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Minimizing the non-revenue water in Bahrain networks

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Abstract

Bahrain has invested in minimizing the Non-Revenue Water (NRW) since long time ago through its Electricity and Water Authority (EWA). In recent researches, it was found that the yearly total NRW in Bahrain is approximately equal to 21,535 M Gallon with a total cost of BD 71 Million. One of EWA strategic goals is to complete the 99% of all complains within 2 hours.

A queuing model is developed for each depot to find the optimum number of maintenance teams that satisfy the condition of completing 99% of received complaints within 2 hours. A survey sheet was designed to collect the required information for the model from Muharraq, Budaya and Riffa depots while the maintenance teams were responding to complaints. Due to the shift arrangement and due to the type of maintenance teams in each depot, a linear programming model is developed in order to distribute and schedule EWA and contractor maintenance teams while keeping the EWA current maintenance teams.

To validate the results, Arena simulator is used to verify whether the results obtained are practical or not by ensuring that the delay time to start serving a complaint is minimized. To evaluate the robustness of the findings with the increase of the volume of the complaints or the decrease of the number of maintenance teams, a sensitivity analysis is conducted to ensure the completion of 99% of complaints within 2 hours. The results obtained show that the objectives of this research are achieved, which indicate that a considerable reduction in the NRW can be maintained.

Dedication

To my family, wife, and to my father,,,

Acknowledgment

I would like to thank Professor Saad Suliman my thesis supervisor for his support, advice and encouragement.

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	Number of complaints arrival to the depots
	Average arrival rate
	Number of maintenance teams
	Average service rate
	Service utilization
T	Threshold time
	Probability of zero complaints in the system
	Probability that there are complaints in the system
	Average number of complaints in queue
	Average waiting time in queue
	Average waiting time in system
	Average number of complaints in the system
	Erlang formula
	Objective function for the optimum distribution
	Number of contractors maintenance teams
	Number of EWA maintenance teams
	Cost of contractor maintenance teams
	Cost of EWA maintenance teams

Glossary of Abbreviations

NRW	Non-Revenue Water
EWA	Electricity and Water Authority
WDD	Water Distribution Directorate
VIP	Very Important People
GIS	Geographical Information System
CSS	Customer Services System
DI	Ductile Iron pipes
PP	Polythene Pipes
AC	Asbestos Cement pipes
BCM	Billion Cubic Meter
IWA	International Water Association
DMA	District Meter Area
BABE	Burst and Background Estimates
WSS	Water Supply Scheme
UARL	Unavoidable Annual Real Losses
ELL	Economic Level of Leakage
SANFLOW	South African Night Flow
ANN	Artificial Neural Networks
CDF	Cumulative Distribution Function
FCFS	First Come First Served
SAP	System Applications Products

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A	EWA CEO Presentation
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C	Sample of Muharraq Depot Survey
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Chapter 1

Introduction

1.1 Electricity and Water Authority

1.2 Non-Revenue Water (NRW)

1.3 Research Problem

1.4 Research Questions

1.5 Research Objectives

1.6 Research Significance

1.7 Methodology

Chapter 1: Introduction

1.1 Electricity and Water Authority

Electricity and Water Authority (EWA) is a Bahrain based government owned electricity and water service company. It is engaged in power generation as well as related activities like transmission and distribution. The company is also involved in the production, transmission, and distribution of water. EWA is headquartered in Manama, Bahrain.

EWA provides these critical services to nearly one million people, it is one of the largest and best run government agencies in Bahrain. EWA's 3,500 employees in 17 locations live a customer-centric culture, allocate resources effectively, and focus on performance and results.

1.1.1 EWA mission, vision and objectives

- **Mission**

Provide reliable and quality supply of electricity and water for sustainable development of Bahrain (EWA web page).

- **Vision**

By 2017 EWA is a Model of Excellence in the provision of Electricity and Water services with minimum interruptions and timely revenue collection.

The pillars of EWA Strategy supporting the Vision are:

- Delivering a responsive and consistent service to customers.

- Providing sufficient and sustainable capacity supporting the Kingdom of Bahrain's Economic Development.
- Ensuring effective financial management of EWA's affairs.
- Maintaining a talented, high performing workforce to deliver on the Authorities Objectives (EWA web page).

- **Authority's objectives**

The objectives of EWA can be listed as below:

- Provide excellent, reliable, cost effective and quality supply of electricity and water to different sectors of consumers.
- Minimizing the Non-Revenue Water in Bahrain water pipelines networks.
- Make plans and conduct studies to complete existing projects as well as future projects for the expansion of the Ministry services to consumers.
- Maintain, develop and improve the existing transmission and distribution network to ensure highest standards of operational efficiency and minimum energy loss.
- Meet the Kingdom ever increasing demands for electricity and water consumption.
- Utilize information technology and other advanced systems like Geographical Information System (GIS), Customer Services System (CSS) and Resource Planning Project to provide excellent customer services.

EWA strategy map is divided into four important divisions: Financial outcome; customer outcome; internal process; and learning and growth, as shown in Figure (1.1) (EWA web page).

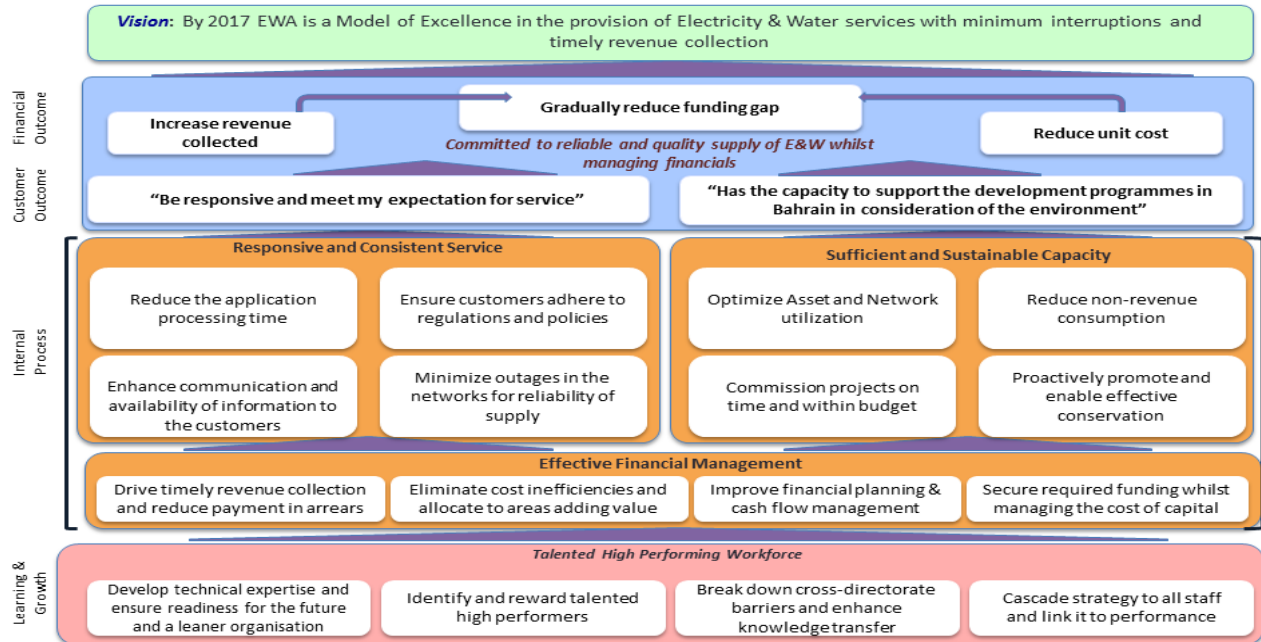


Figure (1.1)
EWA Strategy Map (Appendix B)

1.1.2 Water Distribution Directorate in EWA

Water Distribution Directorate (WDD) addresses the challenge of distributing water to the customers through adequate pipeline connectivity. WDD striving its best level to be in pace with the Kingdom's development and the future needs. New initiatives at corporate and WDD levels to alleviate the public concerns are presenting a new face to WDD as more customer friendly and efficient organization.

State of the art technologies are being implemented in WDD for planning, Design, Constructions and monitoring. The introduction of Geographic Information Systems, modeling, Balanced Scorecard, Bahrain excellence, SAP are few examples to confirm the above statement.

WDD main duties falls in planning, Design, Execute and future maintenance for water pipeline networks projects using different materials of pipeline including Ductile Iron pipes (DI) and Polythene Pipes (PP). These projects are categorized as following:

- Replacement: To replace Asbestos Cement pipes (AC) to DI pipes.
- Extension: To lay new DI or PP pipes for undeveloped or newly developed areas.
- Diversion: To Divert the location of the old pipelines to meet the new physical status on the site.

1.2 Non-Revenue Water (NRW)

Providing an adequate water supply is a major challenge facing many public water utilities in developing countries. A significant part of this challenge is Non-Revenue Water (NRW), which is the difference between the volume of water put into a water distribution system and the volume that is billed to customers. It is estimated that water utilities in developing countries can lose 30-50% of the water they put into their systems and they are unable to bill their customers for this loss. High levels of NRW are damaging to the financial viability of water utilities, as well as to the quality of water service.

NRW can occur through **physical losses** from leaking and broken pipes, which are caused by poor operations and maintenance, the lack of active leakage control, and poor quality of underground assets. NRW can also come from **commercial losses** caused by the under-registration of customer meters, data handling errors, illegal connections and theft. Another cause of NRW is **unbilled authorized consumption**, which includes water used by utilities for operational purposes, water used for firefighting, and water provided for free to certain consumer groups.

Reducing NRW can significantly improve the performance of developing country public water utilities by:

- ✓ Increasing the amount of treated water in the system that can be available to service customers without having to look for new sources of water (new water treatment plants, dams, desalination plans, etc).
- ✓ Increasing the revenue collected.
- ✓ Discouraging illegal connections which promotes fairness and improves the operational capacity of the system.
- ✓ Improving service to existing customers, promoting economic growth with new business opportunities created through NRW reduction activities, and new job creation through labor intensive leakage reduction activities.

Despite the potential benefits, NRW is not a simple matter for public utilities to overcome. New technical approaches need to be adopted and effective arrangements need to be established in the managerial and institutional environments. Some of the reasons for insufficient NRW reductions efforts are lack of:

- ✓ Understanding the magnitude of the problem.
- ✓ Capacity of skilled staff in various professions.
- ✓ Management focus.
- ✓ Most importantly, the enabling environment and incentives.

1.2.1 Global level of NRW and the acceptable level

The global level of NRW is very high. The average percentage of the global NRW is estimated at 35% (Farley M., et. al. 2008). Further, the global volume of NRW is 48.6 Billion Cubic Meter (BCM) per Year of which 32.7 BCM is real losses

(Kingdom et al., 2006). Water wastage of this amount costs water utilities worldwide US\$14 billion a year. Accordingly, saving half of this amount could provide water service to an additional 100 million people without further investments (Farley et al., 2008 and Kingdom et al., 2006).

Based on the International Water Association (IWA) (IWA, 2000), the general rule for the assessment of network condition based on project experience is:

Good condition of system = $\text{NRW} < 250 \text{ litre/connection/day}$

Average condition = $250 < \text{NRW} < 450 \text{ litre/connection/day}$

Bad condition of system = $\text{NRW} \geq 450 \text{ litre/connection/day}$

or expressed in litre/km main/day:

Good condition of system = $\text{NRW} < 10\,000 \text{ litre/km main/day}$

Average condition = $10\,000 < \text{NRW} < 18\,000 \text{ litre/km main/day}$

Bad condition of system = $\text{NRW} \geq 18.000 \text{ litre/km main/day}$

For example, Bahrain is experiencing a daily NRW rate of 16,512 litre/km main/day, according to IWA general rules, Bahrain water network falls in the category of an average condition.

1.2.2 Non revenue water in Bahrain

Bahrain has invested in minimizing the NRW since long time ago through EWA in order to save Bahrain natural resources for future generations and to ensure the durability of its services in providing Electricity and Water. In recent researches (Appendix A), it was found that the yearly total NRW is approximately equal to 21,535 M Gallon with a total cost of BD 71 Million which indicate the urgent needs for further investigations and studies in this regard to minimize the huge cost that EWA is bearing yearly. As a result, EWA has identified the main reasons that contributed in generating the high quantity of the NRW which are:

1. Visual leakages in the pipelines (ductile iron, asbestos cement and poly pipes).
2. Damaged domestic meters resulting in losses.
3. Damaged bulk meters.
4. Illegal connections.

EWA has introduced three main Depots all over Bahrain (Muharraq, Budaya and Riffa Depots) each with several teams to be responsible for any type of complaints raised by the public. Muharraq and Budaya Depots are managed by EWA but Riffa Depot is totally managed by a third party. In a recent research carried out by the Maintenance Department in EWA (Appendix A), it was found that the time needed to reach to a location of a complaint and to do the remedial actions in order to overcome the complaint is considered high. This time has affected the NRW proportionally and lead in an increase in the total yearly wasted budget.

Reaching to a complain location within a **very short period of time** and adapting a **practical and sufficient procedure** to overcome the complaints by a **professionalized team** while maintain a **durable water pipeline network** could have a huge effect in reducing the NRW.

