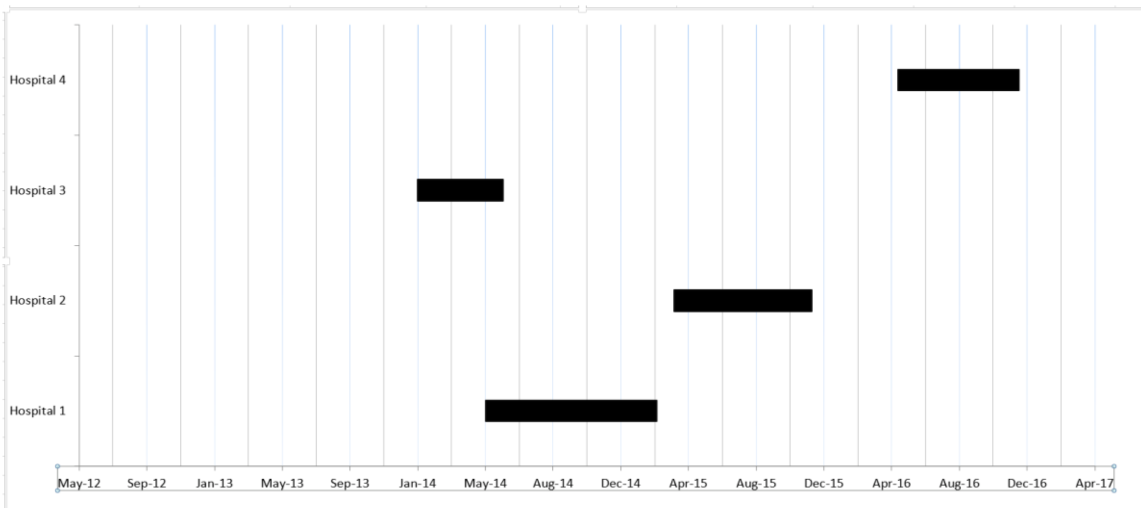

Figure 4-2: Schedule chart for case 1

Table 4-11: Rehabilitation strategy for case 1

Rehabilitation Strategy				
Item	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Rusting repair	90.20%	89.15%	94.76%	89.50%
Minor Reinforcement & Concreting	90.77%	89.97%	58.61%	88.48%
Major Reinforcement & Concreting	32.77%	12.02%	0.0%	16.63%

Table 4-12: Patients distribution for Case 1

Patients Distribution	Hospital 1	Hospital 2	Hospital 3	Hospital 4	Sum Served	Available Beds	Unserved Patients
Jan-14	782	405	165	394	1746	2085	0
Feb-14	782	405	165	394	1746	2085	0
Mar-14	782	405	165	394	1746	2085	0
Apr-14	782	405	165	394	1746	2085	0
May-14	0	480	165	450	1095	1065	651
Jun-14	0	480	165	450	1095	1065	651
Jul-14	0	480	300	450	1230	1230	516
Aug-14	0	480	300	450	1230	1230	516
Sep-14	0	480	300	450	1230	1230	516
Oct-14	0	480	300	450	1230	1230	516
Nov-14	0	480	300	450	1230	1230	516
Dec-14	0	480	300	450	1230	1230	516
Jan-15	0	480	300	450	1230	1230	516
Feb-15	0	480	300	450	1230	1230	516
Mar-15	0	480	300	450	1230	1230	516
Apr-15	1002	0	298	446	1746	1770	0
May-15	1002	0	298	446	1746	1770	0
Jun-15	1002	0	298	446	1746	1770	0
Jul-15	1002	0	298	446	1746	1770	0
Aug-15	1002	0	298	446	1746	1770	0
Sep-15	1002	0	298	446	1746	1770	0
Oct-15	1002	0	298	446	1746	1770	0
Nov-15	1002	0	298	446	1746	1770	0
Dec-15	1002	0	298	446	1746	1770	0
Jan-16	714	384	270	378	1746	2250	0
Feb-16	714	384	270	378	1746	2250	0
Mar-16	714	384	270	378	1746	2250	0
Apr-16	714	384	270	378	1746	2250	0
May-16	982	468	296	0	1746	1800	0
Jun-16	982	468	296	0	1746	1800	0
Jul-16	982	468	296	0	1746	1800	0
Aug-16	982	468	296	0	1746	1800	0
Sep-16	982	468	296	0	1746	1800	0
Oct-16	982	468	296	0	1746	1800	0
Nov-16	982	468	296	0	1746	1800	0
Dec-16	982	468	296	0	1746	1800	0
Jan-17	714	384	270	378	1746	2250	0

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4.2 NEHIR model Validation

The actual scenario of the four projects was considered and compared with the Pareto frontier resulted from NEHIR model. Table (4-13) and figure (4-3) depict the starting and end dates. The starting dates were entered to NEHIR model and results obtained from this scenario was compared with the Pareto frontier of NEHIR model. The resulted rehabilitation cost was EGP 37,401,815 and the number of unserved patients were 7930 with rehabilitation duration of 884 days. The actual scenario was compared with the nine points of the Pareto frontier showed in figure (4-4). Point (9) was having less rehabilitation time (580 days or 20 months) and less rehabilitation cost (EGP 30,164,810), however the number of unserved patients is greater (10671). Point (8) was having less rehabilitation cost (EGP 30,385,162) but higher rehabilitation duration (1065 days or 35 months) and greater number of unserved patients (9084) compared to the actual scenario. Point (6) is the most feasible option in comparison with the actual scenario. Point (6) has almost the same rehabilitation duration (884 days) in addition it had less rehabilitation cost of EGP (31,098,233.69) and less number of unserved patients (7359) compared to the actual scenario. Since the overlapping percentage of the actual scenario is 26% unlike point (6) which has an overlapping percentage of 20% hence the number of unserved patients were less in point (6). In addition, the rehabilitation cost of the actual scenario was greater by almost EGP 6 million. The reason for this is that hospital (1) & hospital (4) began later by 2 months in the actual scenario. Delaying the rehabilitation means more deterioration and higher costs due to inflation as explained earlier. Consequently, NEHIR model provided better option compared to the actual scenario. Figure (4-5) and table (4-14) show the schedule and starting dates of the proposed option (point 6).

Table 4-13: Actual scenario starting dates for projects

Project	Starting date	Finishing date
Hospital 1	March 2014	January 2015
Hospital 2	October 2014	June 2015
Hospital 3	April 2015	September 2015
Hospital 4	January 2016	August 2016

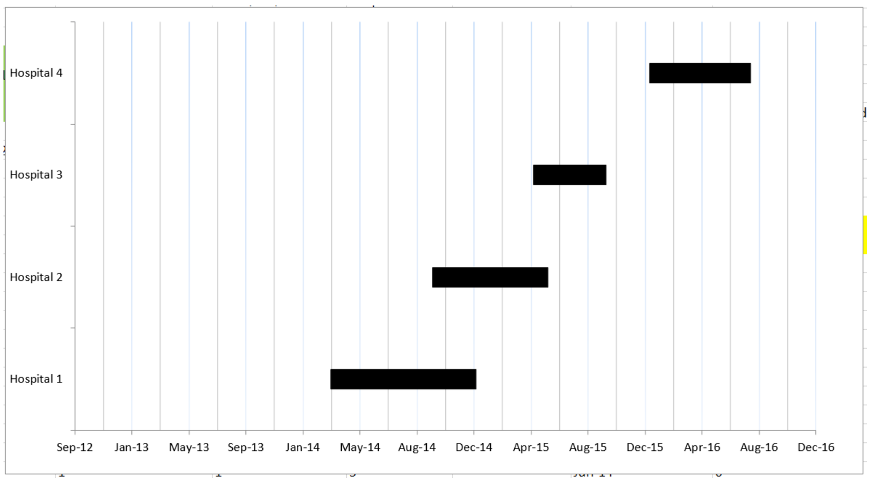

Figure 4-3: Actual scenario Chart

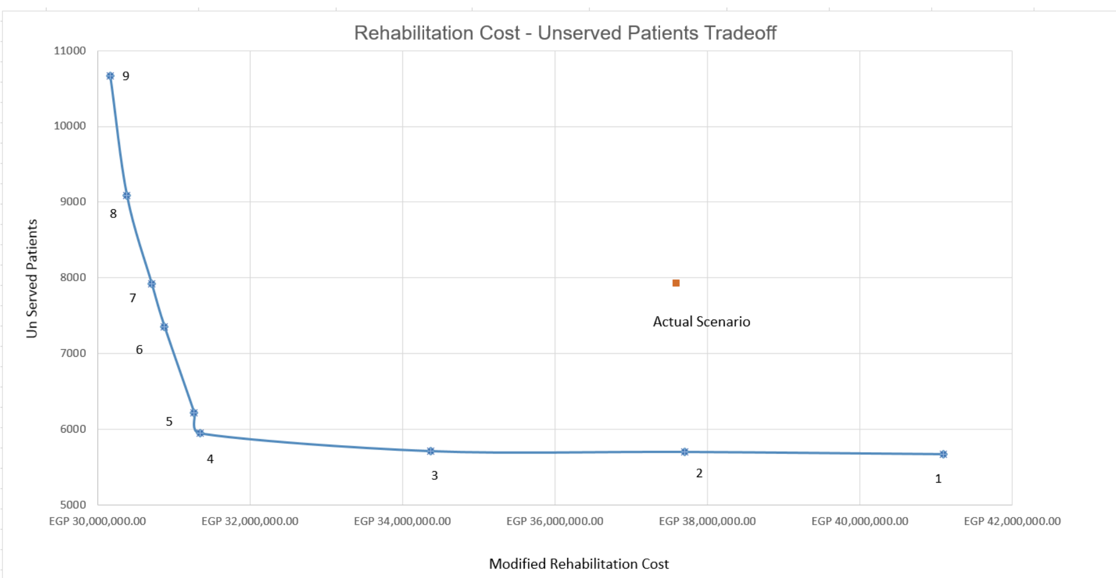

Figure 4-4: NEHIR Pareto frontier vs actual scenario

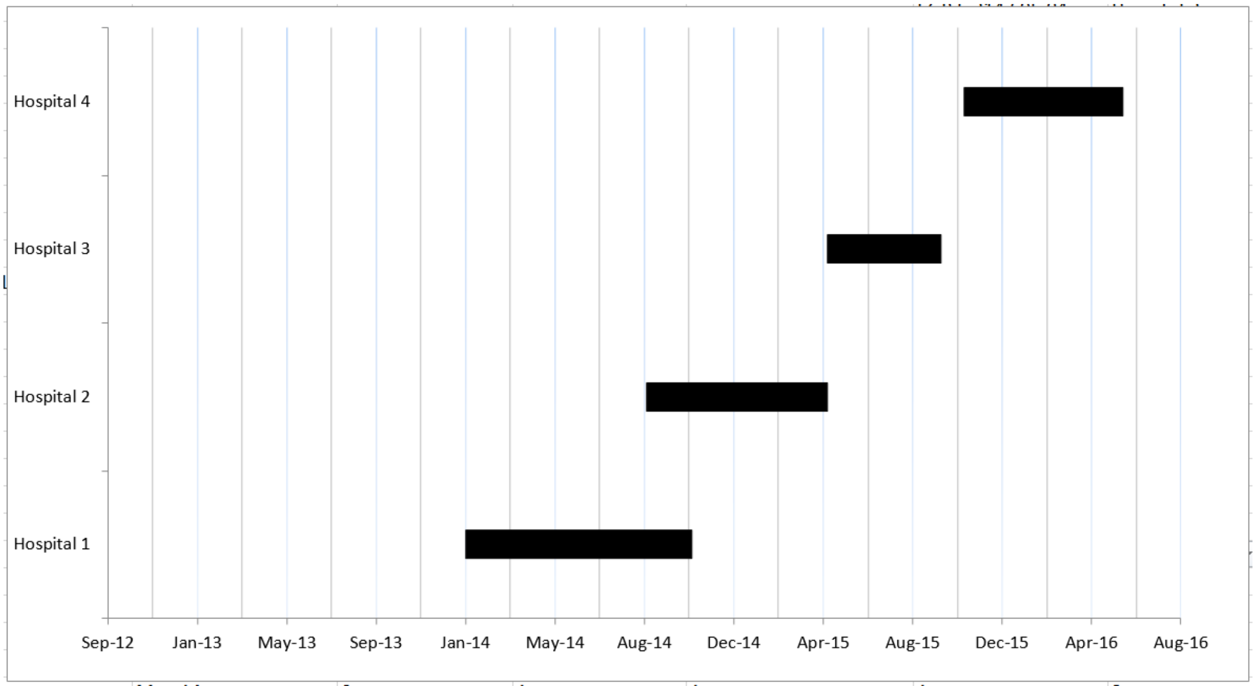

Figure 4-5: Proposed Chart by NEHIR model

Table 4-14: Proposed Option dates

Project	Starting date	Finishing date
Hospital 1	January 2014	November 2014
Hospital 2	September 2014	May 2015
Hospital 3	April 2015	September 2015
Hospital 4	November 2015	June 2016

4.3 HOREM Model verification and validation

Hospital (1) in table 4-1 was taken as a case study for the application & verification and validation purposes of HOREM model. As mentioned the hospital contains 340 beds including the regular rooms, emergency units, intensive care units in addition to five operating units. The hospital is being served by a medical gas system that includes central oxygen plant and medical air compressor. Moreover, five air handling units for serving the ORs and ICUs, in addition to twenty two air handling unit for the remaining rooms. Furthermore, six elevators were used for the vertical transportation to and from the operating units, intensive care units and regular rooms.

Genetic algorithms optimization engine was used and applied on results obtained from Monte-Carlo simulation module and fuzzy logic system.

4.3.1 HOREM Results analysis

Monte-Carlo simulation was used to simulate the p-f interval given by the experts to identify the probability of failure of different inspection intervals. Appendix (E) depict the results obtained from Monte-Carlo simulation module which has formed 500 iterations with uniform distribution of p-f intervals. The probability of failure is calculated using these tables, consequently the Expected Downtime (EDT) is derived. Increasing the inspection interval will have higher probability of failure hence, more expected downtime.

Fuzzy logic system was used to simulate the probability of failure given a certain operating conditions determined by the user. Fuzzy logic system was applied on the failure modes that require preventive maintenance which are saturated pre-filters and saturated secondary filters. Figures (4-6 to 4-11) show results obtained by fuzzy logic system given that the location is moderately acceptable and a workload of twenty hours. Results explain the effect of age on pre-filter given a several application of washing intervals. Washing pre-filters ensure better performance and less prone to failure. The second step is to get the average probability of failure for each washing interval as shown in tables (4-15 to 4-26) and figure (4-12). The average probability of failures are then expressed against the washing intervals as shown in figure (4-13).

Figure (4-14) depicts the results of applying fuzzy logic system on secondary filter replacement. The same operating context (location and working hours) was considered. The probability of failure is constant for the first five months which is considered as the useful life. Exceeding this useful life will make the filter vulnerable to higher probability of failure. Experts have ensured that the pattern of failure obtained from fuzzy logic system for pre-filter is representing the actual behavior to some extent, the failure pattern is similar to (type F) as shown in figure (2-12). However experts suggested some trial tests to double check and compare results obtained. On the other hand, failure pattern of secondary filter that is similar to (type A) as shown in figure (2-13) and was similar to experts view. The results shows that the average useful life of the filter is almost five months which mimics the reality and shows that leaving the filter un-replaced over this period will increase the probability of failure.

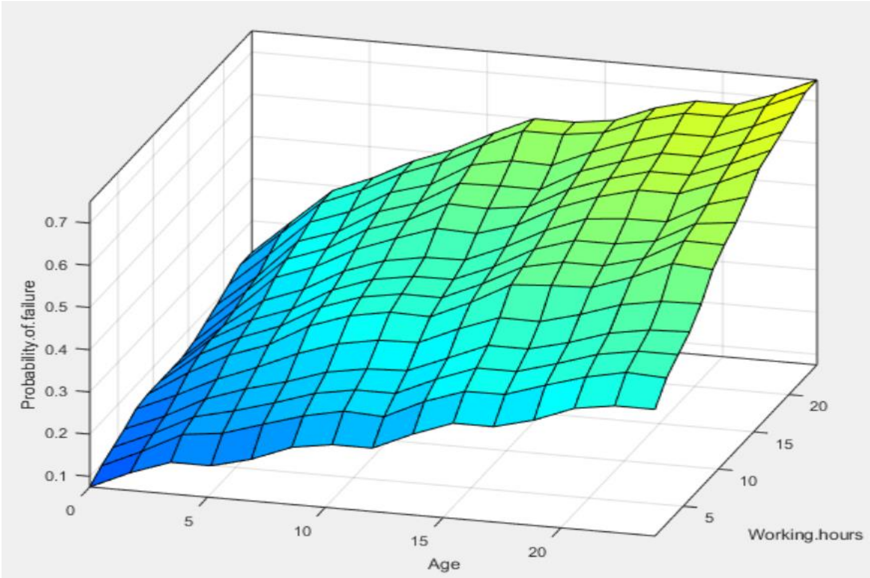

Figure 4-6: Working hours and age (months) vs Probability of failure (Pre-filter)

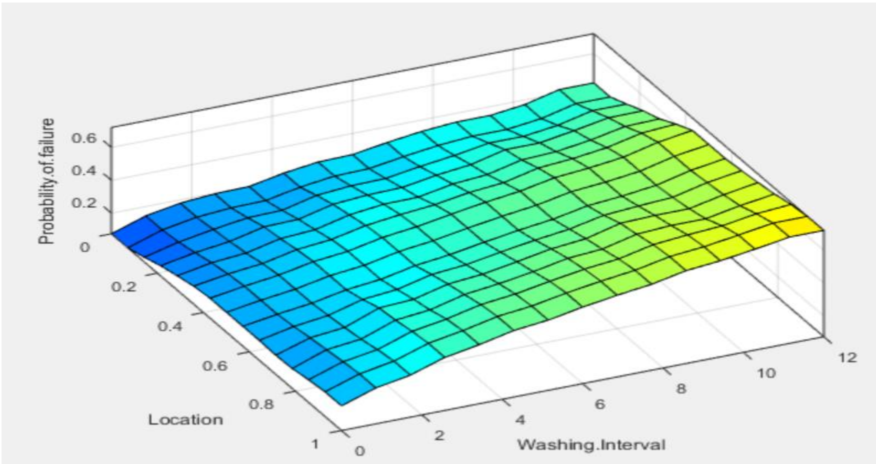

Figure 4-7: Location (AQI) and washing interval (month) vs probability of failure (Pre-filter)

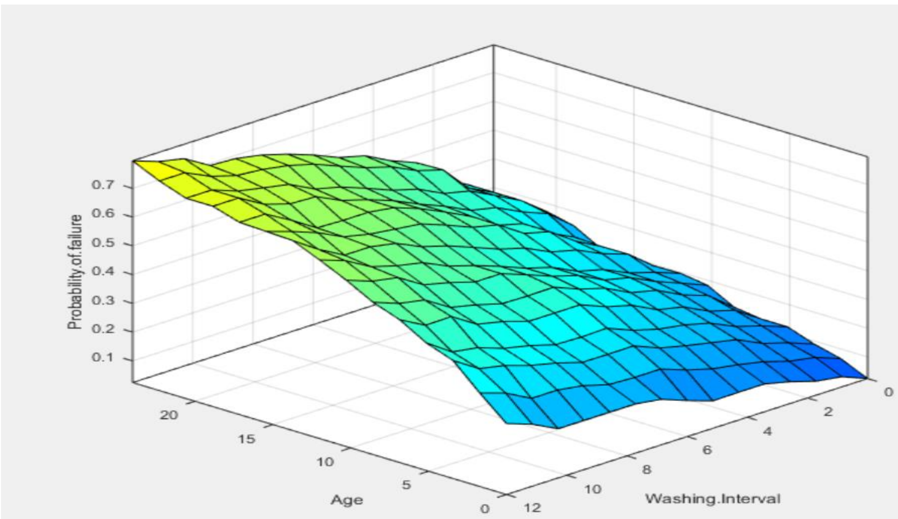

Figure 4-8: Age (months) and Washing interval (months) vs Probability of failure (Pre-filter)