In brief, the main causes affecting the NRW in the water pipeline networks can be summarized as following:

1. The time a complaint has to wait before it is being served.
2. The time needed to reach to the location of a complaint.
3. The procedures handled in order to rectify a complaint.
4. The crew's right workmanship in each maintenance team.
5. The quality of the water pipeline network.

Overcoming the above causes will lead to save Bahrain natural resources as well as Bahrain national funds for future generations.

1.3 Research Problem

The reports of WDD (Appendix A) show that the average time needed to rectify and overcome a complaint is varying between 4 to 6 hours from receiving officially the complaint until it is being closed including the transportation of the maintenance team as well as the workmanship on the site. This is considered a long time for the remedial activities and it should be shortened. One of WDD strategic goals, as shown in Appendix A, is to complete 99% of all complaints within 2 hours. If this strategic goal can be met then a huge reduction in the NRW as well as in the yearly wasted budget will be accrued.

As mentioned earlier, EWA has three main centralized Depots with maintenance teams for the emergency works in Muharraq, Budaya and Riffa regions. However, reducing the time needed to serve a complaint by finding the optimal number of teams per each region in Bahrain will have positive effect. With regard to the procedure of the remedial activities for the complaints, minimizing the time of each activity will lead to a better time saving. The specialization of the maintenance teams needs to be under investigation too.

All of the above will participate in achieving EWA strategic goals of completing complaints within the 2 hours which will have positive reduction of NRW.

1.4 Research Questions

1. What is the optimum number of the maintenance teams required for each region in Bahrain?

2. Is it possible to maintain EWA strategic goals of completing complaints within 2 hours?
3. Is it possible to reduce the delay time to serve a complaint to the minimum?
4. How much reduction in the NRW will be saved after modifying the current procedures?
5. What are the cost implications of using the optimal number of maintenance teams and modifying the current procedures?

1.5 Research Objectives

The main objectives of the research are as follows:

1. To achieve EWA strategic goal of completing complaints within 2 hours.
2. To find out the optimal number of maintenance teams needed for each region in Bahrain in order to minimize the NRW.
3. To minimize the delay time to serve a complaint in order to achieve the 2 hours strategy.

1.6 Research Significance

One of the major issues affecting water utilities in the developing world is the considerable difference between the amount of water put into the distribution system and the amount of water billed to consumers (NRW). High levels of NRW reflect huge volumes of water being lost through leaks, not being invoiced to customers, or both. It seriously affects the financial viability of water utilities through lost revenues and increased operational costs. A high NRW level is normally a surrogate for a poorly run water utility that lacks the governance, the autonomy, the accountability, and the technical and managerial skills necessary to provide reliable service to their population. Records show (Kingdom et al., 2006)

that more than US\$ 14 billion is lost every year by water utilities around the world due to NRW. The World Bank recommends that NRW should be less than 25% of the total water produced, while in many countries NRW is up to 60% (Ranhill and USAID, 2008).

In Bahrain, it was estimated that the yearly cost of the NRW to be BD 71 million with a total waste of 21,535 M Gallon. This represents 38% of the total water production, which indicates the need for an urgent solution of this matter. The significance of this research is not only about reducing the yearly wastage of money but for saving the natural resources for Kingdom of Bahrain's next generation.

1.7 Methodology

In this subsection the research methodology used in the study is described. The geographical area where the study was conducted, the study design and the population and sample are described. The instrument used to collect the data, including methods implemented to maintain validity and reliability of the instrument are presented.

1.7.1 Data collection

The research methodology requires collecting relevant data and information regarding complaints received by each depot and the time needed for each activity in the maintenance remedial action. The data will be analyzed and the total time needed to complete each type of complaint is established for each depot.

Formatted sheets were designed to collect the required information while the teams were responding to complaints. The sample taken was 100 complaints for each depot. The sheets were filled by the depot foremen in each shift. To verify the data,

a sample of 15 complaints (i.e. 15 sheets) in each depot were randomly chosen during the process and cross checked with the relevant maintenance team to ensure its accuracy.

The data obtained is as the following:

- Types of complaints received.
- The arrival rate of complaints for each depot.
- The service rate of each complaint for each depot.
- The time needed to complete each remedial activity.
- The location of the complaints.

A specified period was given to each depot to submit the filled sheets. This approach is considered as a quantitative approach where the output is mainly numbers and percentages.

1.7.2 Data analysis

The approach used to analyze the data is mainly using Microsoft Excel where data was uploaded and then averages were obtained.

These results were to be used as an input for the model developed to establish the optimum number of maintenance teams for each depot.

Chapter 2

Non-Revenue Water Components

2.1 Definition and Components of Non-Revenue Water

2.1.1 Physical losses

2.1.2 Apparent losses

2.1.3 Unbilled authorized consumption

Chapter 2: Non-Revenue Water Components

2.1 Definition and Components of Non-Revenue Water

Non-Revenue Water (NRW) can be defined as the difference between the System Input Volume and the Billed Authorized Consumption as given by the expression below:

$$\text{NRW} = \text{Total System Input} - \text{Billed Authorized Consumption}$$
 (Mutikanaga et al. 2009)

Figure (2.1) indicates the IWA Standard International Water Balance and Terminology.

System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorized Consumption	Unbilled Metered Consumption	Non Revenue Water
			Unbilled Unmetered Consumption	
	Water Losses	Commercial Losses	Unauthorized Consumption	
			Customer Meter Inaccuracies and Data Handling Errors	
		Physical Losses	Leakage on Transmission and Distribution Mains	
			Leakage and Overflows from the Utilities Storage Tanks	
			Leakage on Service Connections up to the Customer Meter	

Figure (2.1)
Water Balance

NRW can be divided into 3 main components: physical losses, apparent losses, and unbilled authorized consumption. Figure (2.2) summarizes the components of Non-Revenue Water and its constituents.

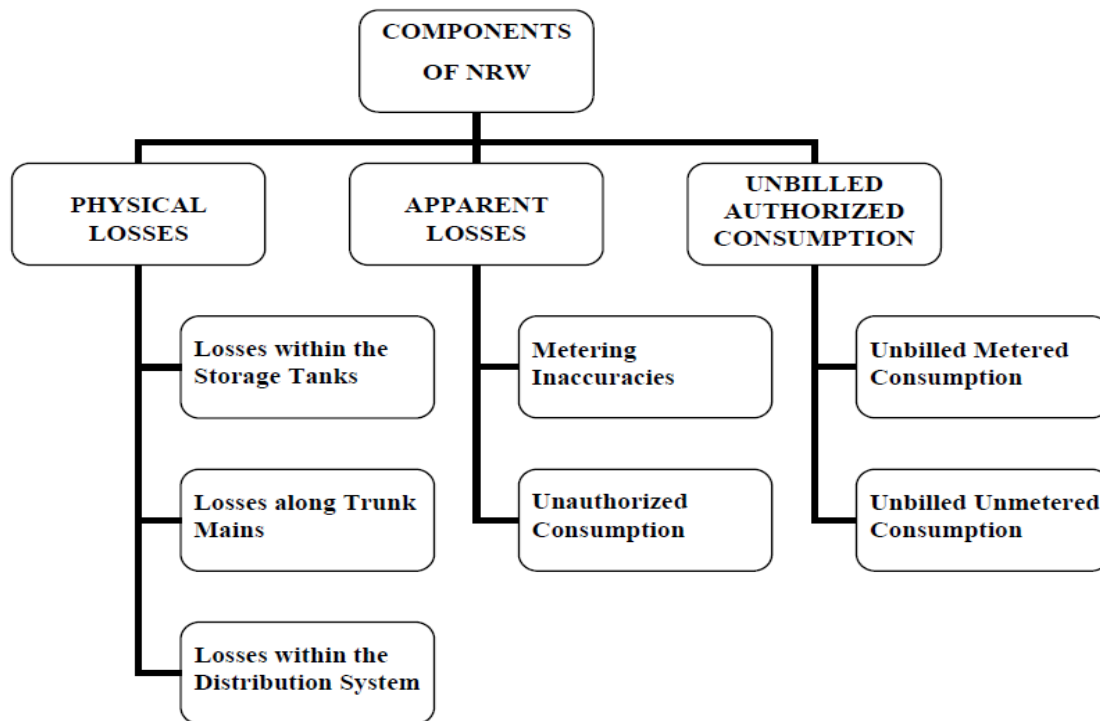


Figure (2.2)
NRW Components

2.1.1 Physical losses

Lambert et al. (1999), Physical losses basically are water lost through leakage and it is referring to real losses. These losses can be severe, and may go undetected for months or even years. The volume lost will depend largely on the characteristics of the pipe network. Physical losses result from losses at mains, service reservoirs, and service connections up to the point of customer metering. The annual volume lost through all types of leaks, bursts, and overflows depends on their individual

frequencies, flow rates, and duration. Experience has shown that most leakage results from service connections, and to a large extent, to poor construction

2.1.1.1 Leakage on transmission and/or distribution mains

The system of piping is often categorized into transmission / trunk mains and distribution mains. Transmission mains consist of components that are designed to convey large amounts of water over great distances, typically between major facilities within the system. For example a transmission main may be used to transport water from a treatment facility to storage tanks throughout several cities and towns. Individual customers are usually not served from transmission mains.

Distribution mains on the other hand are an intermediate step toward delivering water to the end customers. Distribution mains are smaller in diameter than transmission mains, and typically follow the general topology and alignment of the city streets. Elbows, tees, wyes, crosses and numerous other fittings are used to connect and redirect sections of pipe. Fire hydrants, isolation valves, control valves, blow offs and other maintenance and operational accessories are frequently connected directly to the distribution mains to the end customers.

Meanwhile, leakage on transmission and/or distribution mains is due to leakage from trunk mains, including the main from the source to the treatment plant, from the plant to the reservoir, and from the reservoir to the first deviation within the reticulation system.

Due to the bulk amounts transported, and in most cases with high pressures, the volumes of water losses might be considerable, but they are relatively easy to detect by visual inspection and low in numbers. Trunk mains are usually designed

and constructed at high standards of reliability, because of their importance, and leakage along them is an indication of aging and the need of replacement.

2.1.1.2 Leakage on service connections up to point of customer metering

These losses are usually small in volumes but numerous in numbers. The larger losses are usually from burst pipes, or from the sudden rupture of a joint, while smaller losses are from leaking joints, fittings, service pipes and connections. Their identification and location is difficult because of the large area covered by the reticulation system. Measures for leakage control and detection cover all physical losses but leakage on service connections usually makes up the greatest number of leaks located.

This is also supported by the fact that the water supply projects executed in conditions of financial restrictions sometimes can result in less reliable solutions. Correspondingly, the expected number of breakdowns is higher, especially in high pressure zones.

2.1.2 Apparent losses

Apparent Losses consist of unauthorized consumption and all types of inaccuracies associated with production metering and customer metering. Apparent losses or formerly known as non-physical losses or commercial losses refers to water consumed but not recorded by consumers' meters or otherwise accounted for by government or other public use. These implies a loss of revenue. It includes water consumed through illegal connections and meter under-registrations. It is estimated

that in Asian cities, 50-65% of NRW is due to apparent losses (Ranhill and USAID, 2008).

2.1.2.1 Unauthorized consumption

Unauthorized consumption can be in the forms of illegal connections, misuse of fire hydrants and firefighting systems, vandalized or bypassed consumption meters, corrupt practices of meter readers and finally open boundary valves to external distribution systems (unknown export of water). All in all, the estimation of unauthorized consumption is always a difficult task and should at least be done in a transparent, component-based way so that the assumptions can be easily checked and/or modified later.

2.1.2.2 Metering inaccuracies

Metering inaccuracies can include under or over-recording of source meters and production meters, under or over-recording of meters measuring consumption, errors in reading meters, adjustments due to meter reading lag times, malfunctioning water meters, estimated water consumption (when meters are not working) and meter under-registration.

Industrial meters and master meters have the same problems of inaccuracies. In addition, industrial meters can have an additional source of error if they are compound meters operating in the changeover range of the meter. Meter sizing is important for industrial meters. Whilst commercial meters are subject to the same problems that industrial meters face, in addition commercial meters can be more difficult to be properly sized, compared with industrial meters because they may be

used over a shorter period of time, which gives a wider range between peak and low flows through the meter.

As for the domestic meters, it has fewer problems than those found with larger meters, but the problems can be serious. Domestic meters are subject to wear due to water quantity and quality, improper gearing or wrong registers, wrong readings, or billing errors. Domestic meters are also subject to poor readings at low flows, and a significant amount of the water passing through a domestic meter can be at low flows.

Data handling errors are sometimes a very substantial component of apparent losses. Many billing systems do not reach the expectations of the utilities but problems often remain unrecognized for years. It is possible to detect data handling errors and problem with the billing systems by analyzing billing data (of say the last 24 months) using standard database software.

2.1.3 Unbilled authorized consumption

Unbilled authorized consumption is the annual volume of metered and non-metered water, which is not recorded in the customer billing system, taken by registered customers, water supplier and others who are implicitly or explicitly authorized to do so by the water supplier. It is mainly used for domestic, commercial and industrial purposes.