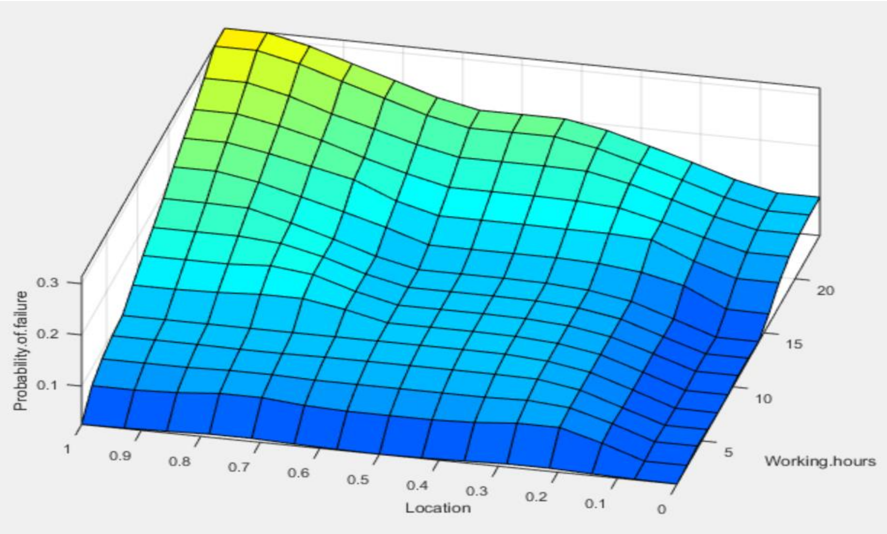

Figure 4-9: Working hours and Location (AQI) vs Probability of failure (Secondary filter)

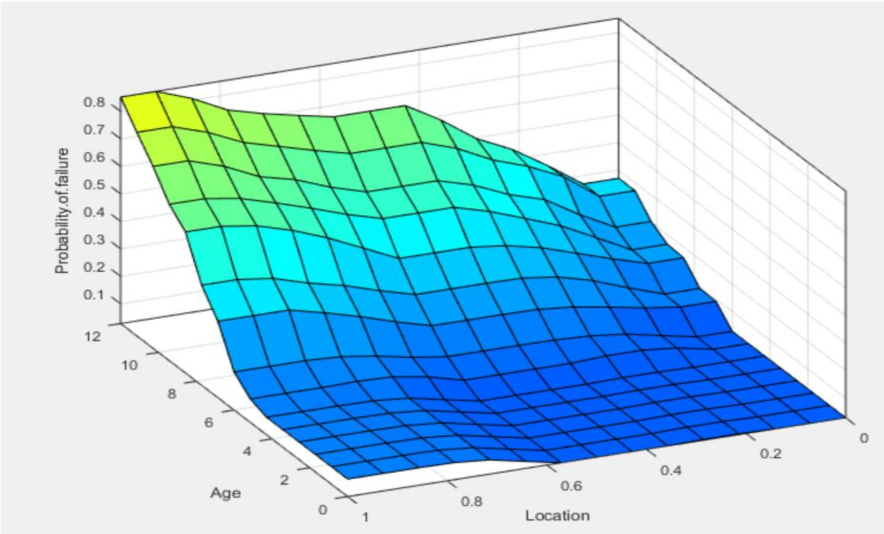

Figure 4-10: Age (months) and Location (AQI) vs Probability of failure (Secondary filter)

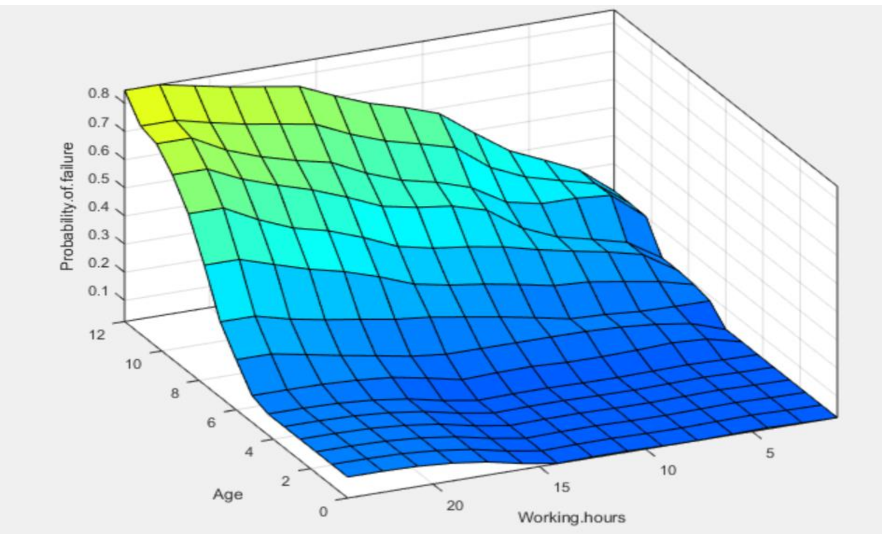

Figure 4-11: Age (months) and working hours vs Probability of failure (Secondary filter)

Table 4-15: Average Probability of failure at washing interval = 1 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.106	0.113	0.141	0.159	0.187	0.211	0.225	0.229	0.236	0.24	0.26	0.183

Table 4-16: Average Probability of failure at washing interval = 2 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.15	0.176	0.197	0.225	0.252	0.272	0.29	0.301	0.31	0.32	0.226

Table 4-17: Average Probability of failure at washing interval = 3 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.216	0.233	0.263	0.291	0.308	0.312	0.322	0.33	0.34	0.252

Table 4-18: Average Probability of failure at washing interval = 4 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.273	0.3	0.328	0.348	0.358	0.364	0.38	0.38	0.283

Table 4-19: Average Probability of failure at washing interval = 5 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.338	0.368	0.384	0.4	0.408	0.41	0.41	0.309

Table 4-20: Average Probability of failure at washing interval = 6 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.397	0.42	0.432	0.439	0.45	0.45	0.329

Table 4-21: Average Probability of failure at washing interval = 7 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.407	0.43	0.44	0.467	0.48	0.49	0.339

Table 4-22: Average Probability of failure at washing interval = 8 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.407	0.44	0.45	0.48	0.5	0.53	0.346

Table 4-23: Average Probability of failure at washing interval = 9 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.407	0.44	0.487	0.517	0.53	0.56	0.357

Table 4-24: Average Probability of failure at washing interval = 10 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.407	0.44	0.487	0.552	0.57	0.6	0.366

Table 4-25: Average Probability of failure at washing interval = 11 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.407	0.44	0.487	0.552	0.65	0.67	0.378

Table 4-26: Average Probability of failure at washing interval = 12 month

Age	1	2	3	4	5	6	7	8	9	10	11	12	Average Probability of Failure
Probability of failure	0.09	0.123	0.187	0.25	0.309	0.375	0.407	0.44	0.487	0.552	0.65	0.68	0.380

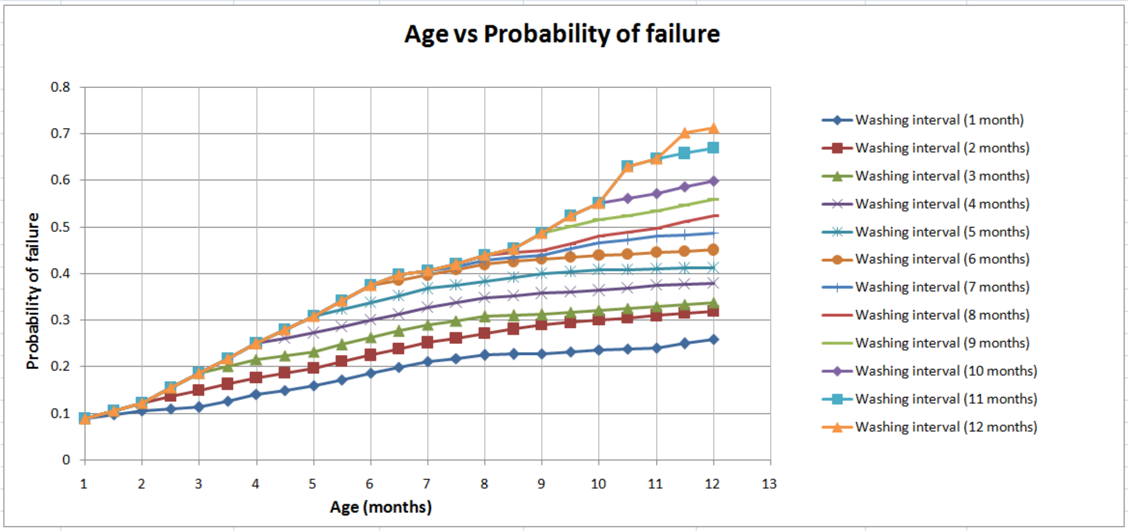

Figure 4-12: Age vs probability of failure

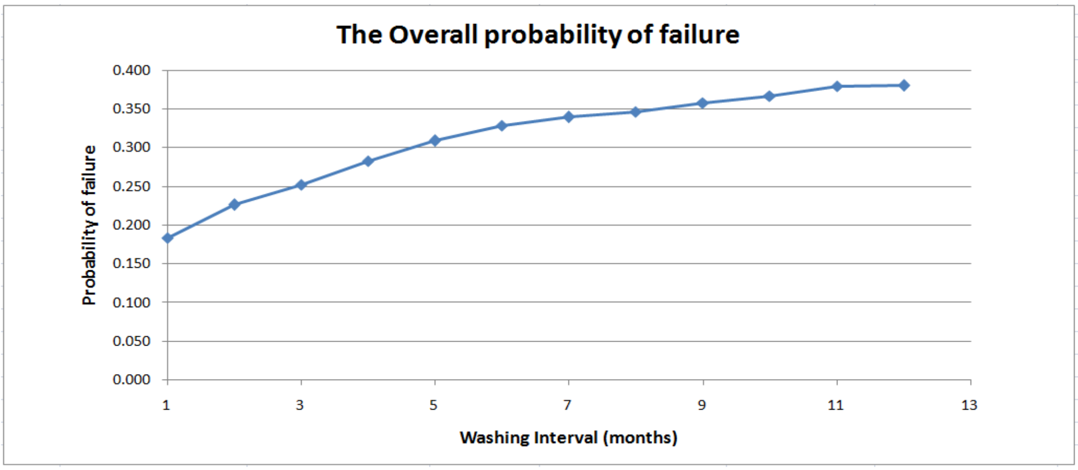

Figure 4-13: Overall probability of failure

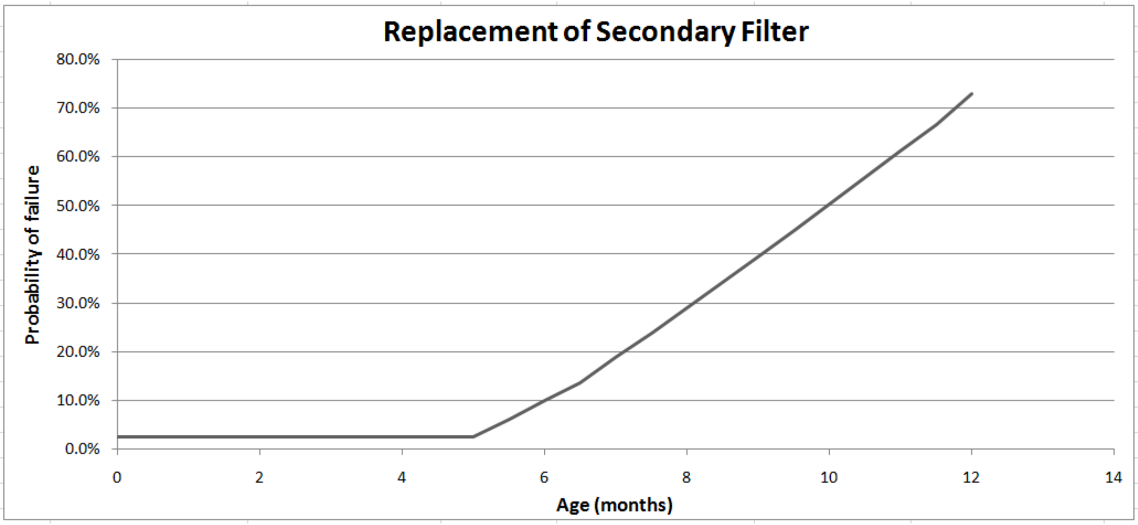

Figure 4-14: Replacement of secondary filter

4.3.2 Maintenance plan development

Results obtained from the fuzzy logic system and Monte-Carlo simulation were used to provide a tradeoff between the maintenance cost (equation 3.24) and the EDT (equation 3.27) using genetic algorithm. As mentioned, the decision variable is set to be the replacement/restoration and inspection intervals which will result in a probability of failure hence the (EDT) is calculated together with the maintenance and inspection costs. The population size was set to be 100, the crossover and mutation threshold were 90% and 10% respectively and the termination condition is to achieve 500 trials with maximum change 0.01%.

The following figures (4-15 to 4-18) depict the results obtained from the optimization engine for the four systems. The results indicate a direct relation between the maintenance cost and the (EDT), as increasing the maintenance budget will be reflected on the performance of these systems by reducing the hours of service suspension and vice versa. Table (4-27) shows the maintenance plan for primary HVAC that will result in a total maintenance cost of EGP 274,200 and EDT of 46 hours. However, for practical application it was suggested to approximate the inspection intervals so that to reduce the mobilization cost of the inspection crews. In this context, the inspection crew can inspect for several failure modes of different components per visit without violating the original maintenance plan developed. The same table (4-27) depicts the modified inspection intervals, this plan will result in 8% decrease in EDT to be 42 hours instead of 46 hours of the original one, in addition the maintenance cost will be increased compared to the original one by 3% to be EGP 282,500.