2.1.3.1 Unbilled metered consumption

Unbilled metered consumption is the amount of water that is not recorded in the customer billing system as being consumed by metered customers. This will include metered water taken for domestic, commercial, industrial and agricultural

purposes. It may also include metered water that is taken for export to other systems.

2.1.3.2 Unbilled unmetered consumption

Unbilled unmetered consumption is the estimated amount of water that is taken with the approval of the water supplier by all registered customers that do not have water meters. It is mainly for residential, commercial and industrial purposes. This shall include all types of consumption by the utility for operational purposes, such as for firefighting, flushing of mains and sewers, reservoir cleaning, street cleaning, watering of municipal gardens, public fountains, highway rest areas, forest protection and building water. As this consumption is not metered, it will be an estimation based on standard default values used by the water supplier.

2.2 International Measures of NRW

To have a better understanding where Bahrain Stands with regard to its NRW percentage compared with other countries, Figure (2.3) shows that Bahrain scored 37% in between the highest and lowest percentages shown by Bulgaria (68%) and Singapore (5%), respectively (Lambert et al., 1999).

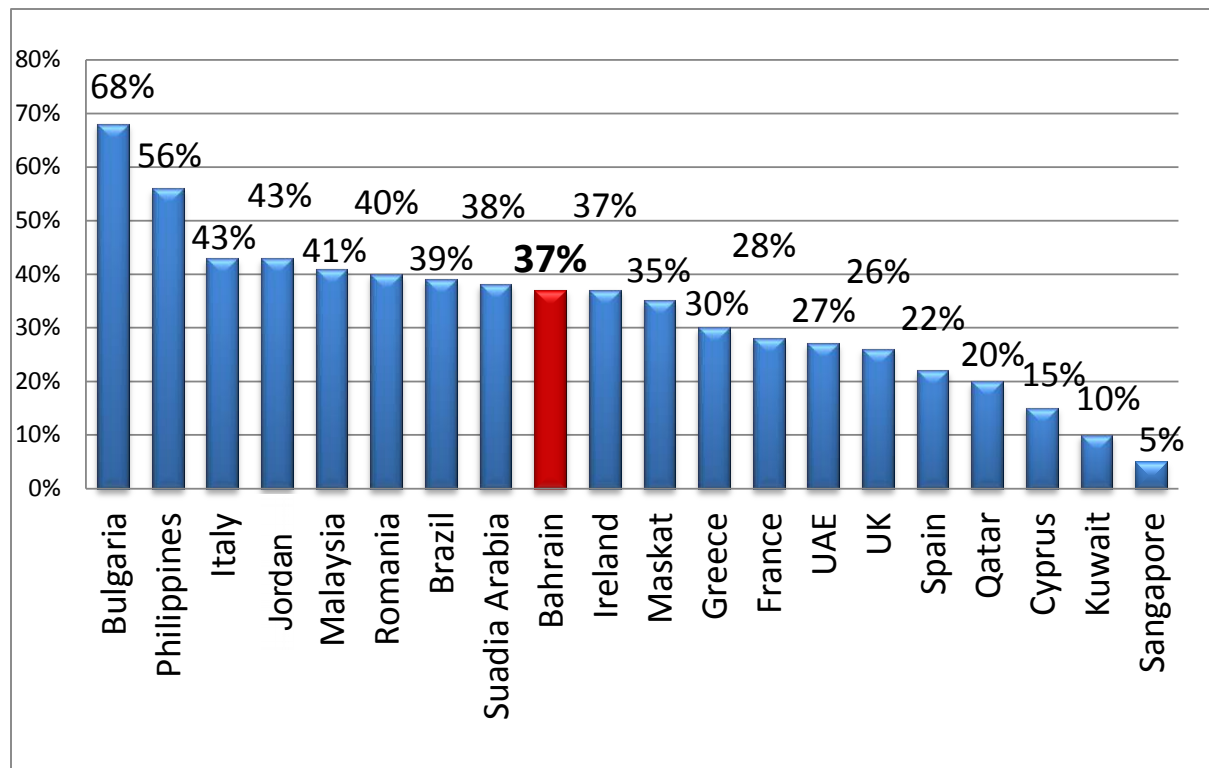


Figure (2.3)
International Measures of NRW Percentage

Chapter 3

Literature Review

3.1 Introduction

3.2 District Meter Area Method

3.3 NRW Assessment and Reduction in Various Cities

3.4 Other NRW Research.

3.5 Literature Review Conclusion

Chapter 3: Literature Review

3.1 Introduction

To start with, it became necessary to review the existing literature to get a better view of the main issues involving non-revenue water. It was obvious from the onset that there was no official documentation on non-revenue water for the water utility in Kingdom of Bahrain. It was therefore necessary to gather general views on the issue in order to be able to access the situation in Bahrain more scientifically in line with agreed international principles.

3.2 District Meter Area Method

In Malaysia, the water situation has changed from one of relative abundance to one of relative scarcity as was reported by Hedaya (2005). This is because the population growth and rapid urbanization and industrialization are imposing rapidly growing demands and pressure on the water resources where NRW reached up to 44.72% out of the total production. She has suggested prudent strategies that are undertaken in order to eradicate high levels of non-revenue water which was mainly the District Meter Area Method (DMA). Estimation of initial rate of Non-Revenue Water was calculated by utilizing Burst and Background Estimates (BABE) Analysis. A zone of Taman Wawasan 3, located in Puchong, Selangor has been implemented and reduction strategies and control were carried out complying with the District Area Method. The results where indicated that after leakage remedial work took place, 91% of NRW was recovered.

Another successful DMA project was held in Italy to reduce water leakages within the water distribution systems as reported by Fantozzi et al. (2007). The real losses

were calculated from night flows and water balance (each with confidence limits), then they were compared with a more reliable estimates in each DMA using a specialist software. This leads into an improved overall management of DMAs for Active Leakage Control with less cost. The leakage reduction programme has been implemented in 93% of the total length of the network (4850 km), where the distribution systems were divided into more than 260 DMAs. DMA creation also allowed a more efficient pressure management. The project since 2001 has resulted into more than 16% reduction of the per capita daily inflow and more than 20% reduction in the number of repairs, mainly due to pressure reduction and focused network renewal.

The proven method around the world to reduce leakage from the water distribution system is to proactively find the leaks before they appear at the surface. This has the benefits of reducing the time the leaks are running, and wasting water. The methodology is called District Meter Areas (DMAs), where the City is divided into sections, and the flow of water that enters the area is checked against a theoretical flow of water. When a significant difference occurs, targeted leak detection activities are undertaken to find the leaks that may be causing the difference. The leaks are then quickly repaired and the overall NRW starts to decrease (Farley et al., 2008).

3.3 NRW Assessment and Reduction in Various Cities

In Bangkok, the city had been suffering from a rapidly growing population which strained the water supply and distribution system as reported by Kingdom et al. (2006). During the 1990s the system's supply increased from 3.0 to 4.5 million

m³/day to meet demand, however, NRW also rose dramatically to a peak in 1997 of 1.9 million m³/day, presumably caused by supply improvements and pressure increases. The system input was then reduced to below 4 million m³/day, and NRW consequently decreased and stabilized in 1999 at 1.5 million m³/day. In 2000, a contract was awarded to reduce real losses in 3 of 14 service branches (each around 100,000 connections). The main focus of all contractors was the pressure regime as they had maintained a proper pressure for the pipeline during the day to minimize NRW. By the end of these contracts, real losses had been reduced by 165,000 m³/day, thus providing enough water to serve 0.5 million inhabitants, NRW was reduced to 1.3 million m³/day while system input had increased to 4.2 million m³/day.

Peiris et al. (2008) presented NRW reduction program that was carried out during October 2006 and May 2007 to determine and reduce the NRW of Hantana water supply scheme (WSS) of Sri Lanka. The results of the program were used to check the applicability of latest performance indicators developed by IWA and to modify them to suit local conditions. The average NRW in Hantana WSS was 36.12% where the real and apparent water losses were 9.18% and 26.94%, respectively. The Unavoidable Annual Real Losses (UARL) were 6.4%. According to the findings, rectification of water leakages did not significantly reduce the NRW. The infrastructure leakage index of Hantana WSS was 5.6, which was a very high value in comparison to that of the other water supply systems.

Fanner (2009) addressed the Bahamas case where it was required to reduce the average daily NRW in the New Providence distribution system by 1 million imperial gallons per day. The NRW reduction strategy adopted on this project included controlling transients by using: variable speed controls or pumps control

valves; pressure management in order to control excessive pressures, particularly during the minimum demand periods; district metering; active leak detection and repair; and a large revenue meter improvement program. The system input had been reduced to 3,150.9 MG from 4,551 MG, despite the addition of new customers, i.e. a reduction of NRW by an annual rate of 431.8 MG. This reduction rate was significantly exceeding the target.

Moreover, Fanner (2009) mentioned that in 1997 the State of Selangor of Malaysia experienced a serious water crisis. An estimated 40 percent of the water produced was not invoiced. Leakage was estimated at 25 % of system input, or around 0.5 million m³/day. Reducing real losses by 50% would provide sufficient water to serve the equivalent of an additional 1.5 million people and avert the water shortage in Kuala Lumpur. The State Waterworks Department initiated a contract to reduce NRW by 200,000 m³/day over a 10 year period for an agreed lump-sum payment. The NRW reduction strategy included: selective customer revenue meter replacement, the identification of illegal connections, DMAs with pressure management installed on every DMA, leak detection and repair, and service line renewal where appropriate.

In Sana'a (Yamen) a study made by Al-Washali (2011) which aims to assess the quantity, supply management options, and measure awareness of NRW in Sana'a water utility. For measuring the awareness level, interviews, report analysis and awareness questionnaire with opinion questions were conducted. For assessment of NRW components involved, a review of the existing methods and their applicability for the case of Sana'a water distribution system was conducted. A novel methodology, the reverse approach, was developed, introduced, and implemented. The study found that volume of NRW in Sana'a water distribution

system made up 38.75% of system input volume of which 26.57% was apparent losses; 11.67% was real losses; and 0.51% was unbilled authorized consumption. Further analysis showed that causes of unauthorized consumption were poor customer-utility relation and lack of monitoring measures. Although results showed that leaks made up more than 5% of Sana'a basin safe yield, not much was expected to be reduced till the utility apply zoning principle for its network. In consequence, the study recommended optimizing the speed and quality of repairs for reported leaks and involving the private sector to supply the right technology for achieving zoning in the network. For apparent loss reduction, the study recommended working on enhancing the customer-utility relation, customer confidence on the utility, monitoring measures, and the utility employees' commitment. For improved NRW management, the study suggested assessing NRW and drawing water balance annually, and getting use of the free NRW software's with their associated performance indicators to allow better NRW monitoring.

3.4 Other NRW Research

On the other hand, Farley (2003) introduced the base to develop a strategy for management of non-revenue water (NRW), which provided a better understanding of the reasons for NRW and the factors that influence its components. Hence, techniques and procedures could be developed, and tailored to the specific characteristics of the network and local influencing factors, to tackle each of the components in order of priority. A diagnostic approach, followed by practical implementation of solutions which are achievable, could be applied to any water company, anywhere in the world, to develop a strategy for NRW management. The first step in developing a strategy is to ask some questions about the network

characteristics and the operating practices, and then use the available tools and mechanisms to suggest appropriate solutions, which are used to formulate the strategy. Typical questions are; how much water is being lost? Where is it being lost from? Why is it being lost? What strategies can be introduced to reduce losses and improve performance? How can we maintain the strategy and sustain the achievements gained?

Ismail (2006) had taken a case study in India where the following strategies were adopted: selective customer revenue meter replacement, the identification of illegal connections, with pressure management installed on every DMA, leak detection and repair and service line renewal where appropriate. It is concluded that NRW in any water system could be minimized to the minimum if the above strategies were adopted.

Wyatt (2010) reported that NRW levels were high in many developing countries, and they could be expensive to reduce. Members of the IWA, Water Loss Task Force developed the Economic Level of Leakage (ELL), which outlined the optimal level of physical losses based on engineering inputs. However, the ELL approach was less useful in developing countries than in developed countries, as it ignored commercial losses, the annualized cost of water supply capacity expansion, and situations in which production capacity did not meet demand. The report presented a financial model that address the limitations noted above and provide acceptably accurate values of optimal steady-state NRW without the need for large data collection efforts. The model used an NRW framework adapted from the IWA Water Balance and the Burst and Background Estimates (BABE) and Econoleak methodologies. Wyatt report presented specific results for 59 utilities in 27 countries in Asia, Africa, and Eastern Europe; these included optimal NRW,

optimal physical losses, optimal commercial losses, optimal meter replacement frequencies, optimal leak detection survey frequencies, actual losses, and impacts on utility revenue and water supply coverage. This model allowed utility managers and regulators to establish NRW targets and to optimally allocate resources to NRW management. Ultimately, use of the model would help in saving water, increasing utility revenues, expanding coverage, and reducing health and economic impacts.

As reported by Svitak et al. (2011), operational and infrastructure problems in water supply systems are usually closely dependent on each-other. In their research they presented the results of two case studies where a complex strategy was applied in the form of master plans for optimization of the water supply systems, reducing leakage, securing capacity for future development, and reconstruction plans. The mathematical model applied was based on extensive in-situ measurements and used to closely monitor existing problems in the water supply system with detailed solutions. The applied approach resulted in great technical outputs and financial savings such as:

- i. Leakage detection activities were resulted in quick leakage reduction by 30%. As a result, more than 50% return of the master plan cost was achieved just during the project period by this particular task.
- ii. The future urban development was expected to increase consumption by 20-25%. Due to this, the existing reserves in water sources capacity would be spent in 10-20 years. Therefore the leakage reduction strategy was set as fundamental principal for keeping water balance in the cities and keeping reasonable reserve of water sources.

- iii. A lot of small but very important investments such as new pressure reduction and flow measurement sites, short interconnections, local pumping stations were proposed in order to combine solution of several tasks:
 - a) Pressure optimization taking into account the resulting pressure above the roofs– reduction of pressure by 0.1-0.3 MPa in critical zones.
 - b) Optimization of measurement system, supply zones and DMAs – the average length of DMA size dropped from 15 km to 9 km.
 - c) Securing high standard water supply for new development areas and existing customers with under standard water supply as well as exceptional situations.
 - d) Solving of the water quality problems caused by instability of flow conditions in some parts of the system.
 - e) Reconstruction plan of water distribution system based on multi-criteria analysis, where leakage and pipe burst reduction plays fundamental part.

Hensel (2015) endorsed that many water loss management studies assessed non-revenue water without evaluating the contribution of leakages to total water losses. As a result total water losses were not partitioned accordingly. Therefore, there was a need for specialized application tools for assessing partitions of non-revenue water. One such tool could be the South African Night Flow (SANFLOW) Analysis Model, which was developed by the Water Research Commission of South Africa for analyzing flows and pressure within district metered areas. The SANFLOW analysis model was found to be suitable for partitioning water leakages. Thus, SANFLOW analysis model was an alternative tool, relevant and highly adaptable to the developing world. Computational approaches could be used

to detect leakages in water distribution networks. Another approach was the Artificial Neural Networks (ANNs) technique. ANNs could be trained to forecast flow dynamics in a water distribution network. Such flow dynamics could be compared with water demands in a particular area. A multi-layer feed-forward back propagation artificial neural network was used for modeling water flow in a district metered area. In this regard a MATLAB algorithm was developed to simulate water demand. The difference between the actual and the simulated water demands represented the water leakage in a water distribution network. It was found that an ANN could be trained and used to forecast flow with up to 99% confidence. Thus, ANNs technique was a flexible and efficient approach to detection of leakages in water distribution networks.

3.5 Literature Review Conclusion

The literature review focuses the attention to the different techniques in the field of minimizing NRW. It reveals that decision makers adapt proper techniques that saves cost and natural resources for the long term. Unfortunately, there was no research to establish the optimal number of maintenance teams. However, some of the papers emphasized the importance of minimizing the service time in order to minimize the NRW.

Chapter 4

Electricity and Water Authority Current Status

4.1 Introduction

4.2 Electricity and Water Authority Water Balance

4.3 Volume of Complaints Received

4.4 Water Distribution Directorate Depots

Chapter 4: Electricity and Water Authority Current Status

4.1 Introduction

It is very important to evaluate the current status in EWA with regard to the procedures implemented by the maintenance department in response of the complaints received before developing any model to enhance these procedures, and before giving any recommendations.

4.2 Electricity and Water Authority Water Balance

As discussed earlier, to start any investigation related to NRW, it is mandatory to highlight the Water Balance calculations for EWA to know the main causes of the NRW in Bahrain, and to have further understanding of the effect of each component in the water balance on the NRW in Bahrain. Table (4.1) shows the Water Balance for the year 2015 (IWA, 2000).

Table (4.1)
Water Balance for the Year 2015

System Input Volume (m³)	Authorized consumption (m³) 173,028,647 [70%]	Billed authorized consumption	Billed metered Consumption		Revenue Water (m³)
			Billed un-metered Consumption		155,996,784 [63%]
	Water Losses (m³) 73,073,400 [30%]	unbilled authorized consumption	Unbilled Metered/ unmetered consumption (m³)	17,031,863 [7%]	Non Revenue Water [NRW] (m³) 90,105,263 [37%]
		Apparent Losses	Unauthorized Consumption (m³)	5,622,624 [3%]	
Real Losses			Customer Meter Inaccuracies (m³)	5,442,287 [2%]	
246,102,047 [100%]			Leakage from Distribution mains (m³)	62,008,489 [25%]	

Referring to the global level of NRW and the acceptable level mentioned in Sub-section 1.2.1, the condition of Bahrain water network can be assessed as an average condition. To have a better understanding of the NRW fluctuation in Bahrain, the NRW parentages for the last five years are shown in Table (4.2). It can be noticed from the table that the NRW for the last 4 years is almost stable unlike that of year 2011 as it considered relatively high. It is clearly obvious that the main component in NRW having the highest rate is the real losses, which is mainly caused by leakages from the distribution mains, with an average rate for the last five years of 26.8% out of the total yearly production, and a percentage of 70.8% out of the total NRW in Bahrain. This ratio indicates the immediate need to tackle the leakages from the distribution mains in order to reduce the NRW. With reference to the other components of the NRW, the percentages are very small compared to the real losses with an approximate total percentage of 30% out of the total NRW.

Table (4.2)
Percentages of NRW Components

NRW component	Year				
	2011	2012	2013	2014	2015
Unbilled Authorized Consumption	8%	7%	8%	8%	7%
Apparent Losses%	3%	4%	3%	2%	5%
Real Losses %	30%	27%	26%	26%	25%
Total NRW %	41%	38%	37%	36%	37%

Since the NRW is mainly affected by the leakages from the distribution mains as discussed in the above paragraph. Three type of pipes are used in the distribution mains, namely, DI, AC, and PP. The amount of leakage from each of these three types can be figured out from the number of complaints related to each pipe type. The percentages of complaints for each pipe type over the last five years, which were obtained from the historical data are given in Table (4.3).

Table (4.3)
Distributions of Yearly Complaints Among Pipe Types

Pipe type	Year				
	2011	2012	2013	2014	2015
Ductile Iron (DI)	18%	16%	15%	14%	15%
Asbestos Cement (AC)	41%	38%	42%	39%	39%
Poly pipe (PP)	41%	46%	43%	47%	46%
Total No of Complaints	8754	8847	8509	7198	7215

4.3 Volume of Complaints Received

To have a better understanding of the volume of complaints received yearly of each type of complaint, it is necessary to find out the total complaints received during the last five years relevant to each complaint type. To segregate these complaints by area, it is mandatory to link the complaints to the depot area as well as to the network in the same area. Tables (4.4)-(4.6) indicate the number of complaints received over the last five years in each depot and the size of the network in the same area.

Table (4.4)
Numbers of Complaints Received by Muharraaq Depot During Years 2011-2015

Type of complaint	2011		2012		2013		2014		2015	
	No. of compalints	Data	No. of compalints	Data	No. of compalints	Data	No. of compalints	Data	No. of compalints	Data
Leak from main	1393	368952 m	1436	371625 m	1258	378053 m	1189	381562 m	1227	388198 m
Leak from service line	1024	380578 m	1044	387512 m	807	390153 m	855	394561 m	818	408637 m
Leak from water meter	451	29065 no's	633	29862 no's	440	30254 no's	520	30458 no's	483	31239 no's
Leak from valve	205	5865 no's	261	5978 no's	257	6035 no's	223	6157 no's	186	6357 no's
Leak from fire hydrant	246	1405 no's	218	1450 no's	147	1489 no's	186	1506 no's	223	1533 no's
Leak from fitting	860	49065 no's	783	49812 no's	697	50157 no's	780	50318 no's	818	50980 no's
3rd party damage	30	****	55	****	82	****	81	****	91	****
Total no. of compalints	4209		4449		3715		3834		3847	

Table (4.5)
Numbers of Complaints Received by Budaya Depot During Years 2011-2015

Type of complaint	2011		2012		2013		2014		2015	
	No. of compalints	Data	No. of compalints	Data	No. of compalints	Data	No. of compalints	Data	No. of compalints	Data
Leak from main	4453	681523 m	4336	687542 m	4541	690657 m	4620	694752 m	5071	726162 m
Leak from service line	2799	678542 m	2890	680574 m	3339	687461 m	3321	692458 m	3688	711268 m
Leak from water meter	1527	57985 no's	1708	55321 no's	1469	56142 no's	2021	56842 no's	2305	57397 no's
Leak from valve	891	9842 no's	657	9912 no's	668	10032 no's	866	10154 no's	922	10875 no's
Leak from fire hydrant	509	1601 no's	788	1645 no's	801	1694 no's	722	1714 no's	768	1867 no's
Leak from fitting	2417	83256 no's	2890	83558 no's	2805	84921 no's	3032	85014 no's	2766	85521 no's
3rd party damage	93	****	152	****	112	****	114	****	185	****
Total no. of compalints	12689		13421		13734		14696		15707	

Table (4.6)
Numbers of Complaints Received by Riffa Depot During Years 2011-2015

Type of complaint	2011		2012		2013		2014		2015	
	No. of complaints	Data	No. of complaints	Data	No. of complaints	Data	No. of complaints	Data	No. of complaints	Data
Leak from main	5730	1761256 m	6202	1768542 m	6064	1771578 m	5822	1779581 m	6472	1781088 m
Leak from service line	4119	101253 m	4560	107523 m	4410	110674 m	3881	113097 m	4068	1139327 m
Leak from water meter	2507	50562 no's	2006	81654 no's	2756	82162 no's	2293	82654 no's	2219	83664 no's
Leak from valve	1074	13784 no's	912	13975 no's	1103	14014 no's	882	14108 no's	1294	14261 no's
Leak from fire hydrant	895	3195 no's	1094	3215 no's	919	3252 no's	1059	3291 no's	740	3301 no's
Leak from fitting	3760	120786 no's	3830	121235 no's	3308	121842 no's	3881	122048 no's	3513	122206 no's
3rd party damage	160	****	144	*****	168	****	178	****	188	****
Total no. of complaints	18246		18749		18728		17996		18495	

4.4 WDD Depots

To evaluate the current status of each of the three depots in Bahrain and their capacities, it was necessary to find out the number of maintenance teams in each shift and in each depot. Table (4.7) indicates the number of maintenance teams and the shift arrangement in each depot.

Table (4.7)
Number of Maintenance Teams and Shift Arrangement in Each Depot.

Depot	Number of shifts in one day	Total hrs in each shift	Starting time of shifts	Number of maintenance teams per shift
Muharraq	3 shifts	8 hrs	6 am - 2 pm - 10 pm	3 teams
Budaya	3 shifts	8 hrs	6 am - 2 pm - 10 pm	6 teams
Riffa	2 shifts	12hrs	6 am - 6 pm	7 teams in morning shift and 2 teams in night shift

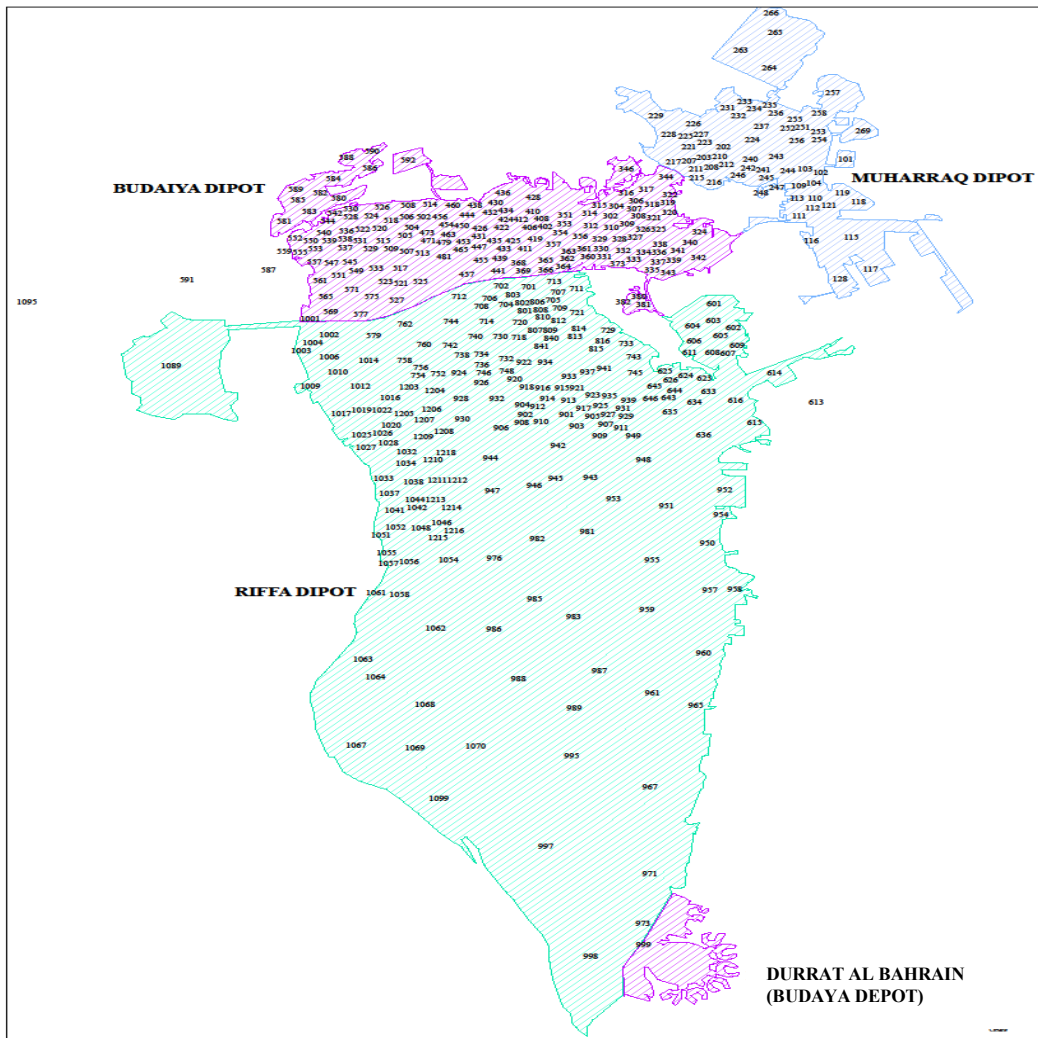


Figure (4.1)
Area Covered by Each Depot

Figure (4.1) shows the area covered by each depot. As can be noticed that Riffa depot is covering large area of Bahrain while Budaya depot comes second

As mentioned earlier, Muharraq and Budaya depots are managed by EWA but due to the EWA lack of manpower, the depots are forced to hire manpower from local contractors to help them in handling complaints. Table (4.8) categorizes the maintenance teams in Muharraq and Budaya depots per shift.