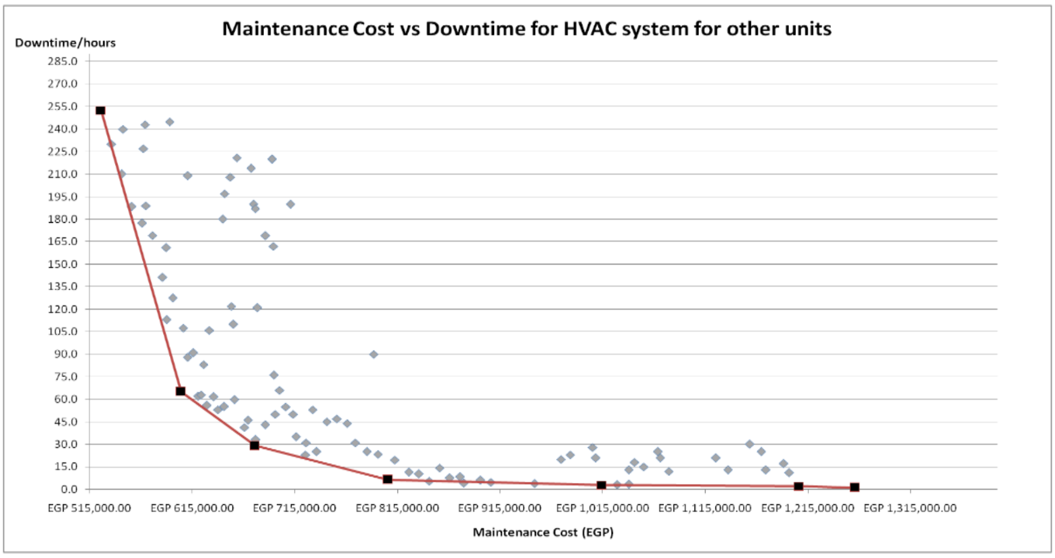

Figure 4-15: Pareto frontier for secondary HVAC system

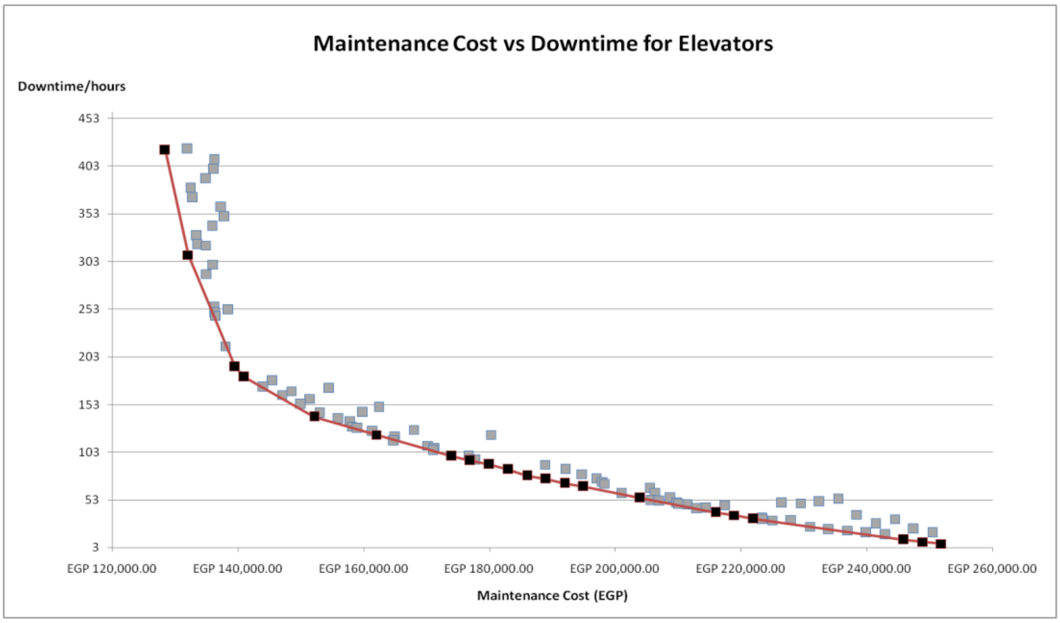

Figure 4-16 Pareto frontier for Elevators

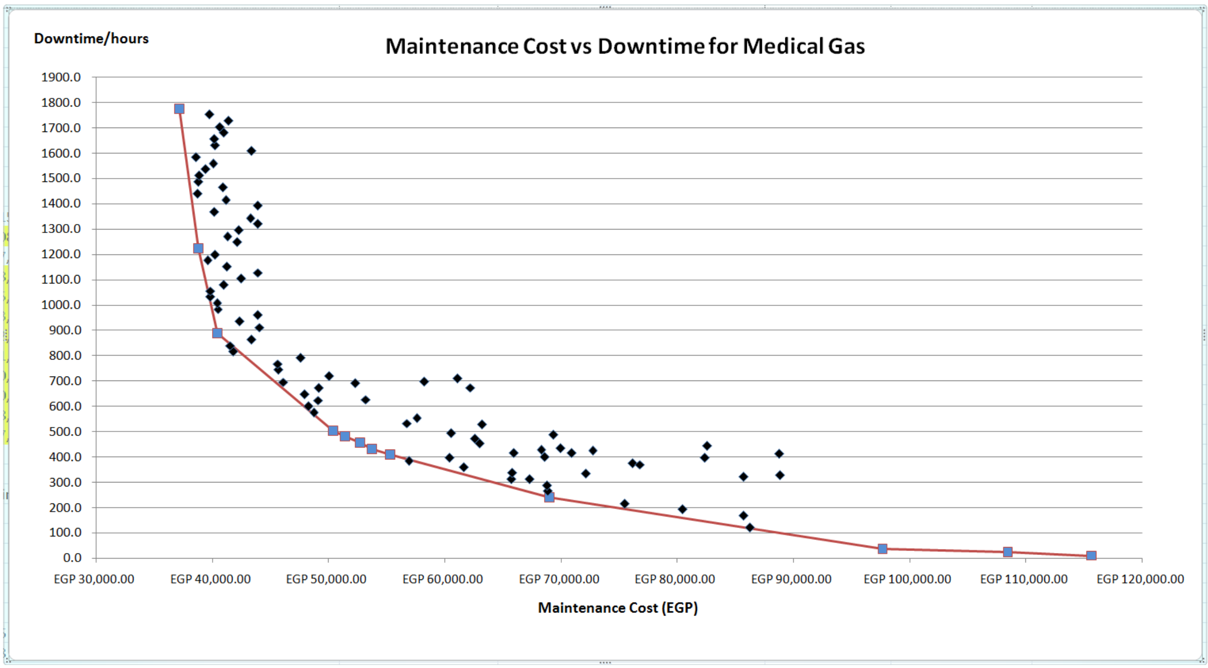

Figure 4-17: Pareto frontier for Medical Gas system

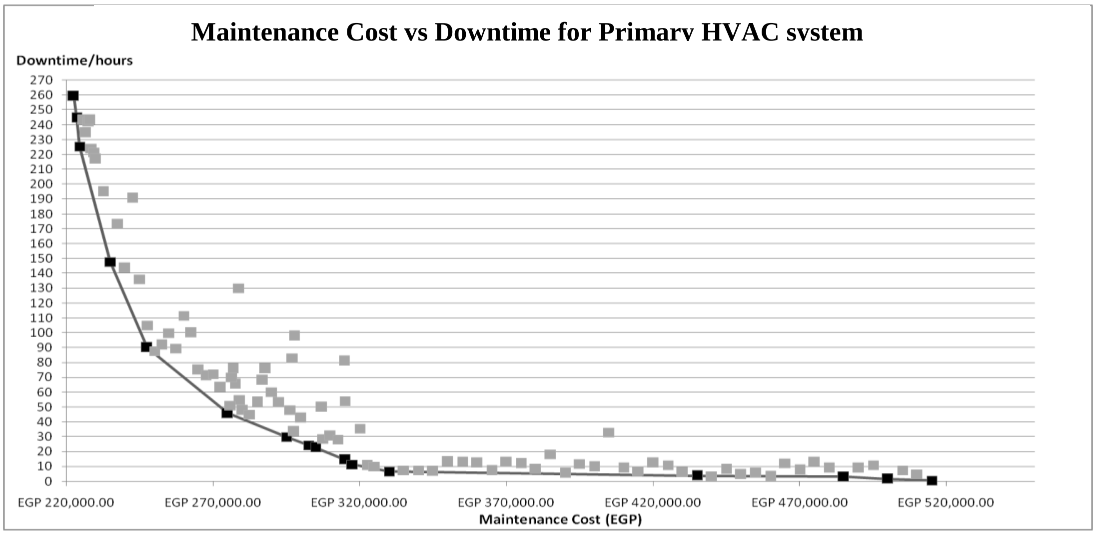

Figure 4-18: Pareto frontier for primary HVAC

Table 4-27: Maintenance plan Option for Primary HVAC

Component	Failure mode	Action	Original intervals	Approximated intervals
Pre-filter	Saturated filter	Restoration	3 months	3 months
Secondary filter	Saturated filter	Replacement	5 months	5 months
Pre-filter	Torn Filter		20 days	20 days
Secondary Filter	Torn Filter		19 days	20 days
Cooling Coil	Coil leaks		61 days	60 days
Cooling Coil	Freon gas pipe leaks		37 days	40 days
Blower	Defective fan belt		43 days	40 days
Blower	Shaft bent		31 days	30 days
Blower	Ball bearing fatigue		60 days	60 days
Blower	Impellers Fatigue		62 days	60 days
Axial Blower	Defective fan belt	Inspection	43 days	40 days
Axial Blower	Bent Shaft		60 days	60 days
Axial Blower	Impellers Fatigue		83 days	80 days
Axial Blower	Ball bearing fatigue		77 days	80 days
HEPA Filter	HEPA Filter leaks		14 days	15 days
Blower	Bearing improper lubrication		18 days	20 days
Axial Blower	Bearing improper lubrication		28 days	30 days

4.3.3 HOREM Validation

Maintenance contractor proposed maintenance costs with the associated downtime estimated for primary and secondary HVAC, Elevators and Medical gas systems. The maintenance costs include the inspections costs and cost of replacing the components that require preventive maintenance e.g. (secondary filter replacement). Table (4-28) depicts the contractor's proposals for maintaining the primary HVAC systems and their associated downtime. The proposals were plotted compared with the Pareto frontier resulted from HOREM model as shown in figure (4-19).

Table 4-28: Maintenance contractor proposals for Primary HVAC

Maintenance cost (EGP)	Downtime (hours)
320,000	50
280,000	100
250,000	150

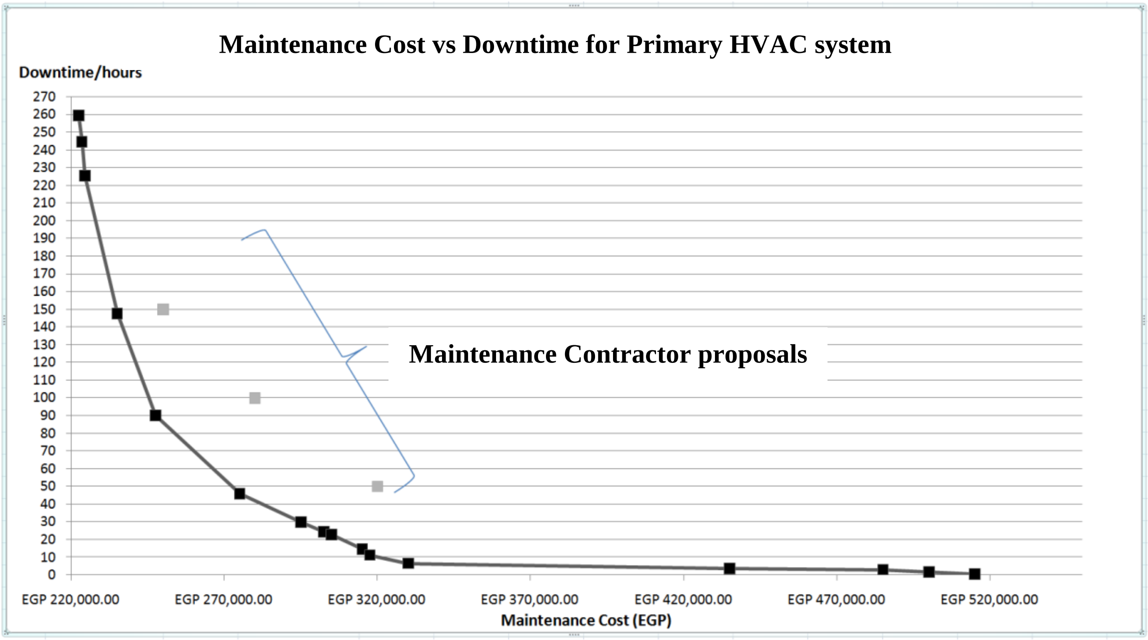

Figure 4-19: Validation for Primary HVAC

Maintenance contractor proposed a maintenance cost of EGP 320,000 for a downtime of 50 hours for every AHU. However HOREM model proposed EGP 270,000 for the same downtime. Moreover HOREM model provided a maintenance cost of EGP 250,000 for downtime of 100 hours while the contractor estimated his cost to be EGP 280,000. HOREM provided a maintenance cost of EGP 235,000 for downtime of 150 hours which was more feasible than contractor's proposal (EGP 250,000).

As for the elevators, table (4-29) depicts the maintenance contractor proposals for maintaining the six elevators of the hospital. HOREM model provided a maintenance cost of EGP 204,000 for a downtime of 50 hours. However, contractor proposed EGP 230,000 for the same downtime. In the same context, contractor proposed EGP 190,000 for a downtime of 100 hours which was more than the one proposed by HOREM model (EGP 170,000). Figure (4-20) depicts the contractor's proposals against the Pareto frontier.

Table 4-29: Maintenance contractor proposals for Elevators

Maintenance cost (EGP)	Downtime (hours)
230,000	50
190,000	100
160,000	150

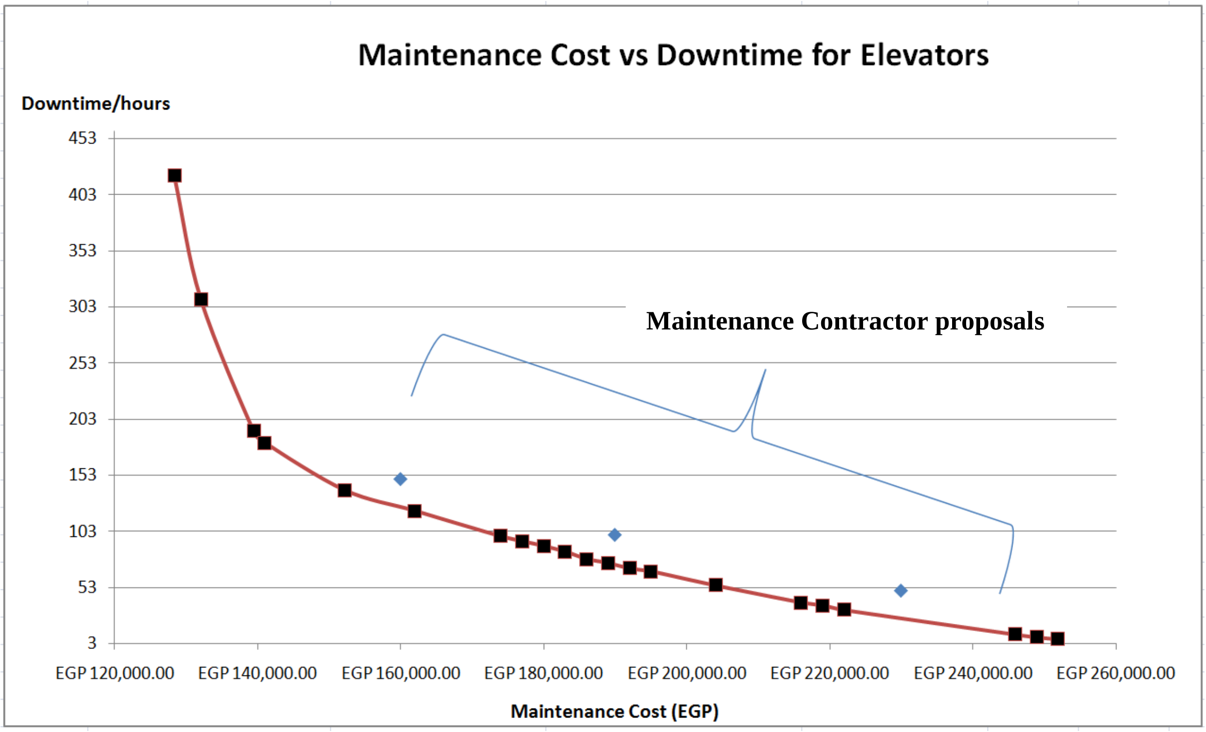

Figure 4-20: Validation for Elevators

As for the secondary HVAC, table (4-30) depicts the maintenance contractor proposals for maintaining the secondary HVAC system of the hospital. The contractor proposed a maintenance cost of EGP 680,000 for a downtime of 50 hours. However HOREM provided the same amount for a downtime of 30 hours. Moreover, HOREM model provided a maintenance cost of EGP 625,000 for 70 hours while the contractor provided the same amount for 100 hours. Figure (4-21) depicts the contractor's proposals against the Pareto frontier of secondary HVAC.

Table 4-30: Maintenance contractor proposals for Secondary HVAC

Maintenance cost (EGP)	Downtime (hours)
680,000	50
620,000	100
580,000	150

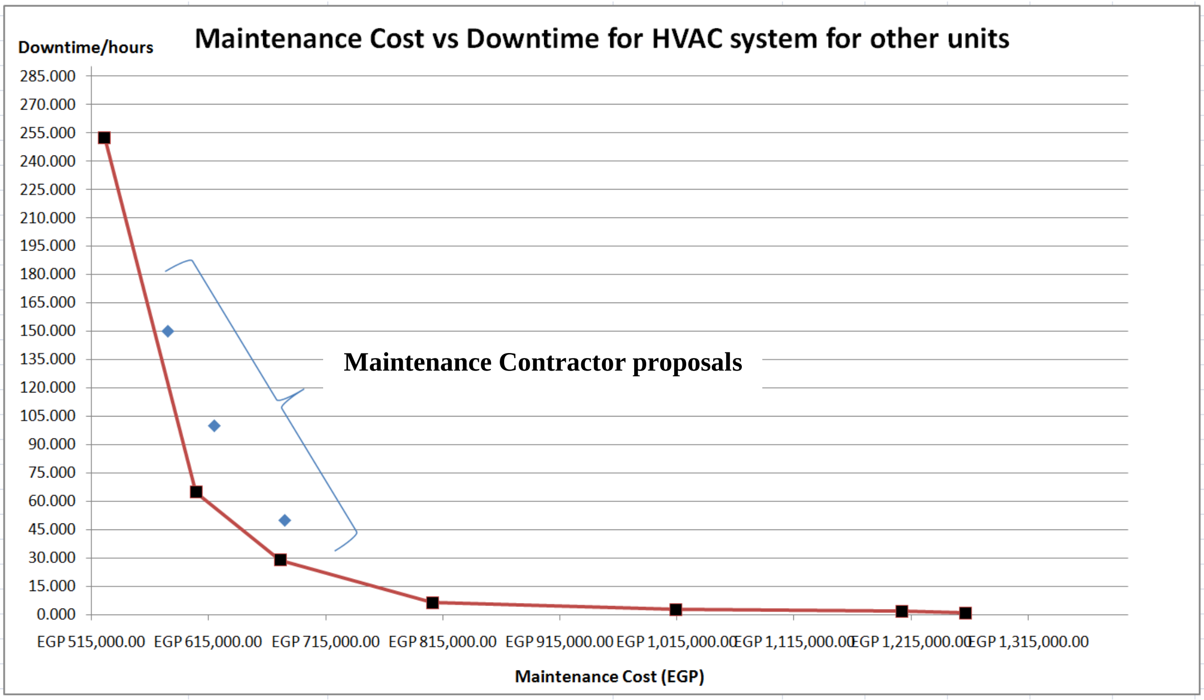

Figure 4-21: Validation for Secondary HVAC

Regarding Medical gas system, table (4-31) depicts the maintenance contractor proposals for maintaining the medical gas system of the hospital. The contractor proposed a maintenance cost of EGP 128,000 for a downtime of 10 hours. However HOREM provided a maintenance cost of EGP 114,000 for almost the same downtime. Moreover, HOREM model provided a maintenance cost of EGP 107,043 for downtime of 24 hours while contractor proposed EGP 118,000 for the same downtime hours. Figure (4-22) depicts the contractor's proposals against the Pareto frontier of Medical gas system. Consequently, HOREM model provided better options through adopting more optimized maintenance plans than the common practice. This is due to the fact that RCM approach minimize the unnecessary equipment inspections and overhauls that is adopted by traditional methods (Moubray, 1997).

Table 4-31: Maintenance contractor proposals for Medical gas system

Maintenance cost (EGP)	Downtime (hours)
128,000	10
116,000	24
107,000	36

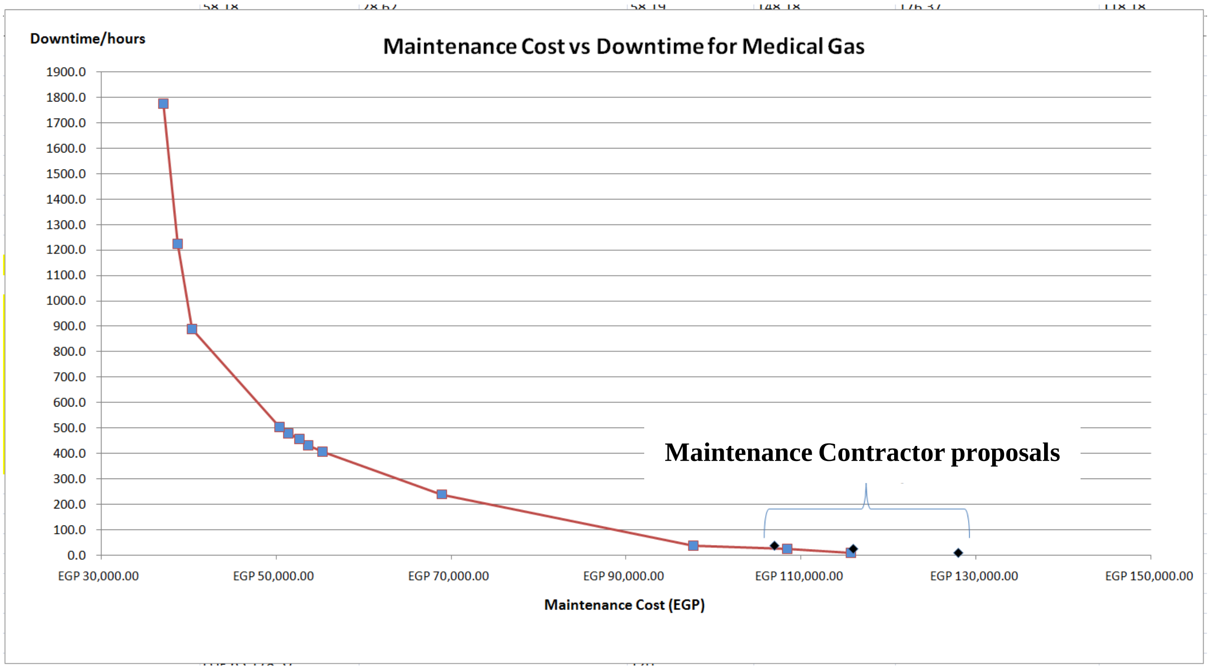

Figure 4-22: Validation for Medical gas

4.3.4 Systems Integration

In this part the research proposes a methodology for distributing the maintenance budget among the hospital systems. The estimated patients per month for the four types of units (RRs, ORs, ICUs and ERs) as mentioned earlier were considered as shown in table (4-32). In addition table (4-33) depicts the degree of criticality that was determined according to table (3-28) in section 3.3.4 for the intensive care units, regular rooms, emergency rooms and operating rooms. As a result the Average Patients Served per hour by each system (APS) will be calculated as shown in table (4-34) according to equation (3.28). Solutions formed by the multi-objective maintenance optimization module (maintenance cost and their associated expected downtime) were fed into the systems integration optimization module in order to calculate the total un-served patients for every solution according to equation (3.29).