Table (4.8)
Categorization of Maintenance Teams Per Shift

Depot	EWA maintenance teams	Contractor maintenance teams
Muharraaq	2	1
Budaya	3	3

EWA and contractor maintenance teams are having different hourly rates as indicated in Tables (4.9) and (4.10), while Table (4.11) shows the cost of contractor maintenance teams per period for each depot.

Table (4.9)
Hourly Rates of Contractor Maintenance Teams (BD)

Sr.	Item	Rate per hr*	Over Time rate/hr**	after 6 P.M rate/hr
1	Pick up	2.19	2.19	2.19
2	Driver	1.35	1.69	2.03
3	Forman	2.16	2.70	3.24
4	Labours	1.08	1.35	1.62
5	Plumber	2.16	2.70	3.24

* From 6 am to 2 pm

** From 2 pm to 4 pm

Table (4.10)
Rate of Items in EWA Maintenance Teams (BD)

Sr.	Item	Unit	Rate per hr *	Over Time rate**	after 6 P.M rate/hr
1	Pick up	hr	2.19	2.19	2.19
2	EWA Employee	Day	18.34	18.34	18.34
3	Labors	hr	1.08	1.35	1.62
Total Cost per period of two hours			BD 20.036	BD 21.65	BD 23.27

* From 6 am to 2 pm

** From 2 pm to 4 pm

Table (4.11)
Cost of Contractor Maintenance Teams Per Period (2 hours)

Timing	Muharraq Depot	Budaya Depot	Riffa Depot
6 am to 2 pm	15.73	15.73	22.21
2 pm to 6 pm	18.56	18.56	26.66
6 pm to 6 am	21.40	21.40	31.12

Once a complaint being received at the depot, one of the depot's maintenance teams is assigned to handle this complaint. All depots follow a standard procedure for handling complaints as illustrated in Figure (4.2).

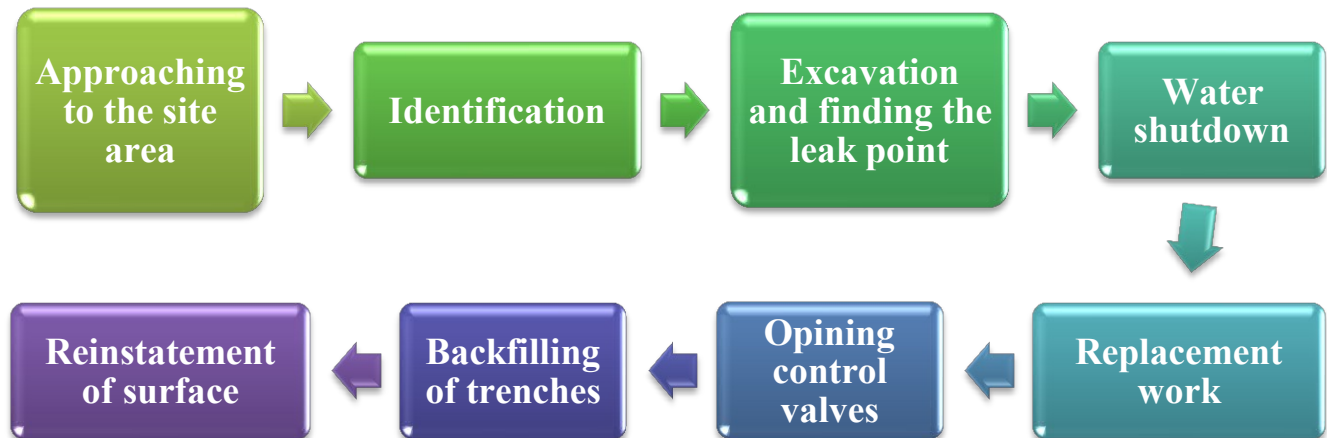


Figure (4.2)
Procedure for Handling Complaints

With regard to the water pressure in the system, EWA has introduced two periods to pressurize water into the pipeline networks in order to supply the water to the consumers effectively. These periods are called posting and non-posting. The water is pumped into the system during the posting hours (6 am to 5:30 pm), and the pressure is reduced to minimum during the non-posting hours (5:30 pm to 6 am). The volume of complaints increases during the posting hours when the pressure at the pipeline is at the maximum level increasing the number and flow of leakages, which give an indication that the number of the maintenance teams during the posting hours is more than the non-posting period. Table (4.12) summarizes the overall current status of the three depots.

Table (4.12)
Summary of the Depots Current Status

Item	Muharraq Depot	Budaya Depot	Riffa Depot
Depot management	EWA	EWA	Private Contractor
Avg yearly No of Complaints	3910	13847	18131
Percentage of average complaints	11%	39%	50%
Area covered (% of Bahrain total area)	11%	18%	71%
Network covered	16%	27%	57%
Traffic type	Congested	Highly congested	Moderate
No. of maintenance team per hr.	3	6	7 in the morning 2 in the night
Level of tools in each maint. team	Basic	Basic	Advanced / Automated
Manpower in each maint. team	Mostly unprofessional except one Forman	Mostly unprofessional except one Forman	Diversity of professional manpower

Chapter 5

Model Development

5.1 Introduction

5.2 Survey for Data Collection

5.3 Theoretical Background of the Modeling Approach

5.4 Implementation of the Queuing Model

5.5 Results of the Model

5.6 Maintenance Teams Shift Arrangements

Chapter 5: Model Development

5.1 Introduction

After reviewing the current status of EWA and visualizing the volume of the problem, it becomes necessary to find out a proper solution that might satisfy the objectives of this research. In this chapter, a model is developed based on certain criteria to come up with results which is to be tested in the next chapter.

Before going further in the model development, assumptions and notations for the problem need to be addressed and noted as following:

- The objective is to minimize the cost of maintenance teams such that the service completion time does not exceed 2 hours for 99% of all complaints received, i.e. to achieve EWA strategic goal.
- The arrival of complaints to depot during period is a Poisson process with rate . The period is assumed to be 2 hours (e.g., from 2:00 pm to 4:00 pm in one period).
- The service time (per maintenance team) in depot is exponentially distributed with rate , which depends on the skill level of the manpower in the depot and the traffic conditions.
- The shift in Muharraaq and Budaya depots is 8 hours starting from 6 am and in Riffa depot is 6 hours starting from 6 am.
- EWA maintenance teams are not to be affected (no decreasing on the existing EWA maintenance teams), i.e. EWA policy to keep current resources intact.
- The maintenance teams that start their shift at the beginning of a period should serve the complaints arriving in that period and the next two periods, e.g. the maintenance teams that start at 2:00 pm should serve complaints arriving till 8:00 pm.

- In case a complaint received before the end of a shift, the same maintenance team at that shift should handle this complaint until its completion even if overtime is needed.
- All the calculations are based on the actual conditions of manpower and service rate of each depot.
- Durrat Al Bahrain Complaints to be neglected as it may give inaccurate values for Budaya depot. This is because of the lengthy distance needed to reach the location as shown in Figure (4.1).

5.2 Survey for Data Collection

As discussed earlier in the methodology, a survey was needed to be conducted to have a better understanding on the following points:

1. Service rate per each depot.
2. Type of complaints received in each depot.
3. The percentage of each type of complaints in each depot.
4. Percentage of complaints received in posting and non-posting hours for each depot.

Accordingly, a survey sheet was designed to collect the required information while the teams were responding to complaints. The sample taken was 100 complaints to be recorded for each depot. The sheets were filled by the depot foreman in each shift. The duration of data collection started on December 13, 2015 up to December 24, 2015 for 50 complaints, then from January 7, 2016 to January 14, 2016 for another 50 complaints in each depot with a total of 300 complaints. Table (5.1) shows the sheet used in the survey.

Table (5.1)
Survey Sheet for Data Collection

Depot Name									
Date:				Area:					
Time:				Blk No.:					
Type of the complaint	Timing (Mints)								
	Approach to the site area	Identify the exact location	Excavation and find leak point	water shutdown	Replacement work	Opening Control valves	Backfilling of Trenches	Reinstatement of Surface	
Leak from Main Pipe									
Leak from Service pipe									
Leak from Valve									
Leak fire Hydrant									
Leak from a Fitting									
3rd party damage									
Leak from Water Meter									
Complaint Receiving Time:									
Complaint Completion Time:									
Comments:									

5.2.1 Results of the survey

The survey collected data for the three depots is shown in Table (5.2). The table shows the frequency and the average completion time for each type of complaints, and for each depot.

Table (5.2)
Survey Results

Type of complaint	Muharraq depot		Budaya depot		Riffa depot	
	Frequency	Average completion time (min)	Frequency	Average completion time (min)	Frequency	Average completion time (min)
leak from FH	2	219	2	241	0	0
leak from fitting	25	218	31	238	40	155
leak from main pipe	22	200	27	244	21	154
leak from service pipe	30	211	24	221	22	191
leak from valve	11	204	5	214	3	139
leak from water meter	10	99	11	73	14	54
Total	100	Average 191	100	Average 207	100	Average 150

From Table (5.2), the main figure to focus on is the average service time (completion time) needed to complete complaints in each of the three depots. It can be noticed from Table (5.3) that Budaya depot has the highest service time with an average of 207 minutes, while Riffa depot has the lowest service time with an average of 150 minutes, and the service time of Muharraq is 191 minutes.

Table (5.3)
Average service time for the three depots

Depot	Average service time
Muharraq	191
Budaya	207
Riffa	150

With regard to the number of complaints received during the posting and non-posting hours, Table (5.4) shows the percentages for the three depots. As it is expected, most complaints in the three depots are received during the posting hours when the pressure of the water in the pipelines is maximum.

Table (5.4)
Complaints received in posting and non-posting hours.

Depot	% of complaints received during posting hours	Percentage of complaints received during non-posting hours
Muharraq	75%	25%
Budaya	74%	26%
Riffa	79%	21%

5.3 Theoretical Background of the Modeling Approach

In this section, the theoretical background of the modeling approach that will be used in this research is presented.

5.3.1 Queuing modeling

In general, queuing model can be clarified by considering a service channel, a calling population of customers, some of them at some time enter the service

channel in order to obtain the service. It is often the case that the service center can only serve a limited number of customers. If a new customer arrives and the service channel is engaged, he might joins a waiting line and waits until the service facility becomes available. For the problem of this research, the calling population can be considered as the water grid connections, the arrivals are the complaints raised to the depot, the service channels are the depots maintenance teams. This problem can be modeled as a multiple server model. The Kendall's notation of this Queuing Model is as follows:

$(a/b/c) : (d/e/f)$

Where,

a: Is the arrival of complaints to depot during period with a poisson distribution of rate .

b: Is the service time in depot exponentially distributed with rate .

c: Is the number of the servers (maintenance teams).

d: Is the queue discipline which follows FCFS.

e: Is the queue length (complaints arrived to the depot and waiting for service) with infinite size.

f: Is the calling population (all water network in Bahrain) with infinite size.

To evaluate the proportion of time which a maintenance team is busy in handling complaints, its required to calculate the maintenance teams utilization () by using the following equation:

$$\text{---} \quad \text{Equation (5.1)}$$

To link the objective of this research to the queuing modeling, it is necessary to introduce a constraint that ensures achievement of EWA strategic goal to complete

99% of complaints within 2 hours. This is done by setting a threshold time (T) of 2 hours as an upper bound on waiting and service time provided that the desired service level of 99% will be achieved.

The equations used in multiple server queuing model are as the following (Randolph 1991):

- Probability of zero customers in the system () is given by:

$$[\Sigma \frac{(\lambda / \mu)^n}{n!}] \quad \text{Equation (5.2)}$$

- Probability that there are customers in the system () is:

$$\frac{(\lambda / \mu)}{\{ \frac{(\lambda / \mu)}{n!} \}} \quad \text{Equation (5.3)}$$

- Average number of customers waiting in line () is:

$$\frac{(\lambda / \mu)}{(\quad)} \quad \text{Equation (5.4)}$$

- Average time spent waiting in line () is

$$\text{—} \quad \text{Equation (5.5)}$$

- Average time spent in the system, including service () is:

$$— \quad \text{Equation (5.6)}$$

- Average number of customers in the system is:

$$\text{Equation (5.7)}$$

5.3.2 Cumulative Distribution Function CDF (for the Erlang formula)

The cumulative distribution function (CDF) calculates the cumulative probability for a given x -value. The uses of the CDF is to determine the probability that a random observation that is taken from the population will be less than or equal to a certain value. The CDF also can be used to determine the probability that an observation will be greater than a certain value, or between two values.

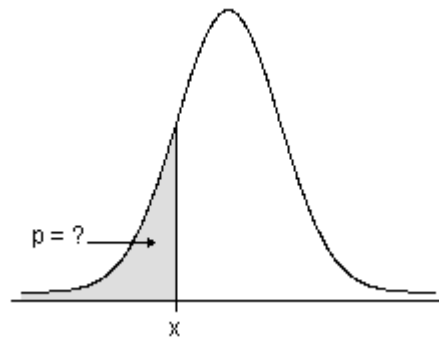


Figure (5.1)
Cumulative Distribution Function

In the case of this research, the CDF is used to calculate the probability that the service time needed to complete a complaint exceeds the threshold. The sum of these probabilities has to be less than 1% in order to meet the desired service level of completing 99% of the complaints within 2 hours. The probability that the

service time exceeds a certain threshold can be obtained from the following equation (Erlang formula):

$$P(n > T) = \sum_{k=n}^{\infty} \frac{e^{-\lambda} \lambda^k}{k!} \quad \text{Equation (5.8)}$$

Where $P(n > T)$ is the probability that waiting time in the queue is greater than the threshold time (T) given a specific number of customers λ . When the number of customers in the system is less than the number of servers, any arriving customer can be served immediately and the waiting time (delay time) is zero. On the other hand, when $\lambda > c$, (number of customers > servers) the arriving customer has to wait in the queue until $\lambda - c$ customers are served before him. The service time of λ customers follows Erlang distribution with parameters c where μ is the service rate per server. However, the result of Erlang formula has to be multiplied by the probability that there are λ customers in the system, and then to sum the probabilities to have the correct results. This can be done easily on a spreadsheet.

5.4 Implementation of the Queuing Model

In order to find the optimum number of maintenance teams, it is required to calculate the arrival rate and service rate for each depot. However, the number of maintenance teams at the beginning stage has to be randomly estimated and then to be checked at later stage if it satisfies our desired service level or not.

For a better understanding of the calculations, Budaya depot is going to be used for illustration.

5.4.1 Arrival rate for Budaya depot

Posting hours arrivals:

$$\begin{aligned}\text{Number of complaints per day} &= \text{Average number of complaints (Table (4.5))} \\ &\quad / 365 \text{ day} \\ &= 13847 / 365 \\ &= 37.9 \text{ complaints per day}\end{aligned}$$

$$\begin{aligned}\text{Number of complaints during posting hours} &= \text{Percentage of complaints during} \\ &\quad \text{posting hours (6 am to 5:30 pm)} \\ &\quad * 37.9 \\ &= 0.74 * 37.9 \\ &= 28.046 \text{ complaints during} \\ &\quad \text{posting hours}\end{aligned}$$

$$\begin{aligned}\text{Number of Complaints per hour during the posting hours} &= \text{Complaints during} \\ &\quad \text{posting hour} / \\ &\quad 12 \text{ hours} \\ &= 28.046 / 12 \\ &= 2.337 \text{ complaints} \\ &\quad \text{per posting hour.}\end{aligned}$$

Non posting hour arrivals:

$$\begin{aligned}\text{Number of complaints during non-posting hours} &= \text{Percentage of complaints} \\ &\quad \text{during non-posting hours} \\ &\quad (5:30 \text{ pm to 6:00 am}) * 37.9 \\ &= 0.26 * 37.9 \\ &= 9.854 \text{ complaints during} \\ &\quad \text{the non-posting hours}\end{aligned}$$

Number of Complaints per hours during the non-posting hours

= Complaints during night shift / 12 hours

= $9.854 / 12 = 0.821$ complaints per non-posting hours.

5.4.2 Service rate for Budaya depot

Average time needed to complete a complaint = 207 minutes (found from the survey held), which equals to 3.45 hours

Service rate per hour = $1 / 3.45 = 0.289$ complaints per hour

5.4.3 Arrival and service rates for other depots

Similar calculations to those of Subsections 5.4.1 and 5.4.2 are carried out to establish the arrival and service rates for Muharraq and Riffa depots. The results are tabulated in Table (5.5).

Table (5.5)
Arrival and Service Rate for Muharraq and Riffa Depot

Parameter	Muharraq depot	Riffa depot
Arrival rate in posting hours	0.669 Complaint/hr	3.270 Complaint/hr
Arrival rate in non-posting hours	0.223 Complaint/hr	0.869 Complaint/hr
Service Rate	0.314 Complaint/hr	0.400 Complaint/hr

5.4.4 Optimum number of maintenance teams for Budaya depot

Budaya depot is used also to illustrate the application of queuing model to establish the optimum number of maintenance teams. At the beginning, the number of maintenance teams during posting hours is randomly estimated as 10. In addition

the following parameters as obtained from Subsections 5.4.1 and 5.4.2 are considered:

Posting hours arrival rate = 2.337 complaints per posting hour

Non-posting hours arrival rate = 0.821 complaints per non-posting hour

Service rate = 0.289 complaints per hour

Threshold time = 2 hours

Accordingly, the service utilization and the probability of zero complaints during posting hours are obtained by Equations (5.1) and (5.2), respectively:

Service utilization = 0.8086

Probability of zero complaints (customers in the system) = 0.0002

The probability of complaints (customers) in the depot and the probability of the service time being more than the threshold time are calculated by Equations (5.3) and (5.8), respectively. To ease the calculations, the Microsoft Excel program is used and the results are shown in Table (5.6). However, a sample of the calculations is described as the following:

$$\text{Servers utilization} = \frac{\lambda}{\mu}$$

The probability of complaints (customers) in the depot where :

$$\sum_{n=0}^{\infty} \frac{(\lambda / \mu)^n}{n!} = \frac{(\lambda / \mu)^n}{n!} \quad \sum_{n=0}^{\infty} \frac{(\lambda / \mu)^n}{n!} = \frac{(\lambda / \mu)^n}{n!}$$

$$[\sum_{n=0}^{\infty} \frac{(\lambda / \mu)^n}{n!}]$$

$$\begin{aligned}
 & * \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \\
 & \quad \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} \frac{(\quad)}{\quad} + \\
 & [\quad \quad \quad]
 \end{aligned}$$

$$\begin{aligned}
 & \frac{(\quad / \quad)}{\quad} \\
 & \frac{(\quad / \quad)}{\quad} \\
 & \{ \quad \quad \quad
 \end{aligned}$$

$$\frac{(\quad / \quad)}{\quad} (\quad)$$

$$\{ \frac{(\quad / \quad)}{\quad} (\quad)$$

$$\frac{(\quad / \quad)}{\quad} (\quad)$$

The probability of the service time being more than the threshold time:

$$(\quad | \quad) (\quad) \Sigma - (\quad)$$

Sum of probabilities of service time in system being more than threshold time:

$$(\quad | \quad)$$

The probability of complaints (customers) in the depot where :

$$\frac{(\quad / \quad)}{\quad} (\quad)$$

The probability of the service time being more than the threshold time:

$$(\quad | \quad) (\quad) \Sigma - (\quad)$$

$$\Sigma - (\quad)$$

$$(\quad | \quad) (\quad) \Sigma - (\quad)$$

$$- (\quad) - (\quad) - (\quad)$$

Sum of probabilities of service time in system being more than threshold time:

$$\Sigma (\quad |)$$

$$(\quad | \quad) (\quad)(\quad)$$

Table (5.6)
Probability of Waiting More Than Threshold Time for 10 Maintenance Teams

Number of customer in system (i)	0	1	2	3	...	29	30	31	...
Probability of i customer in the system	0.0002	0.002	0.0081	0.0219	...	0.0033	0.0027	0.0022	...
Probability of service time in being system more than threshold time	0	0	0	0	...	0.9999	0.9999	1	...
Sum of probabilities of service time in system being more than threshold time	0.1418								

Table (5.6) shows the sum of probability of waiting in the system for more than 2 hours is 14.18% which is greater than 1% indicating that the desired service level is not going to be maintained by selecting 10 maintenance teams for Budaya depot. A trial and error procedure has to be continued until finding the optimum number of maintenance teams that satisfy the desired service level. The estimated number of maintenance teams is increased up to 13 resulting into a sum of probabilities of 0.47% (less than 1%) as shown in Table (5.7), which indicates that 13 is the required number of maintenance teams for Budaya depot. With 13 teams the

service utilization and probability of zero complaints in the system are 0.622 and 0.0003, respectively

Table (5.7)
Probability of Waiting More Than Threshold Time for 13 Maintenance Teams

Number of customer in system (i)	0	1	2	3	...	29	30	31	...
Probability of i customer in system	0.0003	0.0024	0.0099	0.0267	...	0	0	0	...
Probability of service time in system being more than threshold time	0	0	0	0	...	0.9980	0.9991	0.9996	...
Sum of probabilities of service time in system being more than threshold time	0.0047								

5.5 Results of the Model

After implementing the model on each depot for the posting and non-posting period, Table (5.8) shows the results of the optimum number of the maintenance teams required for each depot.

Table (5.8)
Optimum Maintenance Teams

Depot	Minimum number of maintenance teams	
	Posting hours (6 am to 6 pm)	Non-posting hours (6 pm to 6 am)
Muharraq	6	3
Budaya	13	7
Riffa	12	5

It is obvious from Table (5.8) that the optimum numbers of maintenance teams for the posting and non-posting hours are more than the existing numbers of maintenance teams in the three depots as shown in Table (4.8). For example, in Budaya depot the existing number of maintenance teams are 6 teams during the posting as well as non-posting hours, while the optimum numbers of maintenance teams that Budaya has to maintain are 13 and 7 respectively.

5.6 Maintenance Teams Shift Arrangements

As discussed earlier, the shifts in Muharraq and Budaya depots start at 6 am, 2 pm and 10 pm for continuous eight hours for each shift, while in Riffa depot (Managed by third-party) the shifts extend for six hours duration with four shifts in a day.

The results of the queuing model based on the posting and non-posting hours are in conflict with the shift timing. To sort out this matter, an optimization model is developed to find suitable shifts arrangements for EWA and contractor maintenance teams.

5.6.1 Optimal distribution of Muharraaq teams

The objective of this stage is to distribute the maintenance teams of Muharraaq depot among the periods of the different shifts such that the maintenance cost is minimized. The objective function for the optimum distribution of Muharraaq maintenance teams is:

$$\sum \text{Equation (5.9)}$$

Where,

() are the number of contractors maintenance teams at the timings shown below.

() are the number of EWA maintenance teams at the timings shown below.

() are the cost of contractor maintenance teams at the timings shown below.

() are the cost of EWA maintenance teams at the timings shown below.

are the teams assigned for period 6 am to 8 am.

are the teams assigned for period 8 am to 10 am.

are the teams assigned for period 10 am to 12 pm.

are the teams assigned for period 12 pm to 2 pm.

are the teams assigned for period 2 pm to 4 pm.

are the teams assigned for period 4 pm to 6 pm.

are the teams assigned for period 6 pm to 8 pm.

are the teams assigned for period 8 pm to 10 pm.

are the teams assigned for period 10 am to 12 am.

are the teams assigned for period 12 am to 2 am.

are the teams assigned for period 2 am to 4 am.

are the teams assigned for period 4 am to 6 am.