Genetic algorithm was used in optimization where the population size was set to be 100, the cross over and mutation threshold were 90% and 10% respectively and the termination condition is to achieve 500 trials with maximum change 0.01%. Based on the level of service contribution, medical gas system has the greatest contribution to the level of service followed by the elevators followed by the primary HVAC and finally the secondary HVAC. Based on the solutions obtained from the maintenance optimization module, the maximum maintenance budget that provide the minimum expected downtime for primary HVAC, secondary HVAC, medical gas system and elevators are EGP 515,000.00, EGP 1,261,200.00, EGP 114,000 and EGP 251,918.46 respectively. Table (4-35) shows the results obtained by the optimization of budget allocation. The results were logical as the priority was given to the systems that highly contribute to the service delivered. The budget allocated to the medical gas system was EGP 105,541.34 which covers 92.6% of the maximum maintenance budget, followed by the elevators which was given EGP 187,500 that covers 74.4% of the maximum maintenance budget, then primary HVAC which was given EGP 365,650.77 that covers almost 71% of maximum maintenance budget, and finally the secondary HVAC was given EGP 794,556 that covers 63% of the maximum maintenance.

Table 4-32: Patients per month

Item	Patients
Average patients/ month for ICUs	1000
Average patients/ month for ERs	600
Average patients/ month for RRs	2000
Average patients/ month for ORs	1200
Maintenance Budget (EGP)/year	1,500,000

Table 4-33: Degree of criticality

Item	Elevators	Primary HVAC	Secondary HVAC	Medical Gas
ICU	1	1	0	1
ER	0	0	1	1
DR	0.5	0	0.5	1
OR	1	1	0	1

Table 4-34: APS/hour for hospital systems

System	Elevators	Primary HVAC	Secondary HVAC	Medical Gas
APS	4	3	2	7

Table 4-35: Results obtained by integrating system engine

Item	Elevators	Primary HVAC	Secondary HVAC	Medical Gas
% of Budget	12.5%	24.4%	52.9%	7.04%
% of Max maintenance cost required	74.4%	71%	63%	92.58%
Amount allocated (EGP)	187,500	365,650.77	794,556	105,541.34
Total Cost	EGP 1,453,247			
Total un-served patients	512			

4.3.5 What if Scenario

According to what was discussed in previous chapters in addition to the vision of the author that was explained in the model proposed, it is clear that maintaining the hospital systems is quite critical factor in keeping and improving the service provided to the patients. HOREM model provided a detailed study based on reliability centered maintenance, Monte-Carlo simulation and fuzzy logic system, in addition to the optimization engine that enhanced the capabilities of the model in providing near optimum solutions to the decision maker. HOREM model has provided an annual maintenance plan specifying the inspection and maintenance intervals for each failure mode together with associated expected down time and costs.

However, applying these plans precisely might not find the full support from the top management due to the presence of different inspection intervals for each failure mode and item. Consequently, in this section a sensitivity analysis is conducted by applying a fixed inspection interval to the whole system and find out the resulted maintenance cost and the expected downtime.

Figures (4-23 and 4-24) show the inspection costs and EDT resulted from applying a specific inspection interval for all the items of every system. For example, if the management decided to perform a regular maintenance every 40 days for the primary HVAC, the resulted inspection cost will be EGP 273,200 and the EDT will be 128 hours. The results of the other systems are available in Appendix (F).

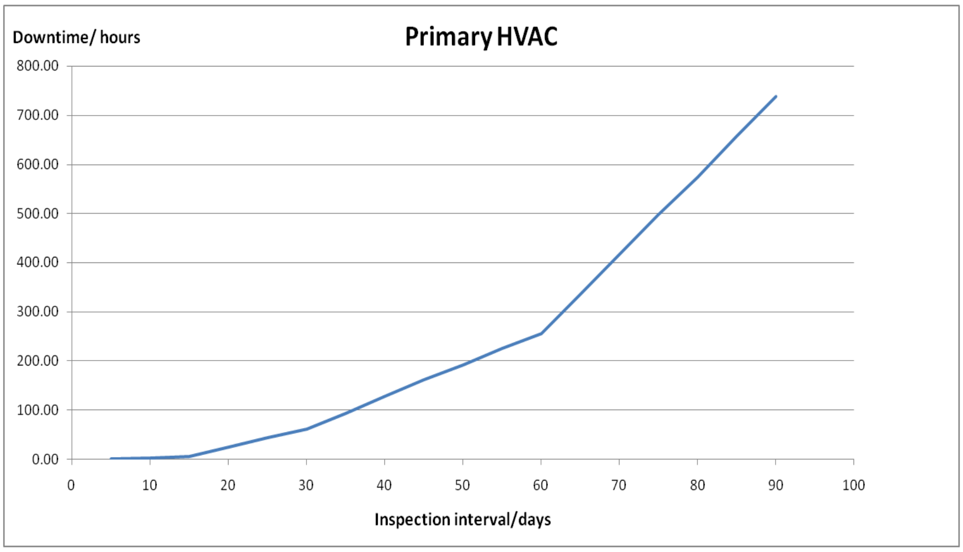

Figure 4-23: Downtime-Inspection interval for Primary HVAC

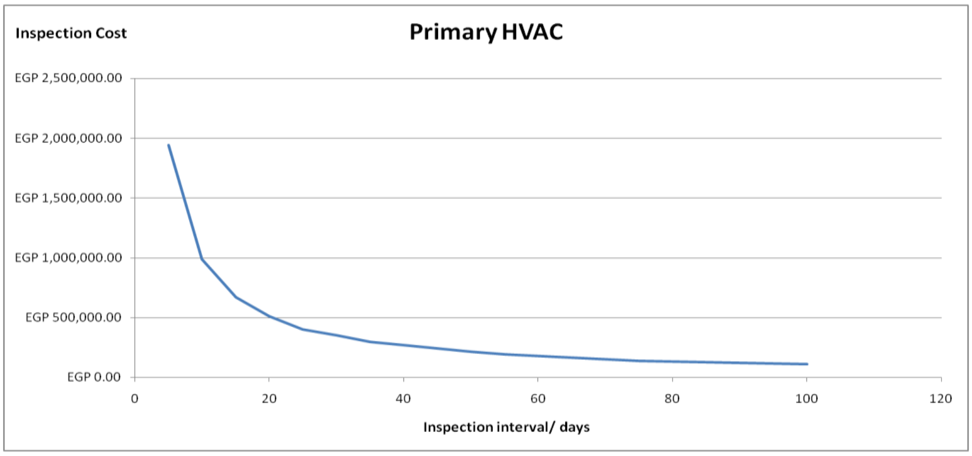

Figure 4-24: Inspection Cost – Inspection interval for Primary HVAC

5 CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Summary

Hospitals are the main provider for the medical services to the patients. The presence of various and several working systems together with the presence of tight budgets proves that there is a need to better understand how hospital systems performance contributed to the delivery of medical services. This research proposed two frameworks dealing with two different tasks. The first model Network-level Hospital Rehabilitation Tradeoff (NEHIR) provides rehabilitation strategies for different hospitals, rehabilitation costs, number of un-served patients, and distribution mechanism for patient diverted from suspended hospitals to working ones and schedule for rehabilitation works. NEHIR uses Genetic algorithms optimization engine and Markov chains for condition prediction. On the other hand, the second proposed model was Hospital-level Reliability Centered Maintenance model (HOREM) provides maintenance plan with the resulted expected downtime. HOREM assist the decision makers in allocating budget on the systems based on their contribution to the level of service. The model has utilized genetic algorithms optimization, Monte-Carlo simulation and fuzzy logic systems to work and demonstrate the results.

5.2 Research Contributions

The research has several contributions as follows:

- The use of Reliability Centered Maintenance (RCM) approach in hospitals for developing maintenance plans. RCM is able to integrate several maintenance type in developing the maintenance plans.
- Genetic algorithm was used to integrate several hospital systems in an overall master maintenance plan. This is crucial as it enables the decision maker to allocate the maintenance budget on the working systems based on their contribution to the level of service.
- Assisting the decision makers by providing the distribution mechanism for the patients diverted from the suspended hospitals on the other working hospitals based on the vacancies available. This was done by using genetic algorithm that optimizes the rehabilitation schedule.

- P-f intervals are uncertain, consequently experts provided range of p-f intervals and considered uniform distribution to represent it to overcome this uncertainty.
- Fuzzy logic system was used in defining the probability of failure resulted from applying specific inspection and replacement/restoration interval for the failure modes that require preventive maintenance.

5.3 Recommendations for further research

- Reliability centered maintenance (RCM) approach was used for planning maintenance actions. Never the less, beyond the advantages of RCM one of its limitations is time consumption required for carrying out the FMEA in addition it requires field experts to provide functions and failure details to the user. Other maintenance approaches e.g. (Streamlined Reliability Centered Maintenance, Total Productive Maintenance…etc.) that could be applied and compared with this model.
- It is recommended to perform experiments to define the most accurate probability distribution to represent the p-f interval.
- HOREM considered HVAC, medical and lift systems as they are part of the systems that mainly contribute to the medical service. Other systems that participate to the medical service in hospitals can be included e.g. generators.
- The Systems integration optimization module examined the contribution and importance of HVAC, medical and lift systems to RRs, ERs, ORs and ICUs. Other spaces and rooms are recommended to be considered that include recovery rooms, special units (X-ray, MRI…etc.).
- Consider studying how hospital architectural design and hospital finishes e.g. (doors, flooring…etc.) could contribute to the level of service delivered to patients.
- HOREM and NEHIR models have considered the percentage of patients served which is one of the parameters that contribute to the level of service. However, some other parameters can be considered in future research e.g. (rate of surgical complications or hospital-acquired infections).
- It is recommended to consider the probability of failure for redundant systems in developing the maintenance plans.

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7 APPENDICES

7.1 Appendix A: Interview Questions to Experts

Question 1: *What are the major components of the System?*

Question 2: *Based on your answer in question 1, briefly describe the function of every component?*

Question 3: *What are the functional failures and failure causes for each component?*

Question 4: *Identify the failure effects, estimated downtime and consequence for each failure mode?*

Question 5*: Based on the discussion with the interviewer and using the RCM decision tree specify the maintenance approach for each failure mode?*

Question 6*: In case of preventive maintenance approach, what are the major deterioration factors that affect the performance of component to be considered in fuzzy logic system?*

Question 7*: According the answer of question 6, what could be the ranges of deterioration factors?*

Question 8: *What is the ranges for the output variable (probability of failure)?*

Question 9*: What is your view regarding the results obtained from the fuzzy logic model?*

Question 10*: For Predictive maintenance, what is the probability distribution for p-f interval and what are their ranges?*

Question 11: *Based on the maintenance approaches given, what is the task required, cost and duration to carry out the maintenance approach?*

Question 12: *What is the cost percentage of this system from the total electromechanical cost?*

7.2 Appendix B: Fuzzy rules

Table 7-1: Fuzzy Rules for the pre-filter saturation

Washing Interval	Working Hours	Age	Location	Output
Short	Moderate.Long	Extreme New	Good. Moderate	Neglible
Moderate Short	Moderate.Long	Extreme New	Good. Moderate	Neglible
Moderate	Moderate.Long	Extreme New	Good. Moderate	V.Extreme Lowest
Moderate Long	Moderate.Long	Extreme New	Good. Moderate	V.Extreme Lowest
Long	Moderate.Long	Extreme New	Good. Moderate	V.Extreme Lowest
Longer	Moderate.Long	Extreme New	Good. Moderate	Extreme Lowest
Very Long	Moderate.Long	Extreme New	Good. Moderate	Extreme Lowest
Extreme	Moderate.Long	Extreme New	Good. Moderate	Extreme Lowest
Short	Moderate.Long	V.New	Good. Moderate	Neglible
Moderate Short	Moderate.Long	V.New	Good. Moderate	V.Extreme Lowest
Moderate	Moderate.Long	V.New	Good. Moderate	Extreme Lowest
Moderate Long	Moderate.Long	V.New	Good. Moderate	Extreme Lowest
Long	Moderate.Long	V.New	Good. Moderate	Lowest
Longer	Moderate.Long	V.New	Good. Moderate	Lowest
Very Long	Moderate.Long	V.New	Good. Moderate	Lowest
Extreme	Moderate.Long	V.New	Good. Moderate	Lower
Short	Moderate.Long	New	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate.Long	New	Good. Moderate	Extreme Lowest
Moderate	Moderate.Long	New	Good. Moderate	Extreme Lowest
Moderate Long	Moderate.Long	New	Good. Moderate	Lowest
Long	Moderate.Long	New	Good. Moderate	Lowest
Longer	Moderate.Long	New	Good. Moderate	Lower
Very Long	Moderate.Long	New	Good. Moderate	Lower
Extreme	Moderate.Long	New	Good. Moderate	Low
Short	Moderate.Long	Mod.New	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate.Long	Mod.New	Good. Moderate	Extreme Lowest
Moderate	Moderate.Long	Mod.New	Good. Moderate	Lowest
Moderate Long	Moderate.Long	Mod.New	Good. Moderate	Lower
Long	Moderate.Long	Mod.New	Good. Moderate	Lower
Longer	Moderate.Long	Mod.New	Good. Moderate	Low
Very Long	Moderate.Long	Mod.New	Good. Moderate	Low
Extreme	Moderate.Long	Mod.New	Good. Moderate	Moderate.Low
Short	Moderate.Long	Moderate	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate.Long	Moderate	Good. Moderate	Lowest
Moderate	Moderate.Long	Moderate	Good. Moderate	Lowest
Moderate Long	Moderate.Long	Moderate	Good. Moderate	Lower
Long	Moderate.Long	Moderate	Good. Moderate	Low
Longer	Moderate.Long	Moderate	Good. Moderate	Low
Very Long	Moderate.Long	Moderate	Good. Moderate	Moderate.Low
Extreme	Moderate.Long	Moderate	Good. Moderate	Moderate.Low
Short	Moderate.Long	Mod.Old	Good. Moderate	Extreme Lowest
Moderate Short	Moderate.Long	Mod.Old	Good. Moderate	Lowest
Moderate	Moderate.Long	Mod.Old	Good. Moderate	Lower
Moderate Long	Moderate.Long	Mod.Old	Good. Moderate	Low
Long	Moderate.Long	Mod.Old	Good. Moderate	Low
Longer	Moderate.Long	Mod.Old	Good. Moderate	Moderate.Low
Very Long	Moderate.Long	Mod.Old	Good. Moderate	Moderate.Low
Extreme	Moderate.Long	Mod.Old	Good. Moderate	Moderate
Short	Moderate.Long	Old	Good. Moderate	Extreme Lowest
Moderate Short	Moderate.Long	Old	Good. Moderate	Lowest
Moderate	Moderate.Long	Old	Good. Moderate	Lower
Moderate Long	Moderate.Long	Old	Good. Moderate	Low

Long	Moderate.Long	Old	Good. Moderate	Moderate.Low
Longer	Moderate.Long	Old	Good. Moderate	Moderate.Low
Very Long	Moderate.Long	Old	Good. Moderate	Moderate
Extreme	Moderate.Long	Old	Good. Moderate	Moderate.High
Short	Moderate.Long	V.Old	Good. Moderate	Extreme Lowest
Moderate Short	Moderate.Long	V.Old	Good. Moderate	Lower
Moderate	Moderate.Long	V.Old	Good. Moderate	Low
Moderate Long	Moderate.Long	V.Old	Good. Moderate	Moderate.Low
Long	Moderate.Long	V.Old	Good. Moderate	Moderate.Low
Longer	Moderate.Long	V.Old	Good. Moderate	Moderate
Very Long	Moderate.Long	V.Old	Good. Moderate	Moderate.High
Extreme	Moderate.Long	V.Old	Good. Moderate	Moderate.High
Short	Moderate.Long	Extreme Old	Good. Moderate	Extreme Lowest
Moderate Short	Moderate.Long	Extreme Old	Good. Moderate	Lower
Moderate	Moderate.Long	Extreme Old	Good. Moderate	Low
Moderate Long	Moderate.Long	Extreme Old	Good. Moderate	Moderate.Low
Long	Moderate.Long	Extreme Old	Good. Moderate	Moderate
Longer	Moderate.Long	Extreme Old	Good. Moderate	Moderate.High
Very Long	Moderate.Long	Extreme Old	Good. Moderate	Moderate.High
Extreme	Moderate.Long	Extreme Old	Good. Moderate	High
Short	Moderate.Long	Extreme New	Moderately Acceptable	Neglible
Moderate Short	Moderate.Long	Extreme New	Moderately Acceptable	V.Extreme Lowest
Moderate	Moderate.Long	Extreme New	Moderately Acceptable	Extreme Lowest
Moderate Long	Moderate.Long	Extreme New	Moderately Acceptable	Extreme Lowest
Long	Moderate.Long	Extreme New	Moderately Acceptable	Lowest
Longer	Moderate.Long	Extreme New	Moderately Acceptable	Lowest
Very Long	Moderate.Long	Extreme New	Moderately Acceptable	Lowest
Extreme	Moderate.Long	Extreme New	Moderately Acceptable	Lower
Short	Moderate.Long	V.New	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Moderate.Long	V.New	Moderately Acceptable	Extreme Lowest
Moderate	Moderate.Long	V.New	Moderately Acceptable	Lowest
Moderate Long	Moderate.Long	V.New	Moderately Acceptable	Lower
Long	Moderate.Long	V.New	Moderately Acceptable	Lower
Longer	Moderate.Long	V.New	Moderately Acceptable	Low
Very Long	Moderate.Long	V.New	Moderately Acceptable	Low
Extreme	Moderate.Long	V.New	Moderately Acceptable	Moderate.Low
Short	Moderate.Long	New	Moderately Acceptable	Extreme Lowest
Moderate Short	Moderate.Long	New	Moderately Acceptable	Lowest
Moderate	Moderate.Long	New	Moderately Acceptable	Lower
Moderate Long	Moderate.Long	New	Moderately Acceptable	Low
Long	Moderate.Long	New	Moderately Acceptable	Low
Longer	Moderate.Long	New	Moderately Acceptable	Moderate.Low
Very Long	Moderate.Long	New	Moderately Acceptable	Moderate.Low
Extreme	Moderate.Long	New	Moderately Acceptable	Moderate
Short	Moderate.Long	Mod.New	Moderately Acceptable	Extreme Lowest
Moderate Short	Moderate.Long	Mod.New	Moderately Acceptable	Lower
Moderate	Moderate.Long	Mod.New	Moderately Acceptable	Low
Moderate Long	Moderate.Long	Mod.New	Moderately Acceptable	Moderate.Low
Long	Moderate.Long	Mod.New	Moderately Acceptable	Moderate.Low
Longer	Moderate.Long	Mod.New	Moderately Acceptable	Moderate
Very Long	Moderate.Long	Mod.New	Moderately Acceptable	Moderate.High
Extreme	Moderate.Long	Mod.New	Moderately Acceptable	Moderate.High
Short	Moderate.Long	Moderate	Moderately Acceptable	Lowest
Moderate Short	Moderate.Long	Moderate	Moderately Acceptable	Lower
Moderate	Moderate.Long	Moderate	Moderately Acceptable	Low
Moderate Long	Moderate.Long	Moderate	Moderately Acceptable	Moderate.Low
Long	Moderate.Long	Moderate	Moderately Acceptable	Moderate