Subject to the following constraints:

Number of teams in the morning shift (posting hours) for Muharraaq depot

$$\sum \text{Equation (5.10)}$$

Maintaining EWA current maintenance teams in the morning shift for Muharraaq depot

$$\sum \text{Equation (5.11)}$$

Number of teams in the evening shift (posting hours) for Muharraaq depot

$$\sum \text{Equation (5.12)}$$

Number of teams in the evening shift (non-posting hours) for Muharraaq depot

$$\sum \text{Equation (5.13)}$$

Maintaining EWA current maintenance teams in the evening shift for Muharraaq depot

$$\sum \text{Equation (5.14)}$$

Number of teams in the night shift (non-posting hours) for Muharraaq depot

$$\sum \text{Equation (5.15)}$$

Maintaining EWA current maintenance teams in the night shift for Muharraaq depot

$$\sum \text{Equation (5.16)}$$

Non-negativity constraints

$$\text{Equation (5.17)}$$

The tool used to solve the above linear program optimization problem is the Solver in Microsoft Excel software. Equations (5.9) to (5.17) and the values of the cost parameters and (from Tables (4.10) and (4.11)) are entered into the Excel sheet. Then the Solver tool is run on an iterative procedure in order to come out with a result. The result

is the maintenance teams distribution required to satisfy the constraints with the minimum cost. Figure (5.2a) shows the Solver tool used for the optimization problem, whereas Figure (5.2b) shows the input matrix to the solver.

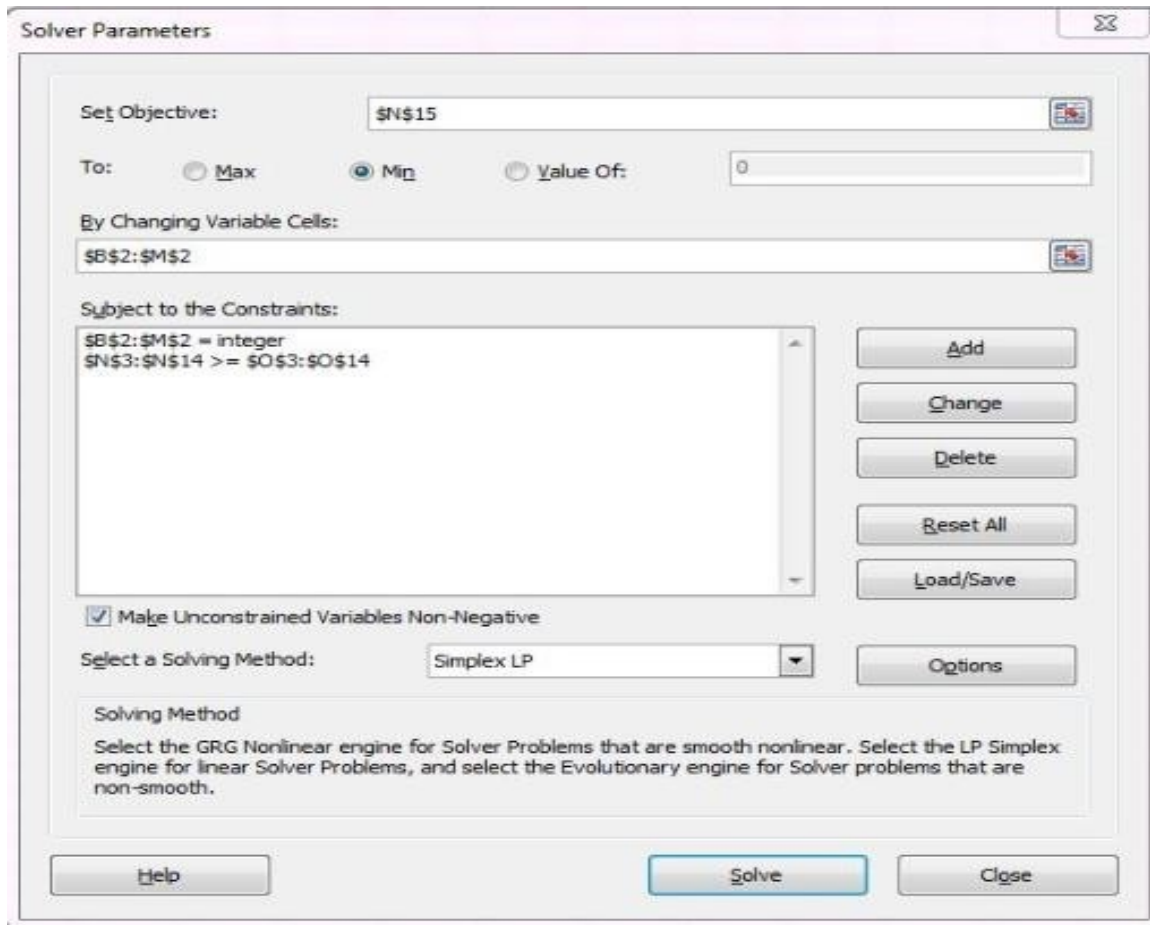


Figure (5.2a)
Solver Tool in Microsoft Excel

Variable	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	LHS	RHS
Value	2	5	3	0	2	7	2	0	5	4	4	0		
Constraint 1	1										1	1	6	6
Constraint 2	1	1										1	7	7
Constraint 3	1	1	1										10	10
Constraint 4		1	1	1									8	8
Constraint 5			1	1	1								5	5
Constraint 6				1	1	1							9	9
Constraint 7					1	1	1						11	11
Constraint 8						1	1	1					9	8
Constraint 9							1	1	1				7	7
Constraint 10								1	1	1			9	9
Constraint 11									1	1	1		13	9
Constraint 12										1	1	1	8	8
Objective	1500	1500	1500	1500	1000	1000	1000	1200	1200	1200	1200	1200	41600	

Figure (5.2b)
Input Matrix to Solver

After running the optimization problem in the Microsoft Excel, the distribution of the maintenance teams are shown in Table (5.9). It can be noticed that in the morning shift, 6 maintenance teams are required: 2 of them are belonging to EWA and the others are belonging to contractors. For the night shift, 3 maintenance teams are required: 2 of them are belonging to EWA and the other one is belonging to contractor. However, in the evening shift, 2 EWA maintenance teams are required during the whole shift, while 4 of contractor maintenance teams are required from 2 pm to 6 pm. For the rest of the shift (from 6 pm to 10 pm) only one contractor maintenance team is required while the remaining teams can be released. The maintenance teams arrangement may be more clarified in Figure (5.3) as it separates EWA from contractor maintenance teams for the different shifts, and then shows the total.

Table (5.9)
Optimal Distribution of Muharraaq Teams

x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}	Y_{11}	Y_{12}
4	0	0	0	4	0	1	0	1	0	0	0	2	0	0	0	2	0	0	0	2	0	0	0

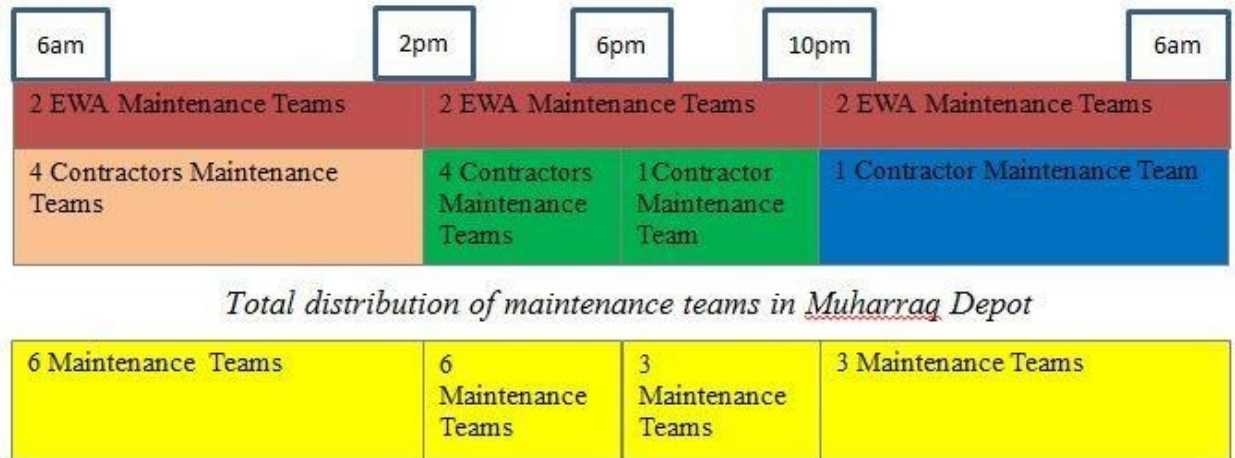


Figure (5.3)
Muharraaq Maintenance Teams Distribution

The minimum cost required to maintain the arrangement shown in Figure (5.3) is BD 1,054.773 for 24 hours a day (Equation (5.9))

5.6.2 Optimal distribution of Budaya depot

The objective of this stage is to distribute the maintenance teams of Budaya depot among the periods of the different shifts such that the maintenance cost is minimized. The objective function for the optimum distribution of Budaya maintenance teams is similar to that of Muharraaq, i.e. Equation (5.9) is valid subject to the following constraints:

Number of teams in the morning shift (posting hours) for Budaya depot

$$\Sigma$$

Equation (5.18)

Maintaining EWA current maintenance teams in the morning shift for Budaya depot

$$\Sigma$$

Equation (5.19)

Number of teams in the evening shift (posting hours) for Budaya depot

$$\Sigma$$

Equation (5.20)

Number of teams in the evening shift (non-posting hours) for Budaya depot

$$\Sigma$$

Equation (5.21)

Maintaining EWA current maintenance teams in the evening shift for Budaya depot

$$\Sigma$$

Equation (5.22)

Number of teams in the night shift (non-posting hours) for Budaya depot

$$\Sigma$$

Equation (5.23)

Maintaining EWA current maintenance in the night shift teams for Budaya depot

$$\Sigma$$

Equation (5.24)

Non-negativity constrains

Equation (5.25)

Solver tool in Microsoft Excel is used to solve Budaya depot optimization. The distribution of the maintenance teams are shown in Table (5.10). It can be noticed that in the morning shift 13 maintenance teams are required where 3 of them related to EWA and the others are related to contractors. In the night shift, 7 maintenance teams are required where 3 of them related to EWA and the others are related to contractor. However, in the evening shift, 3 EWA maintenance teams are required to be maintained during this shift and 10 of contractor maintenance teams are required from 2 pm to 6 pm. For the rest of the shift (from 6 pm to 10 pm) only

4 contractor maintenance teams are required while the rest teams can be released.

The maintenance teams arrangement may be more clarified in Figure (5.4) as it separates EWA from contractor maintenance teams, and then shows the total.

Table (5.10)
Optimal Distribution of Budaya Teams

χ_1	χ_2	χ_3	χ_4	χ_5	χ_6	χ_7	χ_8	χ_9	χ_{10}	χ_{11}	χ_{12}	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}	Y_{11}	Y_{12}
10	0	0	0	10	0	4	0	4	0	0	0	3	0	0	0	3	0	0	0	3	0	0	0

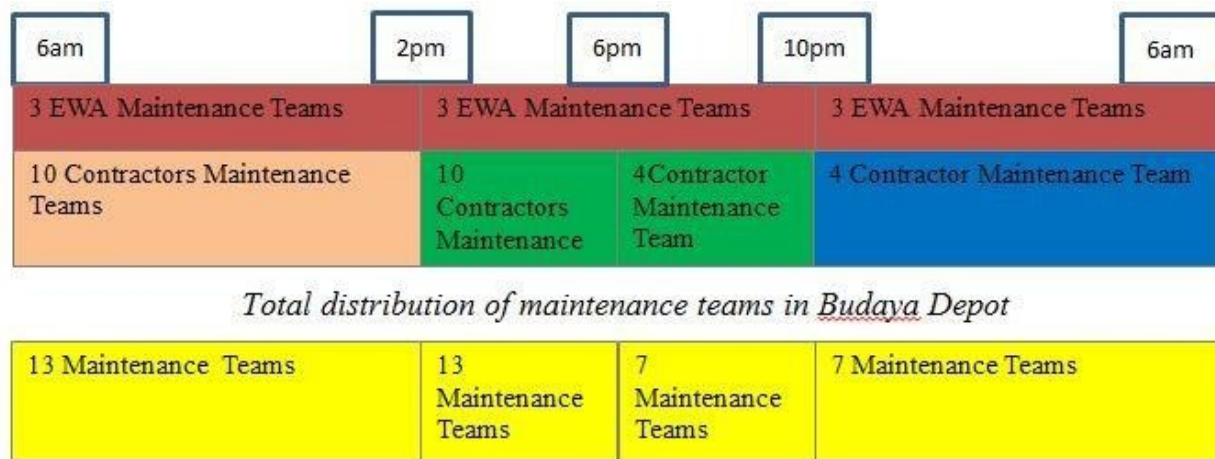


Figure (5.4)
Budaya Maintenance Teams Distribution

The minimum cost required to maintain the arrangement shown in Figure (5.4) is BD 2,302.552 for 24 hours a day (Equation (5.9))

5.6.3 Optimal distribution of Riffa depot

The objective of this stage is to distribute the maintenance teams of Riffa depot among the periods of the different shifts such that the maintenance cost is minimized. The objective function for the optimum distribution of Riffa maintenance teams is:

$$\Sigma \quad \text{Equation (5.26)}$$

Where,

() are the number of contractors maintenance teams at the timings shown below.