Longer	Moderate.Long	Moderate	Moderately Acceptable	Moderate.High
Very Long	Moderate.Long	Moderate	Moderately Acceptable	High
Extreme	Moderate.Long	Moderate	Moderately Acceptable	High
Short	Moderate.Long	Mod.Old	Moderately Acceptable	Lowest
Moderate Short	Moderate.Long	Mod.Old	Moderately Acceptable	Low
Moderate	Moderate.Long	Mod.Old	Moderately Acceptable	Moderate.Low
Moderate Long	Moderate.Long	Mod.Old	Moderately Acceptable	Moderate
Long	Moderate.Long	Mod.Old	Moderately Acceptable	Moderate.High
Longer	Moderate.Long	Mod.Old	Moderately Acceptable	High
Very Long	Moderate.Long	Mod.Old	Moderately Acceptable	High
Extreme	Moderate.Long	Mod.Old	Moderately Acceptable	Higher
Short	Moderate.Long	Old	Moderately Acceptable	Lowest
Moderate Short	Moderate.Long	Old	Moderately Acceptable	Low
Moderate	Moderate.Long	Old	Moderately Acceptable	Moderate.Low
Moderate Long	Moderate.Long	Old	Moderately Acceptable	Moderate.High
Long	Moderate.Long	Old	Moderately Acceptable	High
Longer	Moderate.Long	Old	Moderately Acceptable	High
Very Long	Moderate.Long	Old	Moderately Acceptable	Higher
Extreme	Moderate.Long	Old	Moderately Acceptable	Higher
Short	Moderate.Long	V.Old	Moderately Acceptable	Lower
Moderate Short	Moderate.Long	V.Old	Moderately Acceptable	Moderate.Low
Moderate	Moderate.Long	V.Old	Moderately Acceptable	Moderate
Moderate Long	Moderate.Long	V.Old	Moderately Acceptable	Moderate.High
Long	Moderate.Long	V.Old	Moderately Acceptable	High
Longer	Moderate.Long	V.Old	Moderately Acceptable	Higher
Very Long	Moderate.Long	V.Old	Moderately Acceptable	Higher
Extreme	Moderate.Long	V.Old	Moderately Acceptable	Highest
Short	Moderate.Long	Extreme Old	Moderately Acceptable	Lower
Moderate Short	Moderate.Long	Extreme Old	Moderately Acceptable	Moderate.Low
Moderate	Moderate.Long	Extreme Old	Moderately Acceptable	Moderate.High
Moderate Long	Moderate.Long	Extreme Old	Moderately Acceptable	High
Long	Moderate.Long	Extreme Old	Moderately Acceptable	Higher
Longer	Moderate.Long	Extreme Old	Moderately Acceptable	Higher
Very Long	Moderate.Long	Extreme Old	Moderately Acceptable	Highest
Extreme	Moderate.Long	Extreme Old	Moderately Acceptable	Highest
Short	Moderate.Long	Extreme New	Unhealthy	Neglible
Moderate Short	Moderate.Long	Extreme New	Unhealthy	Neglible
Moderate	Moderate.Long	Extreme New	Unhealthy	V.Extreme Lowest
Moderate Long	Moderate.Long	Extreme New	Unhealthy	V.Extreme Lowest
Long	Moderate.Long	Extreme New	Unhealthy	V.Extreme Lowest
Longer	Moderate.Long	Extreme New	Unhealthy	Extreme Lowest
Very Long	Moderate.Long	Extreme New	Unhealthy	Extreme Lowest
Extreme	Moderate.Long	Extreme New	Unhealthy	Extreme Lowest
Short	Moderate.Long	V.New	Unhealthy	Extreme Lowest
Moderate Short	Moderate.Long	V.New	Unhealthy	Lowest
Moderate	Moderate.Long	V.New	Unhealthy	Lower
Moderate Long	Moderate.Long	V.New	Unhealthy	Low
Long	Moderate.Long	V.New	Unhealthy	Low
Longer	Moderate.Long	V.New	Unhealthy	Moderate.Low
Very Long	Moderate.Long	V.New	Unhealthy	Moderate.Low
Extreme	Moderate.Long	V.New	Unhealthy	Moderate
Short	Moderate.Long	New	Unhealthy	Extreme Lowest
Moderate Short	Moderate.Long	New	Unhealthy	Lower
Moderate	Moderate.Long	New	Unhealthy	Low
Moderate Long	Moderate.Long	New	Unhealthy	Moderate.Low
Long	Moderate.Long	New	Unhealthy	Moderate
Longer	Moderate.Long	New	Unhealthy	Moderate.High

Very Long	Moderate.Long	New	Unhealthy	Moderate.High
Extreme	Moderate.Long	New	Unhealthy	High
Short	Moderate.Long	Mod.New	Unhealthy	Lowest
Moderate Short	Moderate.Long	Mod.New	Unhealthy	Low
Moderate	Moderate.Long	Mod.New	Unhealthy	Moderate.Low
Moderate Long	Moderate.Long	Mod.New	Unhealthy	Moderate
Long	Moderate.Long	Mod.New	Unhealthy	Moderate.High
Longer	Moderate.Long	Mod.New	Unhealthy	High
Very Long	Moderate.Long	Mod.New	Unhealthy	High
Extreme	Moderate.Long	Mod.New	Unhealthy	Higher
Short	Moderate.Long	Moderate	Unhealthy	Lowest
Moderate Short	Moderate.Long	Moderate	Unhealthy	Low
Moderate	Moderate.Long	Moderate	Unhealthy	Moderate
Moderate Long	Moderate.Long	Moderate	Unhealthy	Moderate.High
Long	Moderate.Long	Moderate	Unhealthy	High
Longer	Moderate.Long	Moderate	Unhealthy	Higher
Very Long	Moderate.Long	Moderate	Unhealthy	Higher
Extreme	Moderate.Long	Moderate	Unhealthy	Higher
Short	Moderate.Long	Mod.Old	Unhealthy	Lower
Moderate Short	Moderate.Long	Mod.Old	Unhealthy	Moderate.Low
Moderate	Moderate.Long	Mod.Old	Unhealthy	Moderate.High
Moderate Long	Moderate.Long	Mod.Old	Unhealthy	High
Long	Moderate.Long	Mod.Old	Unhealthy	Higher
Longer	Moderate.Long	Mod.Old	Unhealthy	Higher
Very Long	Moderate.Long	Mod.Old	Unhealthy	Highest
Extreme	Moderate.Long	Mod.Old	Unhealthy	Highest
Short	Moderate.Long	Old	Unhealthy	Lower
Moderate Short	Moderate.Long	Old	Unhealthy	Moderate.Low
Moderate	Moderate.Long	Old	Unhealthy	Moderate.High
Moderate Long	Moderate.Long	Old	Unhealthy	High
Long	Moderate.Long	Old	Unhealthy	Higher
Longer	Moderate.Long	Old	Unhealthy	Highest
Very Long	Moderate.Long	Old	Unhealthy	Highest
Extreme	Moderate.Long	Old	Unhealthy	Extreme Highest
Short	Moderate.Long	V.Old	Unhealthy	Low
Moderate Short	Moderate.Long	V.Old	Unhealthy	Moderate
Moderate	Moderate.Long	V.Old	Unhealthy	High
Moderate Long	Moderate.Long	V.Old	Unhealthy	Higher
Long	Moderate.Long	V.Old	Unhealthy	Higher
Longer	Moderate.Long	V.Old	Unhealthy	Highest
Very Long	Moderate.Long	V.Old	Unhealthy	Extreme Highest
Extreme	Moderate.Long	V.Old	Unhealthy	Extreme Highest
Short	Moderate.Long	Extreme Old	Unhealthy	Extreme Lowest
Moderate Short	Moderate.Long	Extreme Old	Unhealthy	Lower
Moderate	Moderate.Long	Extreme Old	Unhealthy	Low
Moderate Long	Moderate.Long	Extreme Old	Unhealthy	Moderate.Low
Long	Moderate.Long	Extreme Old	Unhealthy	Moderate
Longer	Moderate.Long	Extreme Old	Unhealthy	Moderate.High
Very Long	Moderate.Long	Extreme Old	Unhealthy	Moderate.High
Extreme	Moderate.Long	Extreme Old	Unhealthy	High
Short	Short	Extreme New	Good. Moderate	Neglible
Moderate Short	Short	Extreme New	Good. Moderate	Neglible
Moderate	Short	Extreme New	Good. Moderate	Neglible
Moderate Long	Short	Extreme New	Good. Moderate	Neglible
Long	Short	Extreme New	Good. Moderate	Neglible
Longer	Short	Extreme New	Good. Moderate	Neglible
Very Long	Short	Extreme New	Good. Moderate	V.Extreme Lowest

Extreme	Short	Extreme New	Good. Moderate	V.Extreme Lowest
Short	Short	V.New	Good. Moderate	Neglible
Moderate Short	Short	V.New	Good. Moderate	Neglible
Moderate	Short	V.New	Good. Moderate	Neglible
Moderate Long	Short	V.New	Good. Moderate	V.Extreme Lowest
Long	Short	V.New	Good. Moderate	V.Extreme Lowest
Longer	Short	V.New	Good. Moderate	V.Extreme Lowest
Very Long	Short	V.New	Good. Moderate	V.Extreme Lowest
Extreme	Short	V.New	Good. Moderate	Extreme Lowest
Short	Short	New	Good. Moderate	Neglible
Moderate Short	Short	New	Good. Moderate	Neglible
Moderate	Short	New	Good. Moderate	V.Extreme Lowest
Moderate Long	Short	New	Good. Moderate	V.Extreme Lowest
Long	Short	New	Good. Moderate	V.Extreme Lowest
Longer	Short	New	Good. Moderate	Extreme Lowest
Very Long	Short	New	Good. Moderate	Extreme Lowest
Extreme	Short	New	Good. Moderate	Extreme Lowest
Short	Short	Mod.New	Good. Moderate	Neglible
Moderate Short	Short	Mod.New	Good. Moderate	V.Extreme Lowest
Moderate	Short	Mod.New	Good. Moderate	V.Extreme Lowest
Moderate Long	Short	Mod.New	Good. Moderate	Extreme Lowest
Long	Short	Mod.New	Good. Moderate	Extreme Lowest
Longer	Short	Mod.New	Good. Moderate	Extreme Lowest
Very Long	Short	Mod.New	Good. Moderate	Lowest
Extreme	Short	Mod.New	Good. Moderate	Lowest
Short	Short	Moderate	Good. Moderate	Neglible
Moderate Short	Short	Moderate	Good. Moderate	V.Extreme Lowest
Moderate	Short	Moderate	Good. Moderate	V.Extreme Lowest
Moderate Long	Short	Moderate	Good. Moderate	Extreme Lowest
Long	Short	Moderate	Good. Moderate	Extreme Lowest
Longer	Short	Moderate	Good. Moderate	Lowest
Very Long	Short	Moderate	Good. Moderate	Lowest
Extreme	Short	Moderate	Good. Moderate	Lowest
Short	Short	Mod.Old	Good. Moderate	Neglible
Moderate Short	Short	Mod.Old	Good. Moderate	V.Extreme Lowest
Moderate	Short	Mod.Old	Good. Moderate	Extreme Lowest
Moderate Long	Short	Mod.Old	Good. Moderate	Extreme Lowest
Long	Short	Mod.Old	Good. Moderate	Lowest
Longer	Short	Mod.Old	Good. Moderate	Lowest
Very Long	Short	Mod.Old	Good. Moderate	Lowest
Extreme	Short	Mod.Old	Good. Moderate	Lower
Short	Short	Old	Good. Moderate	V.Extreme Lowest
Moderate Short	Short	Old	Good. Moderate	V.Extreme Lowest
Moderate	Short	Old	Good. Moderate	Extreme Lowest
Moderate Long	Short	Old	Good. Moderate	Lowest
Long	Short	Old	Good. Moderate	Lowest
Longer	Short	Old	Good. Moderate	Lowest
Very Long	Short	Old	Good. Moderate	Lower
Extreme	Short	Old	Good. Moderate	Lower
Short	Short	V.Old	Good. Moderate	V.Extreme Lowest
Moderate Short	Short	V.Old	Good. Moderate	Extreme Lowest
Moderate	Short	V.Old	Good. Moderate	Extreme Lowest
Moderate Long	Short	V.Old	Good. Moderate	Lowest
Long	Short	V.Old	Good. Moderate	Lowest
Longer	Short	V.Old	Good. Moderate	Lower
Very Long	Short	V.Old	Good. Moderate	Lower
Extreme	Short	V.Old	Good. Moderate	Low

Short	Short	Extreme Old	Good. Moderate	V.Extreme Lowest
Moderate Short	Short	Extreme Old	Good. Moderate	Extreme Lowest
Moderate	Short	Extreme Old	Good. Moderate	Extreme Lowest
Moderate Long	Short	Extreme Old	Good. Moderate	Lowest
Long	Short	Extreme Old	Good. Moderate	Lowest
Longer	Short	Extreme Old	Good. Moderate	Lower
Very Long	Short	Extreme Old	Good. Moderate	Lower
Extreme	Short	Extreme Old	Good. Moderate	Low
Short	Short	Extreme New	Moderately Acceptable	Neglible
Moderate Short	Short	Extreme New	Moderately Acceptable	Neglible
Moderate	Short	Extreme New	Moderately Acceptable	Neglible
Moderate Long	Short	Extreme New	Moderately Acceptable	V.Extreme Lowest
Long	Short	Extreme New	Moderately Acceptable	V.Extreme Lowest
Longer	Short	Extreme New	Moderately Acceptable	V.Extreme Lowest
Very Long	Short	Extreme New	Moderately Acceptable	V.Extreme Lowest
Extreme	Short	Extreme New	Moderately Acceptable	Extreme Lowest
Short	Short	V.New	Moderately Acceptable	Neglible
Moderate Short	Short	V.New	Moderately Acceptable	V.Extreme Lowest
Moderate	Short	V.New	Moderately Acceptable	V.Extreme Lowest
Moderate Long	Short	V.New	Moderately Acceptable	Extreme Lowest
Long	Short	V.New	Moderately Acceptable	Extreme Lowest
Longer	Short	V.New	Moderately Acceptable	Extreme Lowest
Very Long	Short	V.New	Moderately Acceptable	Lowest
Extreme	Short	V.New	Moderately Acceptable	Lowest
Short	Short	New	Moderately Acceptable	Neglible
Moderate Short	Short	New	Moderately Acceptable	V.Extreme Lowest
Moderate	Short	New	Moderately Acceptable	Extreme Lowest
Moderate Long	Short	New	Moderately Acceptable	Extreme Lowest
Long	Short	New	Moderately Acceptable	Lowest
Longer	Short	New	Moderately Acceptable	Lowest
Very Long	Short	New	Moderately Acceptable	Lowest
Extreme	Short	New	Moderately Acceptable	Lower
Short	Short	Mod.New	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Short	Mod.New	Moderately Acceptable	Extreme Lowest
Moderate	Short	Mod.New	Moderately Acceptable	Extreme Lowest
Moderate Long	Short	Mod.New	Moderately Acceptable	Lowest
Long	Short	Mod.New	Moderately Acceptable	Lowest
Longer	Short	Mod.New	Moderately Acceptable	Lower
Very Long	Short	Mod.New	Moderately Acceptable	Lower
Extreme	Short	Mod.New	Moderately Acceptable	Low
Short	Short	Moderate	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Short	Moderate	Moderately Acceptable	Extreme Lowest
Moderate	Short	Moderate	Moderately Acceptable	Lowest
Moderate Long	Short	Moderate	Moderately Acceptable	Lowest
Long	Short	Moderate	Moderately Acceptable	Lower
Longer	Short	Moderate	Moderately Acceptable	Lower
Very Long	Short	Moderate	Moderately Acceptable	Low
Extreme	Short	Moderate	Moderately Acceptable	Low
Short	Short	Mod.Old	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Short	Mod.Old	Moderately Acceptable	Extreme Lowest
Moderate	Short	Mod.Old	Moderately Acceptable	Lowest
Moderate Long	Short	Mod.Old	Moderately Acceptable	Lower
Long	Short	Mod.Old	Moderately Acceptable	Lower
Longer	Short	Mod.Old	Moderately Acceptable	Low
Very Long	Short	Mod.Old	Moderately Acceptable	Low
Extreme	Short	Mod.Old	Moderately Acceptable	Moderate.Low
Short	Short	Old	Moderately Acceptable	V.Extreme Lowest

Moderate Short	Short	Old	Moderately Acceptable	Lowest
Moderate	Short	Old	Moderately Acceptable	Lowest
Moderate Long	Short	Old	Moderately Acceptable	Lower
Long	Short	Old	Moderately Acceptable	Low
Longer	Short	Old	Moderately Acceptable	Low
Very Long	Short	Old	Moderately Acceptable	Moderate.Low
Extreme	Short	Old	Moderately Acceptable	Moderate.Low
Short	Short	V.Old	Moderately Acceptable	Extreme Lowest
Moderate Short	Short	V.Old	Moderately Acceptable	Lowest
Moderate	Short	V.Old	Moderately Acceptable	Lower
Moderate Long	Short	V.Old	Moderately Acceptable	Low
Long	Short	V.Old	Moderately Acceptable	Low
Longer	Short	V.Old	Moderately Acceptable	Moderate.Low
Very Long	Short	V.Old	Moderately Acceptable	Moderate.Low
Extreme	Short	V.Old	Moderately Acceptable	Moderate
Short	Short	Extreme Old	Moderately Acceptable	Extreme Lowest
Moderate Short	Short	Extreme Old	Moderately Acceptable	Lowest
Moderate	Short	Extreme Old	Moderately Acceptable	Lower
Moderate Long	Short	Extreme Old	Moderately Acceptable	Low
Long	Short	Extreme Old	Moderately Acceptable	Low
Longer	Short	Extreme Old	Moderately Acceptable	Moderate.Low
Very Long	Short	Extreme Old	Moderately Acceptable	Moderate.Low
Extreme	Short	Extreme Old	Moderately Acceptable	Moderate
Short	Short	Extreme New	Unhealthy	Neglible
Moderate Short	Short	Extreme New	Unhealthy	Neglible
Moderate	Short	Extreme New	Unhealthy	V.Extreme Lowest
Moderate Long	Short	Extreme New	Unhealthy	V.Extreme Lowest
Long	Short	Extreme New	Unhealthy	V.Extreme Lowest
Longer	Short	Extreme New	Unhealthy	Extreme Lowest
Very Long	Short	Extreme New	Unhealthy	Extreme Lowest
Extreme	Short	Extreme New	Unhealthy	Extreme Lowest
Short	Short	V.New	Unhealthy	Neglible
Moderate Short	Short	V.New	Unhealthy	V.Extreme Lowest
Moderate	Short	V.New	Unhealthy	Extreme Lowest
Moderate Long	Short	V.New	Unhealthy	Extreme Lowest
Long	Short	V.New	Unhealthy	Lowest
Longer	Short	V.New	Unhealthy	Lowest
Very Long	Short	V.New	Unhealthy	Lowest
Extreme	Short	V.New	Unhealthy	Lower
Short	Short	New	Unhealthy	V.Extreme Lowest
Moderate Short	Short	New	Unhealthy	Extreme Lowest
Moderate	Short	New	Unhealthy	Extreme Lowest
Moderate Long	Short	New	Unhealthy	Lowest
Long	Short	New	Unhealthy	Lowest
Longer	Short	New	Unhealthy	Lower
Very Long	Short	New	Unhealthy	Lower
Extreme	Short	New	Unhealthy	Low
Short	Short	Mod.New	Unhealthy	V.Extreme Lowest
Moderate Short	Short	Mod.New	Unhealthy	Extreme Lowest
Moderate	Short	Mod.New	Unhealthy	Lowest
Moderate Long	Short	Mod.New	Unhealthy	Lower
Long	Short	Mod.New	Unhealthy	Lower
Longer	Short	Mod.New	Unhealthy	Low
Very Long	Short	Mod.New	Unhealthy	Low
Extreme	Short	Mod.New	Unhealthy	Moderate.Low
Short	Short	Moderate	Unhealthy	V.Extreme Lowest
Moderate Short	Short	Moderate	Unhealthy	Lowest

Moderate	Short	Moderate	Unhealthy	Lowest
Moderate Long	Short	Moderate	Unhealthy	Lower
Long	Short	Moderate	Unhealthy	Low
Longer	Short	Moderate	Unhealthy	Low
Very Long	Short	Moderate	Unhealthy	Moderate.Low
Extreme	Short	Moderate	Unhealthy	Moderate.Low
Short	Short	Mod.Old	Unhealthy	Extreme Lowest
Moderate Short	Short	Mod.Old	Unhealthy	Lowest
Moderate	Short	Mod.Old	Unhealthy	Lower
Moderate Long	Short	Mod.Old	Unhealthy	Low
Long	Short	Mod.Old	Unhealthy	Low
Longer	Short	Mod.Old	Unhealthy	Moderate.Low
Very Long	Short	Mod.Old	Unhealthy	Moderate.Low
Extreme	Short	Mod.Old	Unhealthy	Moderate
Short	Short	Old	Unhealthy	Extreme Lowest
Moderate Short	Short	Old	Unhealthy	Lowest
Moderate	Short	Old	Unhealthy	Lower
Moderate Long	Short	Old	Unhealthy	Low
Long	Short	Old	Unhealthy	Moderate.Low
Longer	Short	Old	Unhealthy	Moderate.Low
Very Long	Short	Old	Unhealthy	Moderate
Extreme	Short	Old	Unhealthy	Moderate.High
Short	Short	V.Old	Unhealthy	Extreme Lowest
Moderate Short	Short	V.Old	Unhealthy	Lower
Moderate	Short	V.Old	Unhealthy	Low
Moderate Long	Short	V.Old	Unhealthy	Moderate.Low
Long	Short	V.Old	Unhealthy	Moderate.Low
Longer	Short	V.Old	Unhealthy	Moderate
Very Long	Short	V.Old	Unhealthy	Moderate.High
Extreme	Short	V.Old	Unhealthy	Moderate.High
Short	Short	Extreme Old	Unhealthy	Extreme Lowest
Moderate Short	Short	Extreme Old	Unhealthy	Lower
Moderate	Short	Extreme Old	Unhealthy	Low
Moderate Long	Short	Extreme Old	Unhealthy	Moderate.Low
Long	Short	Extreme Old	Unhealthy	Moderate
Longer	Short	Extreme Old	Unhealthy	Moderate.High
Very Long	Short	Extreme Old	Unhealthy	Moderate.High
Extreme	Short	Extreme Old	Unhealthy	High
Short	Moderate short	Extreme New	Good. Moderate	Neglible
Moderate Short	Moderate short	Extreme New	Good. Moderate	V.Extreme Lowest
Moderate	Moderate short	Extreme New	Good. Moderate	Extreme Lowest
Moderate Long	Moderate short	Extreme New	Good. Moderate	Extreme Lowest
Long	Moderate short	Extreme New	Good. Moderate	Lowest
Longer	Moderate short	Extreme New	Good. Moderate	Lowest
Very Long	Moderate short	Extreme New	Good. Moderate	Lowest
Extreme	Moderate short	Extreme New	Good. Moderate	Lower
Short	Moderate short	V.New	Good. Moderate	Neglible
Moderate Short	Moderate short	V.New	Good. Moderate	V.Extreme Lowest
Moderate	Moderate short	V.New	Good. Moderate	V.Extreme Lowest
Moderate Long	Moderate short	V.New	Good. Moderate	Extreme Lowest
Long	Moderate short	V.New	Good. Moderate	Extreme Lowest
Longer	Moderate short	V.New	Good. Moderate	Extreme Lowest
Very Long	Moderate short	V.New	Good. Moderate	Lowest
Extreme	Moderate short	V.New	Good. Moderate	Lowest
Short	Moderate short	New	Good. Moderate	Neglible
Moderate Short	Moderate short	New	Good. Moderate	V.Extreme Lowest
Moderate	Moderate short	New	Good. Moderate	Extreme Lowest

Moderate Long	Moderate short	New	Good. Moderate	Extreme Lowest
Long	Moderate short	New	Good. Moderate	Lowest
Longer	Moderate short	New	Good. Moderate	Lowest
Very Long	Moderate short	New	Good. Moderate	Lowest
Extreme	Moderate short	New	Good. Moderate	Lower
Short	Moderate short	Mod.New	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate short	Mod.New	Good. Moderate	Extreme Lowest
Moderate	Moderate short	Mod.New	Good. Moderate	Extreme Lowest
Moderate Long	Moderate short	Mod.New	Good. Moderate	Lowest
Long	Moderate short	Mod.New	Good. Moderate	Lowest
Longer	Moderate short	Mod.New	Good. Moderate	Lower
Very Long	Moderate short	Mod.New	Good. Moderate	Lower
Extreme	Moderate short	Mod.New	Good. Moderate	Low
Short	Moderate short	Moderate	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate short	Moderate	Good. Moderate	Extreme Lowest
Moderate	Moderate short	Moderate	Good. Moderate	Lowest
Moderate Long	Moderate short	Moderate	Good. Moderate	Lowest
Long	Moderate short	Moderate	Good. Moderate	Lower
Longer	Moderate short	Moderate	Good. Moderate	Lower
Very Long	Moderate short	Moderate	Good. Moderate	Low
Extreme	Moderate short	Moderate	Good. Moderate	Low
Short	Moderate short	Mod.Old	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate short	Mod.Old	Good. Moderate	Extreme Lowest
Moderate	Moderate short	Mod.Old	Good. Moderate	Lowest
Moderate Long	Moderate short	Mod.Old	Good. Moderate	Lower
Long	Moderate short	Mod.Old	Good. Moderate	Lower
Longer	Moderate short	Mod.Old	Good. Moderate	Low
Very Long	Moderate short	Mod.Old	Good. Moderate	Low
Extreme	Moderate short	Mod.Old	Good. Moderate	Moderate.Low
Short	Moderate short	Old	Good. Moderate	V.Extreme Lowest
Moderate Short	Moderate short	Old	Good. Moderate	Lowest
Moderate	Moderate short	Old	Good. Moderate	Lowest
Moderate Long	Moderate short	Old	Good. Moderate	Lower
Long	Moderate short	Old	Good. Moderate	Low
Longer	Moderate short	Old	Good. Moderate	Low
Very Long	Moderate short	Old	Good. Moderate	Moderate.Low
Extreme	Moderate short	Old	Good. Moderate	Moderate.Low
Short	Moderate short	V.Old	Good. Moderate	Extreme Lowest
Moderate Short	Moderate short	V.Old	Good. Moderate	Lowest
Moderate	Moderate short	V.Old	Good. Moderate	Lower
Moderate Long	Moderate short	V.Old	Good. Moderate	Low
Long	Moderate short	V.Old	Good. Moderate	Low
Longer	Moderate short	V.Old	Good. Moderate	Moderate.Low
Very Long	Moderate short	V.Old	Good. Moderate	Moderate.Low
Extreme	Moderate short	V.Old	Good. Moderate	Moderate
Short	Moderate short	Extreme Old	Good. Moderate	Extreme Lowest
Moderate Short	Moderate short	Extreme Old	Good. Moderate	Lowest
Moderate	Moderate short	Extreme Old	Good. Moderate	Lower
Moderate Long	Moderate short	Extreme Old	Good. Moderate	Low
Long	Moderate short	Extreme Old	Good. Moderate	Low
Longer	Moderate short	Extreme Old	Good. Moderate	Moderate.Low
Very Long	Moderate short	Extreme Old	Good. Moderate	Moderate.Low
Extreme	Moderate short	Extreme Old	Good. Moderate	Moderate
Short	Moderate short	Extreme New	Moderately Acceptable	Neglible
Moderate Short	Moderate short	Extreme New	Moderately Acceptable	V.Extreme Lowest
Moderate	Moderate short	Extreme New	Moderately Acceptable	V.Extreme Lowest
Moderate Long	Moderate short	Extreme New	Moderately Acceptable	Extreme Lowest

Long	Moderate short	Extreme New	Moderately Acceptable	Extreme Lowest
Longer	Moderate short	Extreme New	Moderately Acceptable	Extreme Lowest
Very Long	Moderate short	Extreme New	Moderately Acceptable	Lowest
Extreme	Moderate short	Extreme New	Moderately Acceptable	Lowest
Short	Moderate short	V.New	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Moderate short	V.New	Moderately Acceptable	Extreme Lowest
Moderate	Moderate short	V.New	Moderately Acceptable	Extreme Lowest
Moderate Long	Moderate short	V.New	Moderately Acceptable	Lowest
Long	Moderate short	V.New	Moderately Acceptable	Lowest
Longer	Moderate short	V.New	Moderately Acceptable	Lower
Very Long	Moderate short	V.New	Moderately Acceptable	Lower
Extreme	Moderate short	V.New	Moderately Acceptable	Low
Short	Moderate short	New	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Moderate short	New	Moderately Acceptable	Extreme Lowest
Moderate	Moderate short	New	Moderately Acceptable	Lowest
Moderate Long	Moderate short	New	Moderately Acceptable	Lower
Long	Moderate short	New	Moderately Acceptable	Lower
Longer	Moderate short	New	Moderately Acceptable	Low
Very Long	Moderate short	New	Moderately Acceptable	Low
Extreme	Moderate short	New	Moderately Acceptable	Moderate.Low
Short	Moderate short	Mod.New	Moderately Acceptable	Extreme Lowest
Moderate Short	Moderate short	Mod.New	Moderately Acceptable	Lowest
Moderate	Moderate short	Mod.New	Moderately Acceptable	Lower
Moderate Long	Moderate short	Mod.New	Moderately Acceptable	Low
Long	Moderate short	Mod.New	Moderately Acceptable	Low
Longer	Moderate short	Mod.New	Moderately Acceptable	Moderate.Low
Very Long	Moderate short	Mod.New	Moderately Acceptable	Moderate.Low
Extreme	Moderate short	Mod.New	Moderately Acceptable	Moderate
Short	Moderate short	Moderate	Moderately Acceptable	Extreme Lowest
Moderate Short	Moderate short	Moderate	Moderately Acceptable	Lowest
Moderate	Moderate short	Moderate	Moderately Acceptable	Lower
Moderate Long	Moderate short	Moderate	Moderately Acceptable	Low
Long	Moderate short	Moderate	Moderately Acceptable	Moderate.Low
Longer	Moderate short	Moderate	Moderately Acceptable	Moderate.Low
Very Long	Moderate short	Moderate	Moderately Acceptable	Moderate
Extreme	Moderate short	Moderate	Moderately Acceptable	Moderate.High
Short	Moderate short	Mod.Old	Moderately Acceptable	Extreme Lowest
Moderate Short	Moderate short	Mod.Old	Moderately Acceptable	Lower
Moderate	Moderate short	Mod.Old	Moderately Acceptable	Low
Moderate Long	Moderate short	Mod.Old	Moderately Acceptable	Moderate.Low
Long	Moderate short	Mod.Old	Moderately Acceptable	Moderate.Low
Longer	Moderate short	Mod.Old	Moderately Acceptable	Moderate
Very Long	Moderate short	Mod.Old	Moderately Acceptable	Moderate.High
Extreme	Moderate short	Mod.Old	Moderately Acceptable	Moderate.High
Short	Moderate short	Old	Moderately Acceptable	Lowest
Moderate Short	Moderate short	Old	Moderately Acceptable	Lower
Moderate	Moderate short	Old	Moderately Acceptable	Low
Moderate Long	Moderate short	Old	Moderately Acceptable	Moderate.Low
Long	Moderate short	Old	Moderately Acceptable	Moderate
Longer	Moderate short	Old	Moderately Acceptable	Moderate.High
Very Long	Moderate short	Old	Moderately Acceptable	High
Extreme	Moderate short	Old	Moderately Acceptable	High
Short	Moderate short	V.Old	Moderately Acceptable	Lowest
Moderate Short	Moderate short	V.Old	Moderately Acceptable	Low
Moderate	Moderate short	V.Old	Moderately Acceptable	Moderate.Low
Moderate Long	Moderate short	V.Old	Moderately Acceptable	Moderate
Long	Moderate short	V.Old	Moderately Acceptable	Moderate.High

Longer	Moderate short	V.Old	Moderately Acceptable	Moderate.High
Very Long	Moderate short	V.Old	Moderately Acceptable	High
Extreme	Moderate short	V.Old	Moderately Acceptable	High
Short	Moderate short	Extreme Old	Moderately Acceptable	Lowest
Moderate Short	Moderate short	Extreme Old	Moderately Acceptable	Low
Moderate	Moderate short	Extreme Old	Moderately Acceptable	Moderate.Low
Moderate Long	Moderate short	Extreme Old	Moderately Acceptable	Moderate
Long	Moderate short	Extreme Old	Moderately Acceptable	Moderate.High
Longer	Moderate short	Extreme Old	Moderately Acceptable	High
Very Long	Moderate short	Extreme Old	Moderately Acceptable	High
Extreme	Moderate short	Extreme Old	Moderately Acceptable	Higher
Short	Moderate short	Extreme New	Unhealthy	Neglible
Moderate Short	Moderate short	Extreme New	Unhealthy	Neglible
Moderate	Moderate short	Extreme New	Unhealthy	Neglible
Moderate Long	Moderate short	Extreme New	Unhealthy	V.Extreme Lowest
Long	Moderate short	Extreme New	Unhealthy	V.Extreme Lowest
Longer	Moderate short	Extreme New	Unhealthy	V.Extreme Lowest
Very Long	Moderate short	Extreme New	Unhealthy	V.Extreme Lowest
Extreme	Moderate short	Extreme New	Unhealthy	Extreme Lowest
Short	Moderate short	V.New	Unhealthy	V.Extreme Lowest
Moderate Short	Moderate short	V.New	Unhealthy	Extreme Lowest
Moderate	Moderate short	V.New	Unhealthy	Lowest
Moderate Long	Moderate short	V.New	Unhealthy	Lower
Long	Moderate short	V.New	Unhealthy	Lower
Longer	Moderate short	V.New	Unhealthy	Low
Very Long	Moderate short	V.New	Unhealthy	Low
Extreme	Moderate short	V.New	Unhealthy	Moderate.Low
Short	Moderate short	New	Unhealthy	Extreme Lowest
Moderate Short	Moderate short	New	Unhealthy	Lowest
Moderate	Moderate short	New	Unhealthy	Lower
Moderate Long	Moderate short	New	Unhealthy	Low
Long	Moderate short	New	Unhealthy	Low
Longer	Moderate short	New	Unhealthy	Moderate.Low
Very Long	Moderate short	New	Unhealthy	Moderate.Low
Extreme	Moderate short	New	Unhealthy	Moderate
Short	Moderate short	Mod.New	Unhealthy	Extreme Lowest
Moderate Short	Moderate short	Mod.New	Unhealthy	Lower
Moderate	Moderate short	Mod.New	Unhealthy	Low
Moderate Long	Moderate short	Mod.New	Unhealthy	Moderate.Low
Long	Moderate short	Mod.New	Unhealthy	Moderate.Low
Longer	Moderate short	Mod.New	Unhealthy	Moderate
Very Long	Moderate short	Mod.New	Unhealthy	Moderate.High
Extreme	Moderate short	Mod.New	Unhealthy	Moderate.High
Short	Moderate short	Moderate	Unhealthy	Lowest
Moderate Short	Moderate short	Moderate	Unhealthy	Lower
Moderate	Moderate short	Moderate	Unhealthy	Low
Moderate Long	Moderate short	Moderate	Unhealthy	Moderate.Low
Long	Moderate short	Moderate	Unhealthy	Moderate
Longer	Moderate short	Moderate	Unhealthy	Moderate.High
Very Long	Moderate short	Moderate	Unhealthy	High
Extreme	Moderate short	Moderate	Unhealthy	High
Short	Moderate short	Mod.Old	Unhealthy	Lowest
Moderate Short	Moderate short	Mod.Old	Unhealthy	Low
Moderate	Moderate short	Mod.Old	Unhealthy	Moderate.Low
Moderate Long	Moderate short	Mod.Old	Unhealthy	Moderate
Long	Moderate short	Mod.Old	Unhealthy	Moderate.High
Longer	Moderate short	Mod.Old	Unhealthy	High

Very Long	Moderate short	Mod.Old	Unhealthy	High
Extreme	Moderate short	Mod.Old	Unhealthy	Higher
Short	Moderate short	Old	Unhealthy	Lowest
Moderate Short	Moderate short	Old	Unhealthy	Low
Moderate	Moderate short	Old	Unhealthy	Moderate.Low
Moderate Long	Moderate short	Old	Unhealthy	Moderate.High
Long	Moderate short	Old	Unhealthy	High
Longer	Moderate short	Old	Unhealthy	High
Very Long	Moderate short	Old	Unhealthy	Higher
Extreme	Moderate short	Old	Unhealthy	Higher
Short	Moderate short	V.Old	Unhealthy	Lower
Moderate Short	Moderate short	V.Old	Unhealthy	Moderate.Low
Moderate	Moderate short	V.Old	Unhealthy	Moderate
Moderate Long	Moderate short	V.Old	Unhealthy	Moderate.High
Long	Moderate short	V.Old	Unhealthy	High
Longer	Moderate short	V.Old	Unhealthy	Higher
Very Long	Moderate short	V.Old	Unhealthy	Higher
Extreme	Moderate short	V.Old	Unhealthy	Highest
Short	Moderate short	Extreme Old	Unhealthy	Extreme Lowest
Moderate Short	Moderate short	Extreme Old	Unhealthy	Lowest
Moderate	Moderate short	Extreme Old	Unhealthy	Lower
Moderate Long	Moderate short	Extreme Old	Unhealthy	Low
Long	Moderate short	Extreme Old	Unhealthy	Low
Longer	Moderate short	Extreme Old	Unhealthy	Moderate.Low
Very Long	Moderate short	Extreme Old	Unhealthy	Moderate.Low
Extreme	Moderate short	Extreme Old	Unhealthy	Moderate
Short	Long	Extreme New	Good. Moderate	Neglible
Moderate Short	Long	Extreme New	Good. Moderate	V.Extreme Lowest
Moderate	Long	Extreme New	Good. Moderate	V.Extreme Lowest
Moderate Long	Long	Extreme New	Good. Moderate	Extreme Lowest
Long	Long	Extreme New	Good. Moderate	Extreme Lowest
Longer	Long	Extreme New	Good. Moderate	Extreme Lowest
Very Long	Long	Extreme New	Good. Moderate	Lowest
Extreme	Long	Extreme New	Good. Moderate	Lowest
Short	Long	V.New	Good. Moderate	V.Extreme Lowest
Moderate Short	Long	V.New	Good. Moderate	Extreme Lowest
Moderate	Long	V.New	Good. Moderate	Extreme Lowest
Moderate Long	Long	V.New	Good. Moderate	Lowest
Long	Long	V.New	Good. Moderate	Lowest
Longer	Long	V.New	Good. Moderate	Lower
Very Long	Long	V.New	Good. Moderate	Lower
Extreme	Long	V.New	Good. Moderate	Low
Short	Long	New	Good. Moderate	V.Extreme Lowest
Moderate Short	Long	New	Good. Moderate	Extreme Lowest
Moderate	Long	New	Good. Moderate	Lowest
Moderate Long	Long	New	Good. Moderate	Lower
Long	Long	New	Good. Moderate	Lower
Longer	Long	New	Good. Moderate	Low
Very Long	Long	New	Good. Moderate	Low
Extreme	Long	New	Good. Moderate	Moderate.Low
Short	Long	Mod.New	Good. Moderate	Extreme Lowest
Moderate Short	Long	Mod.New	Good. Moderate	Lowest
Moderate	Long	Mod.New	Good. Moderate	Lower
Moderate Long	Long	Mod.New	Good. Moderate	Low
Long	Long	Mod.New	Good. Moderate	Low
Longer	Long	Mod.New	Good. Moderate	Moderate.Low
Very Long	Long	Mod.New	Good. Moderate	Moderate.Low

Extreme	Long	Mod.New	Good. Moderate	Moderate
Short	Long	Moderate	Good. Moderate	Extreme Lowest
Moderate Short	Long	Moderate	Good. Moderate	Lowest
Moderate	Long	Moderate	Good. Moderate	Lower
Moderate Long	Long	Moderate	Good. Moderate	Low
Long	Long	Moderate	Good. Moderate	Moderate.Low
Longer	Long	Moderate	Good. Moderate	Moderate.Low
Very Long	Long	Moderate	Good. Moderate	Moderate
Extreme	Long	Moderate	Good. Moderate	Moderate.High
Short	Long	Mod.Old	Good. Moderate	Extreme Lowest
Moderate Short	Long	Mod.Old	Good. Moderate	Lower
Moderate	Long	Mod.Old	Good. Moderate	Low
Moderate Long	Long	Mod.Old	Good. Moderate	Moderate.Low
Long	Long	Mod.Old	Good. Moderate	Moderate.Low
Longer	Long	Mod.Old	Good. Moderate	Moderate
Very Long	Long	Mod.Old	Good. Moderate	Moderate.High
Extreme	Long	Mod.Old	Good. Moderate	Moderate.High
Short	Long	Old	Good. Moderate	Lowest
Moderate Short	Long	Old	Good. Moderate	Lower
Moderate	Long	Old	Good. Moderate	Low
Moderate Long	Long	Old	Good. Moderate	Moderate.Low
Long	Long	Old	Good. Moderate	Moderate
Longer	Long	Old	Good. Moderate	Moderate.High
Very Long	Long	Old	Good. Moderate	High
Extreme	Long	Old	Good. Moderate	High
Short	Long	V.Old	Good. Moderate	Lowest
Moderate Short	Long	V.Old	Good. Moderate	Low
Moderate	Long	V.Old	Good. Moderate	Moderate.Low
Moderate Long	Long	V.Old	Good. Moderate	Moderate
Long	Long	V.Old	Good. Moderate	Moderate.High
Longer	Long	V.Old	Good. Moderate	Moderate.High
Very Long	Long	V.Old	Good. Moderate	High
Extreme	Long	V.Old	Good. Moderate	High
Short	Long	Extreme Old	Good. Moderate	Lowest
Moderate Short	Long	Extreme Old	Good. Moderate	Low
Moderate	Long	Extreme Old	Good. Moderate	Moderate.Low
Moderate Long	Long	Extreme Old	Good. Moderate	Moderate
Long	Long	Extreme Old	Good. Moderate	Moderate.High
Longer	Long	Extreme Old	Good. Moderate	High
Very Long	Long	Extreme Old	Good. Moderate	High
Extreme	Long	Extreme Old	Good. Moderate	Higher
Short	Long	Extreme New	Moderately Acceptable	V.Extreme Lowest
Moderate Short	Long	Extreme New	Moderately Acceptable	Extreme Lowest
Moderate	Long	Extreme New	Moderately Acceptable	Extreme Lowest
Moderate Long	Long	Extreme New	Moderately Acceptable	Lowest
Long	Long	Extreme New	Moderately Acceptable	Lowest
Longer	Long	Extreme New	Moderately Acceptable	Lower
Very Long	Long	Extreme New	Moderately Acceptable	Lower
Extreme	Long	Extreme New	Moderately Acceptable	Low
Short	Long	V.New	Moderately Acceptable	Extreme Lowest
Moderate Short	Long	V.New	Moderately Acceptable	Lowest
Moderate	Long	V.New	Moderately Acceptable	Lower
Moderate Long	Long	V.New	Moderately Acceptable	Low
Long	Long	V.New	Moderately Acceptable	Low
Longer	Long	V.New	Moderately Acceptable	Moderate.Low
Very Long	Long	V.New	Moderately Acceptable	Moderate.Low
Extreme	Long	V.New	Moderately Acceptable	Moderate

Short	Long	New	Moderately Acceptable	Extreme Lowest
Moderate Short	Long	New	Moderately Acceptable	Lower
Moderate	Long	New	Moderately Acceptable	Low
Moderate Long	Long	New	Moderately Acceptable	Moderate.Low
Long	Long	New	Moderately Acceptable	Moderate.Low
Longer	Long	New	Moderately Acceptable	Moderate
Very Long	Long	New	Moderately Acceptable	Moderate.High
Extreme	Long	New	Moderately Acceptable	Moderate.High
Short	Long	Mod.New	Moderately Acceptable	Lowest
Moderate Short	Long	Mod.New	Moderately Acceptable	Low
Moderate	Long	Mod.New	Moderately Acceptable	Moderate.Low
Moderate Long	Long	Mod.New	Moderately Acceptable	Moderate
Long	Long	Mod.New	Moderately Acceptable	Moderate.High
Longer	Long	Mod.New	Moderately Acceptable	Moderate.High
Very Long	Long	Mod.New	Moderately Acceptable	High
Extreme	Long	Mod.New	Moderately Acceptable	High
Short	Long	Moderate	Moderately Acceptable	Lowest
Moderate Short	Long	Moderate	Moderately Acceptable	Low
Moderate	Long	Moderate	Moderately Acceptable	Moderate.Low
Moderate Long	Long	Moderate	Moderately Acceptable	Moderate.High
Long	Long	Moderate	Moderately Acceptable	High
Longer	Long	Moderate	Moderately Acceptable	High
Very Long	Long	Moderate	Moderately Acceptable	Higher
Extreme	Long	Moderate	Moderately Acceptable	Higher
Short	Long	Mod.Old	Moderately Acceptable	Lower
Moderate Short	Long	Mod.Old	Moderately Acceptable	Moderate.Low
Moderate	Long	Mod.Old	Moderately Acceptable	Moderate
Moderate Long	Long	Mod.Old	Moderately Acceptable	Moderate.High
Long	Long	Mod.Old	Moderately Acceptable	High
Longer	Long	Mod.Old	Moderately Acceptable	Higher
Very Long	Long	Mod.Old	Moderately Acceptable	Higher
Extreme	Long	Mod.Old	Moderately Acceptable	Highest
Short	Long	Old	Moderately Acceptable	Lower
Moderate Short	Long	Old	Moderately Acceptable	Moderate.Low
Moderate	Long	Old	Moderately Acceptable	Moderate.High
Moderate Long	Long	Old	Moderately Acceptable	High
Long	Long	Old	Moderately Acceptable	Higher
Longer	Long	Old	Moderately Acceptable	Higher
Very Long	Long	Old	Moderately Acceptable	Highest
Extreme	Long	Old	Moderately Acceptable	Highest
Short	Long	V.Old	Moderately Acceptable	Low
Moderate Short	Long	V.Old	Moderately Acceptable	Moderate
Moderate	Long	V.Old	Moderately Acceptable	Moderate.High
Moderate Long	Long	V.Old	Moderately Acceptable	High
Long	Long	V.Old	Moderately Acceptable	Higher
Longer	Long	V.Old	Moderately Acceptable	Highest
Very Long	Long	V.Old	Moderately Acceptable	Highest
Extreme	Long	V.Old	Moderately Acceptable	Extreme Highest
Short	Long	Extreme Old	Moderately Acceptable	Low
Moderate Short	Long	Extreme Old	Moderately Acceptable	Moderate
Moderate	Long	Extreme Old	Moderately Acceptable	High
Moderate Long	Long	Extreme Old	Moderately Acceptable	Higher
Long	Long	Extreme Old	Moderately Acceptable	Higher
Longer	Long	Extreme Old	Moderately Acceptable	Highest
Very Long	Long	Extreme Old	Moderately Acceptable	Extreme Highest
Extreme	Long	Extreme Old	Moderately Acceptable	Extreme Highest
Short	Long	Extreme New	Unhealthy	V.Extreme Lowest

Moderate Short	Long	Extreme New	Unhealthy	Extreme Lowest
Moderate	Long	Extreme New	Unhealthy	Lowest
Moderate Long	Long	Extreme New	Unhealthy	Lower
Long	Long	Extreme New	Unhealthy	Lower
Longer	Long	Extreme New	Unhealthy	Low
Very Long	Long	Extreme New	Unhealthy	Low
Extreme	Long	Extreme New	Unhealthy	Moderate.Low
Short	Long	V.New	Unhealthy	Extreme Lowest
Moderate Short	Long	V.New	Unhealthy	Lower
Moderate	Long	V.New	Unhealthy	Low
Moderate Long	Long	V.New	Unhealthy	Moderate.Low
Long	Long	V.New	Unhealthy	Moderate.Low
Longer	Long	V.New	Unhealthy	Moderate
Very Long	Long	V.New	Unhealthy	Moderate.High
Extreme	Long	V.New	Unhealthy	Moderate.High
Short	Long	New	Unhealthy	Lowest
Moderate Short	Long	New	Unhealthy	Low
Moderate	Long	New	Unhealthy	Moderate.Low
Moderate Long	Long	New	Unhealthy	Moderate
Long	Long	New	Unhealthy	Moderate.High
Longer	Long	New	Unhealthy	High
Very Long	Long	New	Unhealthy	High
Extreme	Long	New	Unhealthy	Higher
Short	Long	Mod.New	Unhealthy	Lower
Moderate Short	Long	Mod.New	Unhealthy	Moderate.Low
Moderate	Long	Mod.New	Unhealthy	Moderate
Moderate Long	Long	Mod.New	Unhealthy	Moderate.High
Long	Long	Mod.New	Unhealthy	High
Longer	Long	Mod.New	Unhealthy	Higher
Very Long	Long	Mod.New	Unhealthy	Higher
Extreme	Long	Mod.New	Unhealthy	Highest
Short	Long	Moderate	Unhealthy	Lower
Moderate Short	Long	Moderate	Unhealthy	Moderate.Low
Moderate	Long	Moderate	Unhealthy	Moderate.High
Moderate Long	Long	Moderate	Unhealthy	High
Long	Long	Moderate	Unhealthy	Higher
Longer	Long	Moderate	Unhealthy	Higher
Very Long	Long	Moderate	Unhealthy	Highest
Extreme	Long	Moderate	Unhealthy	Extreme Highest
Short	Long	Mod.Old	Unhealthy	Low
Moderate Short	Long	Mod.Old	Unhealthy	Moderate
Moderate	Long	Mod.Old	Unhealthy	High
Moderate Long	Long	Mod.Old	Unhealthy	Higher
Long	Long	Mod.Old	Unhealthy	Higher
Longer	Long	Mod.Old	Unhealthy	Highest
Very Long	Long	Mod.Old	Unhealthy	Extreme Highest
Extreme	Long	Mod.Old	Unhealthy	Extreme Highest
Short	Long	Old	Unhealthy	Low
Moderate Short	Long	Old	Unhealthy	Moderate.High
Moderate	Long	Old	Unhealthy	High
Moderate Long	Long	Old	Unhealthy	Higher
Long	Long	Old	Unhealthy	Highest
Longer	Long	Old	Unhealthy	Extreme Highest
Very Long	Long	Old	Unhealthy	Extreme Highest
Extreme	Long	Old	Unhealthy	V.Extreme Highest
Short	Long	V.Old	Unhealthy	Moderate.Low
Moderate Short	Long	V.Old	Unhealthy	Moderate.High

Moderate	Long	V.Old	Unhealthy	Higher
Moderate Long	Long	V.Old	Unhealthy	Highest
Long	Long	V.Old	Unhealthy	Extreme Highest
Longer	Long	V.Old	Unhealthy	Extreme Highest
Very Long	Long	V.Old	Unhealthy	V.Extreme Highest
Extreme	Long	V.Old	Unhealthy	V.Extreme Highest
Short	Long	Extreme Old	Unhealthy	Moderate.Low
Moderate Short	Long	Extreme Old	Unhealthy	High
Moderate	Long	Extreme Old	Unhealthy	Higher
Moderate Long	Long	Extreme Old	Unhealthy	Highest
Long	Long	Extreme Old	Unhealthy	Extreme Highest
Longer	Long	Extreme Old	Unhealthy	V.Extreme Highest
Very Long	Long	Extreme Old	Unhealthy	V.Extreme Highest
Extreme	Long	Extreme Old	Unhealthy	V.Extreme Highest

Table 7-2: Fuzzy Rules for Secondary filter replacement

Replacement Interval	Working Hours	Location	Output
Short	Moderate	Good. Moderate	Lowest
Moderate Short	Moderate	Good. Moderate	Lowest
Moderate	Moderate	Good. Moderate	Lower
Moderate Long	Moderate	Good. Moderate	Lower
Long	Moderate	Good. Moderate	Low
Longer	Moderate	Good. Moderate	Low
Very Long	Moderate	Good. Moderate	Moderate.Low
Extreme	Moderate	Good. Moderate	Moderate.Low
Short	Low	Good. Moderate	Lowest
Moderate Short	Low	Good. Moderate	Lowest
Moderate	Low	Good. Moderate	Lowest
Moderate Long	Low	Good. Moderate	Lowest
Long	Low	Good. Moderate	Lowest
Longer	Low	Good. Moderate	Lowest
Very Long	Low	Good. Moderate	Lower
Extreme	Low	Good. Moderate	Lower
Short	Moderate.Short	Good. Moderate	Lowest
Moderate Short	Moderate.Short	Good. Moderate	Lowest
Moderate	Moderate.Short	Good. Moderate	Lowest
Moderate Long	Moderate.Short	Good. Moderate	Lower
Long	Moderate.Short	Good. Moderate	Lower
Longer	Moderate.Short	Good. Moderate	Lower
Very Long	Moderate.Short	Good. Moderate	Low
Extreme	Moderate.Short	Good. Moderate	Low
Short	Long	Good. Moderate	Lowest
Moderate Short	Long	Good. Moderate	Lower
Moderate	Long	Good. Moderate	Lower
Moderate Long	Long	Good. Moderate	Low
Long	Long	Good. Moderate	Moderate.Low
Longer	Long	Good. Moderate	Moderate.Low

Very Long	Long	Good. Moderate	Moderate
Extreme	Long	Good. Moderate	Moderate.Long
Short	Moderate	Moderately Acceptable	Lowest
Moderate Short	Moderate	Moderately Acceptable	Lower
Moderate	Moderate	Moderately Acceptable	Low
Moderate Long	Moderate	Moderately Acceptable	Moderate.Low
Long	Moderate	Moderately Acceptable	Moderate
Longer	Moderate	Moderately Acceptable	Moderate.Long
Very Long	Moderate	Moderately Acceptable	High
Extreme	Moderate	Moderately Acceptable	Higher
Short	Low	Moderately Acceptable	Lowest
Moderate Short	Low	Moderately Acceptable	Lowest
Moderate	Low	Moderately Acceptable	Lowest
Moderate Long	Low	Moderately Acceptable	Lower
Long	Low	Moderately Acceptable	Lower
Longer	Low	Moderately Acceptable	Lower
Very Long	Low	Moderately Acceptable	Low
Extreme	Low	Moderately Acceptable	Low
Short	Moderate.Short	Moderately Acceptable	Lowest
Moderate Short	Moderate.Short	Moderately Acceptable	Lower
Moderate	Moderate.Short	Moderately Acceptable	Lower
Moderate Long	Moderate.Short	Moderately Acceptable	Low
Long	Moderate.Short	Moderately Acceptable	Moderate.Low
Longer	Moderate.Short	Moderately Acceptable	Moderate.Low
Very Long	Moderate.Short	Moderately Acceptable	Moderate
Extreme	Moderate.Short	Moderately Acceptable	Moderate.Long
Short	Long	Moderately Acceptable	Lower
Moderate Short	Long	Moderately Acceptable	Low
Moderate	Long	Moderately Acceptable	Moderate.Low
Moderate Long	Long	Moderately Acceptable	Moderate.Long
Long	Long	Moderately Acceptable	High
Longer	Long	Moderately Acceptable	Higher
Very Long	Long	Moderately Acceptable	Higher
Extreme	Long	Moderately Acceptable	Highest
Short	Moderate	Unhealthy	Lower
Moderate Short	Moderate	Unhealthy	Low
Moderate	Moderate	Unhealthy	Moderate
Moderate Long	Moderate	Unhealthy	Moderate.Long
Long	Moderate	Unhealthy	Higher
Longer	Moderate	Unhealthy	Higher
Very Long	Moderate	Unhealthy	Highest
Extreme	Moderate	Unhealthy	Extreme
Short	Low	Unhealthy	Lowest
Moderate Short	Low	Unhealthy	Lowest
Moderate	Low	Unhealthy	Lower
Moderate Long	Low	Unhealthy	Lower

Long	Low	Unhealthy	Low
Longer	Low	Unhealthy	Low
Very Long	Low	Unhealthy	Moderate.Low
Extreme	Low	Unhealthy	Moderate.Low
Short	Moderate.Short	Unhealthy	Lowest
Moderate Short	Moderate.Short	Unhealthy	Lower
Moderate	Moderate.Short	Unhealthy	Low
Moderate Long	Moderate.Short	Unhealthy	Moderate.Low
Long	Moderate.Short	Unhealthy	Moderate
Longer	Moderate.Short	Unhealthy	Moderate.Long
Very Long	Moderate.Short	Unhealthy	High
Extreme	Moderate.Short	Unhealthy	Higher
Short	Long	Unhealthy	Lower
Moderate Short	Long	Unhealthy	Moderate.Low
Moderate	Long	Unhealthy	Moderate.Long
Moderate Long	Long	Unhealthy	Higher
Long	Long	Unhealthy	Highest
Longer	Long	Unhealthy	Extreme
Very Long	Long	Unhealthy	Extreme
Extreme	Long	Unhealthy	Extreme

7.3 Appendix C: Hospitals (2,3 & 4) Individual condition rating

Table 7-3: Hospital 2 (Individual rating matrix)

Hospital 2			
Condition	Slab	Beams	Columns
1	10%	10%	25%
2	15%	15%	10%
3	25%	18%	15%
4	20%	25%	20%
5	30%	32%	25%

Table 7-4: Hospital 3 (Individual rating matrix)

Hospital 3			
Condition	Slab	Beams	Columns
1	20%	25%	23%
2	15%	15%	15%
3	25%	20%	17%
4	15%	20%	20%
5	25%	20%	25%

Table 7-5: Hospital 4 (Individual rating matrix)

Hospital 4			
Condition	Slab	Beams	Columns
1	13%	14%	21%
2	14%	15%	13%
3	25%	18%	14%
4	18%	23%	22%
5	30%	29%	30%

7.4 Appendix D: Rehabilitation Cost Optimization results

Table 7-6: Rehabilitation Strategy for Hospital 2

Hospital 2	2014	2015	2016	2017	2018	2019
Reinforcement cleaning	89.16%	89.15%	89.84%	89.99%	89.68%	89.92%
Partial concrete replacement and reinforcement	89.46%	89.97%	89.03%	89.96%	90.00%	83.93%
Full concrete replacement and reinforcement	6.78%	12.02%	17.14%	20.99%	24.89%	30.70%
Rehabilitation Cost (EGP)	4,867,807	5,492,205	6,138,847	6,774,074	7,439,062	8,205,624

Table 7-7: Rehabilitation Strategy for Hospital 3

Hospital 3	2014	2015	2016	2017	2018	2019
Reinforcement cleaning	94.76%	85.37%	87.82%	90.27%	89.36%	89.99%
Partial concrete replacement and reinforcement	58.61%	78.19%	84.01%	89.84%	88.74%	89.34%
Full concrete replacement and reinforcement	0%	0%	3%	5.07%	11.22%	15.48%
Rehabilitation Cost (EGP)	2,770,575	3,224,378	3,588,360	4,107,103	4,693,831	5,248,468

Table 7-8: Rehabilitation Strategy for Hospital 4

Hospital 4	2014	2015	2016	2017	2018	2019
Reinforcement cleaning	91.02%	90.00%	89.50%	89.93%	90.00%	89.99%
Partial concrete replacement and reinforcement	89.44%	89.93%	88.48%	89.98%	89.01%	89.99%
Full concrete replacement and reinforcement	5.27%	10.90%	16.63%	20.14%	24.40%	27.42%
Rehabilitation Cost (EGP)	5,375,967	6,103,969	6,868,399	7,576,655	8,346,891	9,092,793

7.5 Appendix E: (Monte Carlo simulation results)

Table 7-9: Monte-Carlo for HVAC (Probability of failure vs Inspection intervals/ days)

Probability of failure	Torn Filters	Coil leaks	Freon gas pipe leaks	Defective fan belt	Shaft bending	Bearing fatigue	Impellers Fatigue	HEPA Filter leaks	Bearing failure due to improper lubrication
5%	5.25	61.49	31.48	21.25	31.49	61.50	61.50	10.74	15.74
10%	5.50	62.99	32.98	22.48	33.00	63.00	62.99	11.49	16.50
15%	5.75	64.48	34.48	23.75	34.49	64.48	64.49	12.24	17.24
20%	6.00	65.99	35.98	24.98	35.99	65.99	65.98	13.00	18.00
25%	6.25	67.48	37.49	26.24	37.48	67.50	67.48	13.75	18.74
30%	6.50	68.98	38.98	27.49	38.98	69.00	69.00	14.50	19.50
35%	6.75	70.49	40.49	28.73	40.49	70.49	70.48	15.24	20.24
40%	7.00	71.97	41.98	29.99	41.99	71.97	71.99	15.99	20.99
45%	7.25	73.48	43.49	31.25	43.47	73.47	73.48	16.74	21.74
50%	7.50	74.98	44.99	32.49	44.99	74.97	74.97	17.49	22.50
55%	7.75	76.48	46.48	33.74	46.48	76.49	76.48	18.24	23.24
60%	8.00	77.97	47.97	35.00	47.99	77.97	77.99	19.00	24.00
65%	8.25	79.49	49.49	36.23	49.47	79.49	79.47	19.74	24.74
70%	8.50	80.99	50.99	37.49	50.99	80.99	80.97	20.50	25.49
75%	8.75	82.48	52.49	38.73	52.49	82.47	82.48	21.25	26.24
80%	9.00	83.99	53.99	39.98	53.98	83.98	84.00	22.00	26.99
85%	9.25	85.48	55.49	41.25	55.48	85.49	85.49	22.74	27.74
90%	9.50	86.99	57.00	42.49	56.98	86.99	86.98	23.49	28.49
95%	9.75	88.47	58.49	43.74	58.50	88.48	88.49	24.24	29.24

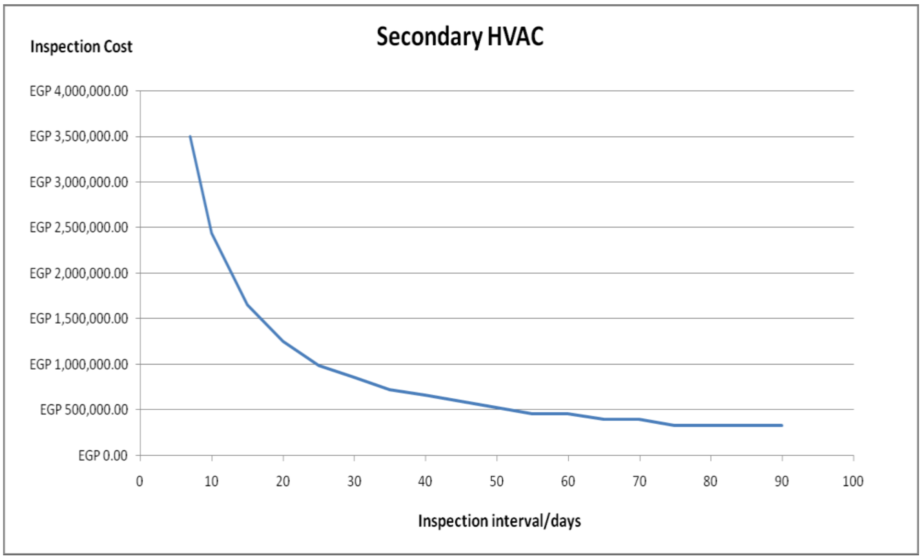
Table 7-10: Monte-Carlo for medical gas (Probability of failure vs Inspection intervals/ days)

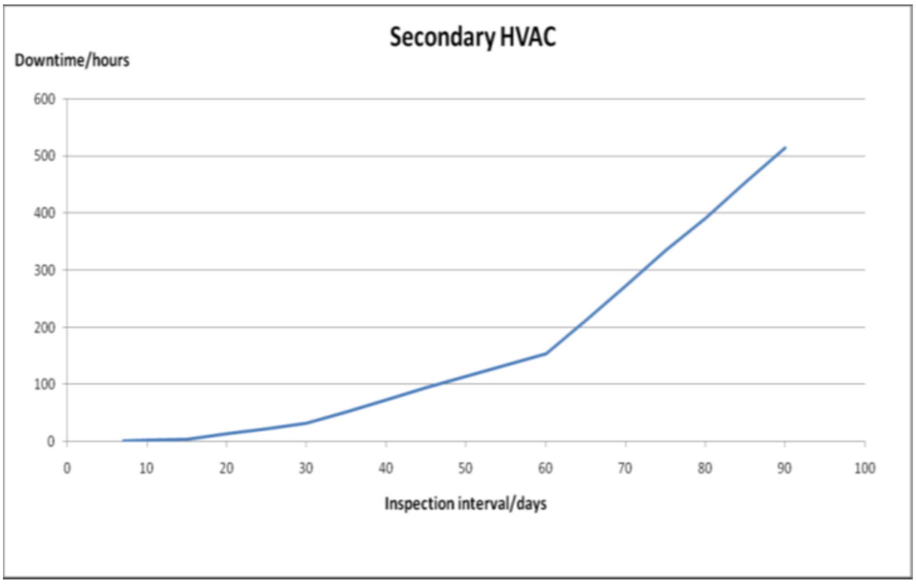
Probability of failure	Vacuum insulated tank	Evaporator	Control Valve	Safety Valve	Super heater	Regulator	Inlet Filter	Carbon Filter	Bacterial Filter	Relief Valve	Air Receiver tank	Dryer	Pressure reducer
5%	124.41	91.50	31.49	31.49	8.13	31.50	121.49	122.98	91.50	31.47	10.98	91.50	31.50
10%	128.93	92.98	32.98	32.98	9.28	32.98	122.98	126.00	92.98	32.98	11.98	92.99	32.99
15%	133.44	94.48	34.49	34.48	10.43	34.47	124.50	128.95	94.48	34.48	12.98	94.48	34.48
20%	137.98	96.00	35.98	35.98	11.58	36.00	125.99	131.95	95.99	35.99	13.98	95.97	35.97
25%	142.46	97.47	37.47	37.48	12.73	37.50	127.48	134.96	97.49	37.47	14.99	97.50	37.49
30%	146.99	99.00	38.97	38.99	13.90	38.99	128.97	137.95	98.99	38.99	16.00	99.00	38.99
35%	151.45	100.47	40.50	40.49	15.03	40.49	130.49	140.95	100.47	40.50	16.98	100.48	40.49
40%	155.93	101.98	41.99	41.98	16.20	41.98	131.98	143.99	101.98	41.99	17.99	101.99	41.99
45%	160.41	103.48	43.50	43.48	17.34	43.47	133.49	146.98	103.47	43.48	19.00	103.47	43.50
50%	164.93	104.99	45.00	44.97	18.48	44.98	134.99	149.96	104.99	44.98	19.99	104.98	44.99
55%	169.44	106.50	46.48	46.48	19.64	46.50	136.50	152.98	106.48	46.50	20.99	106.47	46.48
60%	173.93	107.98	47.97	47.99	20.80	47.97	137.98	155.97	108.00	47.99	21.98	107.99	47.99
65%	178.50	109.48	49.50	49.50	21.94	49.49	139.49	158.96	109.48	49.48	22.99	109.49	49.49
70%	182.99	110.99	50.98	50.98	23.09	50.98	140.97	162.00	110.97	50.98	23.99	110.99	50.97
75%	187.48	112.48	52.50	52.48	24.23	52.49	142.49	164.97	112.48	52.48	24.98	112.49	52.48
80%	191.99	113.98	53.99	53.98	25.39	53.98	143.98	167.98	113.99	53.98	25.99	113.98	53.98
85%	196.42	115.47	55.48	55.48	26.53	55.48	145.49	171.00	115.47	55.49	26.99	115.49	55.50
90%	200.98	116.99	56.99	57.00	27.69	56.98	146.99	173.95	117.00	56.99	27.98	117.00	57.00
95%	205.43	118.49	58.47	58.50	28.84	58.47	148.47	176.98	118.48	58.48	28.99	118.49	58.49

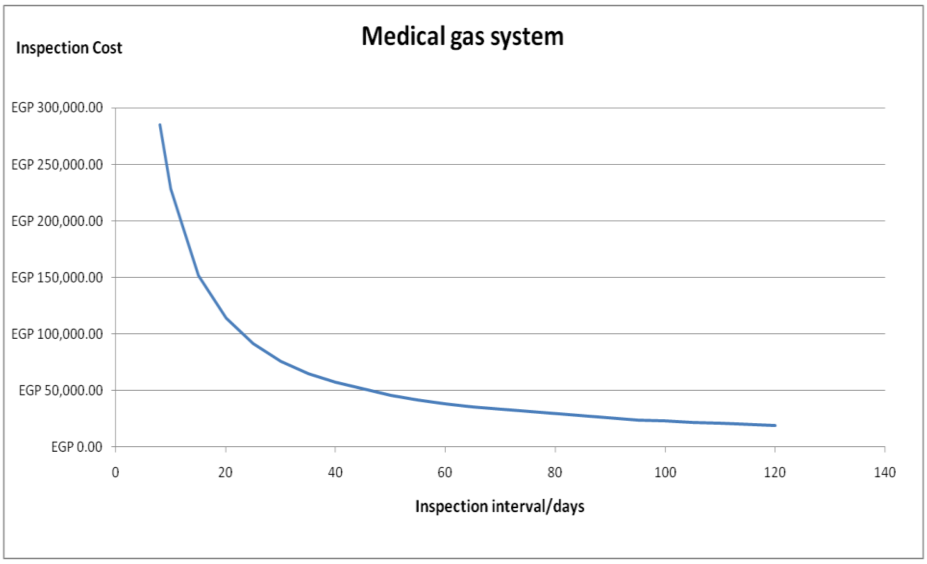
Table 7-11: Monte-Carlo for Elevator (Probability of failure vs Inspection intervals/ days)

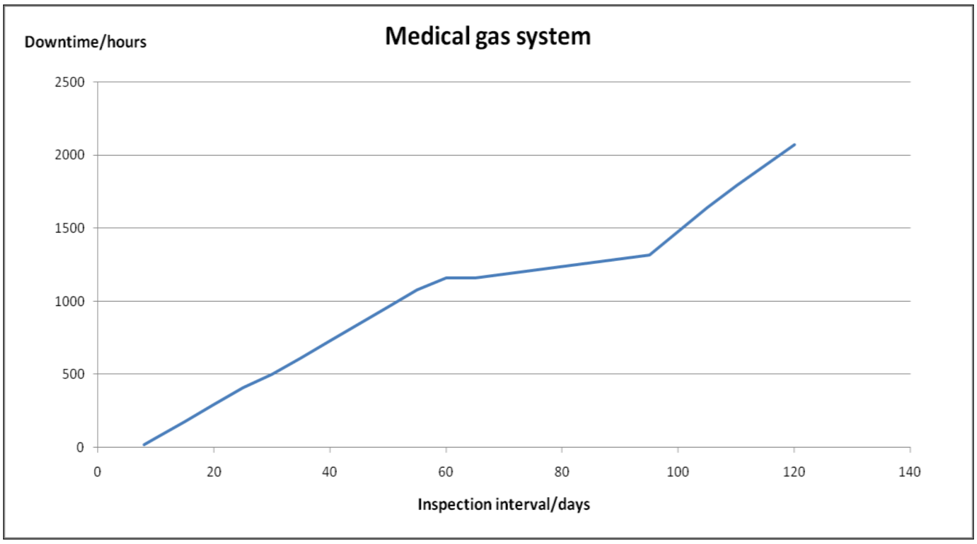
Probability of failure	Guideways	Sheaves	Wire Rope	Elevator Brakes	Bearings	Clutch
5%	91.50	10.49	62.98	7.40	15.74	121.49
10%	92.98	10.99	66.00	7.80	16.49	122.97
15%	94.50	11.49	68.95	8.20	17.25	124.50
20%	95.99	11.99	72.00	8.60	17.99	125.98
25%	97.50	12.50	74.95	8.99	18.74	127.48
30%	99.00	13.00	78.00	9.39	19.49	128.97
35%	100.47	13.49	80.95	9.79	20.25	130.47
40%	101.98	14.00	83.98	10.19	20.99	131.99
45%	103.47	14.49	86.99	10.60	21.74	133.48
50%	104.99	14.99	89.97	10.99	22.49	134.97
55%	106.49	15.49	92.98	11.40	23.24	136.48
60%	107.98	16.00	95.96	11.80	23.99	137.99
65%	109.48	16.49	98.97	12.20	24.75	139.50
70%	110.97	17.00	101.96	12.60	25.50	140.99
75%	112.48	17.49	104.98	13.00	26.24	142.48
80%	113.99	17.99	107.95	13.39	26.99	143.99
85%	115.48	18.50	110.96	13.80	27.74	145.47
90%	117.00	18.99	113.99	14.20	28.50	146.99
95%	118.48	19.49	116.99	14.60	29.25	148.48

7.6 Appendix F: What if Scenarios








Medical gas system
Downtime/hours
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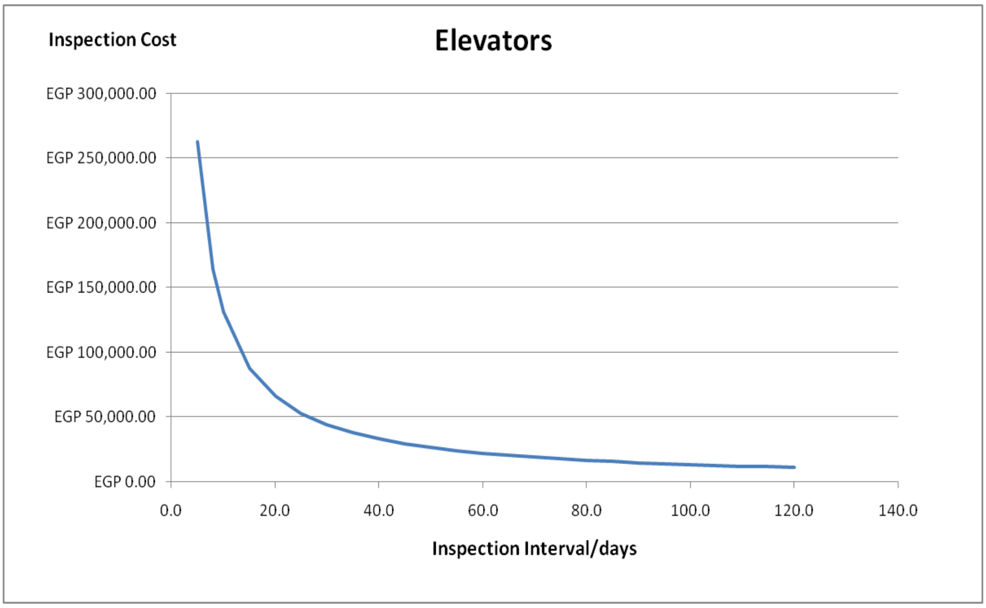
2000
1500
1000
500
0
0
20
40
60
80
100
120
140
Inspection interval/days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0.0
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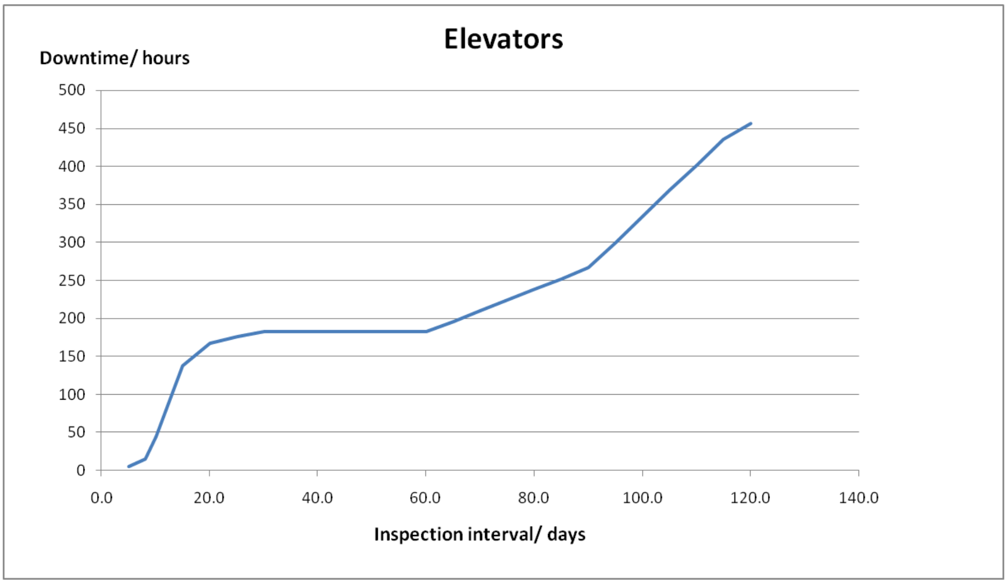
40.0
60.0
80.0
100.0
120.0
140.0
Inspection Interval/days


Elevators
Downtime/ hours
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450
400
350
300
250
200
150
100
50
0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
Inspection interval/ days