() are the cost of contractor maintenance teams at the timings shown below.

is the number of teams assigned for period 6 am to 8 am.

is the number of teams assigned for period 8 am to 10 am.

is the number of teams assigned for period 10 am to 12 pm.

is the number of teams assigned for period 12 pm to 2 pm.

is the number of teams assigned for period 2 pm to 4 pm.

is the number of teams assigned for period 4 pm to 6 pm.

is the number of teams assigned for period 6 pm to 8 pm.

is the number of teams assigned for period 8 pm to 10 pm.

is the number of teams team assigned for period 10 am to 12 am.

is the number of teams team assigned for period 12 am to 2 am.

is the number of teams team assigned for period 2 am to 4 am.

is the number of teams team assigned for period 4 am to 6 am.

Subject to:

Number of teams in the morning shift (posting hours) for Riffa depot

$$\Sigma \quad \text{Equation (5.27)}$$

Number of teams in the evening shift (posting hours) for Riffa depot

$$\Sigma \quad \text{Equation (5.28)}$$

Number of teams in the evening shift (non-posting hours) for Riffa depot

$$\sum$$

Equation (5.29)

Number of teams in the early morning shift (non-posting hours) for Riffa depot

$$\sum$$

Equation (5.30)

Non-negativity constrains

Equation (5.31)

Solver tool in Microsoft Excel is used to solve Riffa depot optimization. The distribution of the maintenance teams are shown in Table (5.11). It can be noticed that in the morning and the evening shifts 12 maintenance teams are required from the contractor to be in the depot. In the night and early morning shifts, 5 maintenance teams are required to be in the depot. The maintenance teams arrangement may be more clarified in Figure (5.5).

Table (5.11)
Optimal Distribution of Riffa Teams

x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}
12	0	0	12	0	0	5	0	0	5	0	0

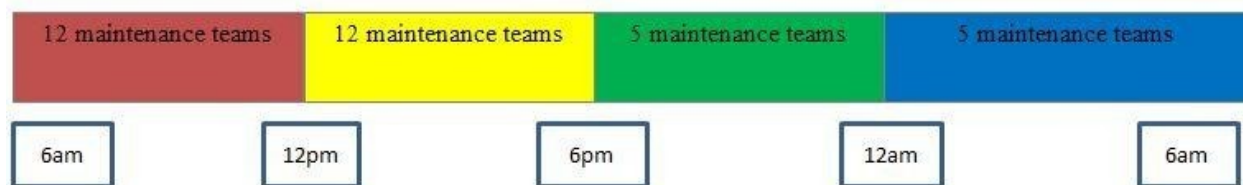


Figure (5.5)
Riffa Maintenance Teams Distribution

The minimum cost required to maintain the arrangement shown in Figure (5.5) is equal to BD 2,638.74 for 24 hours a day (Equation (5.26)).

Chapter 6

Model Evaluation and Discussion

6.1 Introduction

6.2 Arena Simulation Model

6.3 Sensitivity Analysis

6.4 Discussion

Chapter 6: Model Evaluation and Discussion

6.1 Introduction

After developing and solving the model in Chapter 5, the optimum numbers of maintenance teams are found for each depot in Bahrain. However, in order to validate the results obtained, it is mandatory to run a simulator with the actual current status in WDD (actual inter-arrival and service times) to find whether the objectives of this research are achieved or not. For this purpose Arena simulator is used.

6.2 Arena Simulation Model (Arena simulation software)

Arena is a discrete event simulation and automation software Version 14.70.00. It uses the SIMAN processor and simulation language. In Arena, the user builds an experimental model by placing modules (symbols) that represent processes. Connecting lines are used to join these modules together and to specify the flow of entities. While modules have specific actions relative to entities, flow, and timing, the precise representation of each module and entity relative to real-life objects is defined by the modeler. Statistical data such as cycle time, delay time and work in process(WIP) levels, can be recorded and outputted as reports. The delay time can be defined as the time needed to start serving a new complaint raised to the depots. For the case of this research, a diagrammatic model is built using the software. The model represents the current status of WDD depots which includes the entities, service rate and number of servers. The entities are the average number of complaints for the last five years for each complaint type and for each depot. The service times for the maintenance teams are taken from the survey for each type of complaint. Finally, the numbers of servers obtained by the queuing model (Chapter

5) are used for each depot. The model is tested with reference to the average delay time needed to start serving a complaint.

6.2.1 Model input data

Tables (6.1) to (6.3) indicate the inputs which are used for the Arena model.

Table (6.1)
Complaints Inter-arrival Time for Each Depot (from EWA historical data)

Type of complaint	Average yearly complaints (Numbers)			Muharraq inter-arrival (hours)		Budaya inter-arrival (hours)		Riffa inter-arrival (hours)	
	Muharraq	Budaya	Riffa	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs
Leak from main	1374	4761	5857	4.25	12.75	1.24	3.54	0.95	3.56
Leak from service line	1074	4232	4576	5.43	16.31	1.40	3.98	1.21	4.56
Leak from water meter	472	1190	2013	12.36	37.08	4.97	14.15	2.75	10.36
Leak from valve	215	926	915	27.19	81.58	6.39	18.20	6.06	22.79
Leak from fire hydrant	258	1058	1098	22.66	67.99	5.59	15.92	5.05	18.99
Leak from a fitting	902	2380	3844	6.47	19.42	2.49	7.08	1.44	5.43

The first column in Table (6.1) lists the common types of complaints received by depots. The average yearly received complaints for each depot is obtained from historical data for the last five years shows in Tables (4.4) to (4.6). Accordingly, the inter-arrival times are calculated for the three depots as the following example:

$$\begin{aligned}\text{Muharraq posting inter-arrival time (leak from main)} &= 1374/365 \\ &= 3.764 \text{ complaints per day}\end{aligned}$$

$$\begin{aligned}\text{Number of complaints during posting hours} &= 3.764 * 0.75 \\ &= 2.823 \text{ complaints per posting Hours}\end{aligned}$$

Number of complaints during posting hour = $2.823/12$
 $= 0.235$ complain per posting hour

Inter-arrival time during posting hours = $1/0.235$
 $= 4.25$ hours

Table (6.2)
Complaint Average Service Time for Each Depot (Hours)

Type of complaint	Muharraq service time	Budaya service time	Riffa service time
leak from FH	3.65	4.016	2.316
leak from fitting	3.633	3.966	2.58
leak from main pipe	3.333	4.066	2.566
leak from s pipe	3.516	3.683	3.183
leak from valve	3.4	3.566	2.316
leak from water meter	1.65	1.21	0.9

Table (6.2) shows the average service times needed to complete each complaint type in each depot. The service times is obtained from the survey held Table (5.2) to (5.5).

Table (6.3)
Proposed Number of Maintenance Teams for Each Depot

Depot	Proposed number of maintenance teams	
	Posting hours	Non-posting hours
Muharraq	6	3
Budaya	13	7
Riffa	12	5

Table (6.3) shows the proposed numbers of maintenance teams for each depot which are obtained from the queuing model in Chapter 5.

6.2.2 Model results

Each depot is modeled using Arena simulation software as shown in the block diagram of Figure (6.1). The first column of entities represents the different type of complaints, while the entities of the second column represents the actions that should be carried out. For each of these action entities, relevant inter-arrival and service distributions and the values of their associated parameters, namely, average of inter-arrival and service times given in Tables (6.1) and (6.2) are entered, in addition to the current number of maintenance teams as given in Table (4.7). This is to simulate the current service provided by the depots. On the other hand to simulate the proposed solution the complaint completion time (waiting and service) is bounded by 2 hours as maximum, and the optimum number of the maintenance teams for each depot as given in Table (6.3) are the input to the simulation. The main parameter to be tested is the complaint completion time. This time has to be minimized in order to maintain the objective of this research, i.e. to complete 99% of the complaints within a period not exceeding 2 hours.

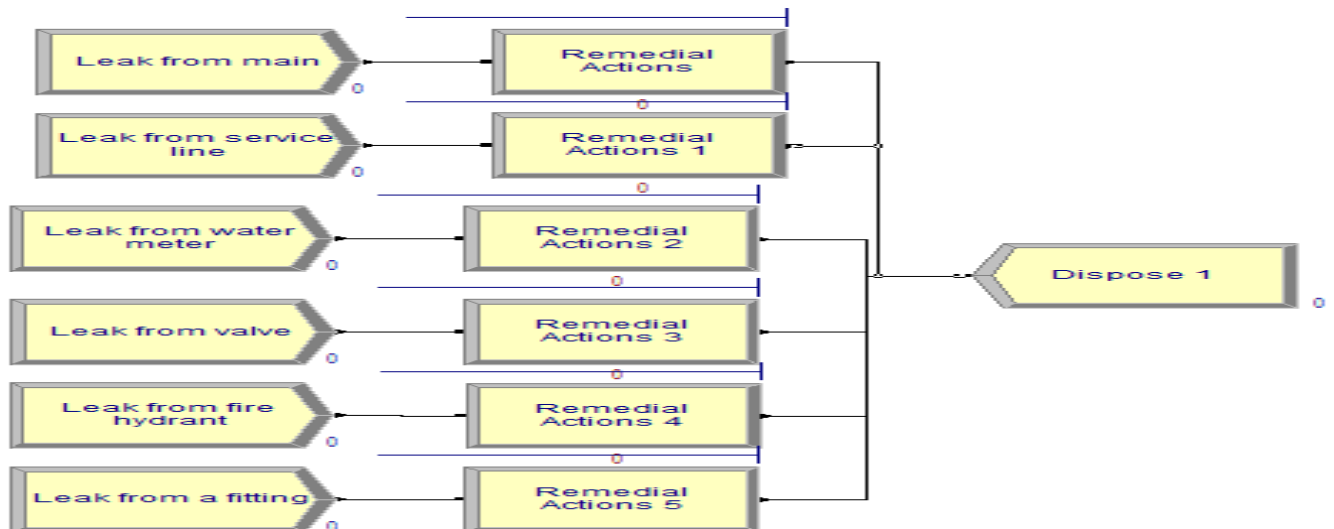


Figure (6.1)
Arena Model

Table (6.4)
Result of Arena Model

	Average delay time (hours)					
	Muharaq		Budaya		Riffa	
	With existing maint. teams	With proposed maint. teams	With existing maint. teams	With proposed maint. teams	With existing maint. teams	With proposed maint. teams
Posting hrs	1.1386	0	1.59	0	2.5	0
Non posting hrs	0	0	0	0	3.3364	0

It is obvious from Table (6.4), which shows the simulation results of the three depots, that the delay time to serve a complaint using the proposed number of maintenance teams is zero. When the current maintenance teams are used, the complaints have to be delayed for a considerable time before it gets served as indicated in the table.

6.3 Sensitivity Analysis

Sensitivity analysis is an analysis that finds out how sensitive an output is to any change in a specific input while keeping other inputs constant. Sensitivity analysis is useful because it tells the model user how dependent the output value is on each input. In the case of this research, its mandatory to test the result obtained against any unanticipated change in the main parameters and to see the effect of such change on the results. The unanticipated change might occur due to the unexpected increase in the volume of received complaints or it might occur due to a significant reduction in the number of the maintenance teams or due to both cases in the same time.

Arena Simulator is used for the sensitivity analysis as well.

6.3.1 Number of maintenance teams

In this subsection, the service time and the inter-arrival time are kept constant while the proposed number of maintenance teams is reduced gradually. During this reduction, the delay time needed to start serving a complaint will be observed and recorded. Table (6.5) shows the delay time needed to start serving a complaint while the number of proposed maintenance teams is reduced.

Table (6.5)
Effect of Number of Maintenance Teams on Delay Time

Muharraq depot				Budaya depot				Riffa depot			
Posting hours		Non-Posting hours		Posting hours		Non-Posting hours		Posting hours		Non-Posting hours	
No. of maint. teams	Delay time (hrs)	No. of maint. teams	Delay time (hrs)	No. of maint. teams	Delay time (hrs)	No. of maint. teams	Delay time (hrs)	No. of maint. teams	Delay time (hrs)	No. of maint. teams	Delay time (hrs)
6	0	3	0	13	0	7	0	12	0	5	0
5	0	2	0.8647	12	0	6	0	11	0	4	0.5784
4	0.3254	1	2.1456	11	0	5	0.0785	10	0	3	1.8346
3	1.1386	***	***	10	0	4	0.9457	9	0	2	3.3364
2	7.2832	***	***	9	0.3159	3	2.0164	8	0.1463	1	4.5784
1	7.9653	***	***	8	1.0054	2	6.2417	7	0.9841	***	***
***	***	***	***	7	1.5953	1	8.3146	6	2.5647	***	***

It can be noticed in Table (6.5) that in the three depots there are a flexibility in the proposed number of the maintenance teams during the posting hours where in Muharraq depot, there was no effect on the delay time until the proposed number of maintenance teams were reduced by 2, i.e. 4 maintenance teams. Where in Budaya and in Riffa depots, there was no effect on the delay time until the

proposed number of maintenance teams were reduced by 4, i.e. 9 and 8 maintenance teams for Budaya and Riffa, respectively.

6.3.2 Volume of received complaints

In this subsection, the service time and the proposed number of maintenance teams are kept constant while the volume of received complaints is increased gradually. The yearly average number of complaints is increased by 15%, 30% and 45% for each type of complaint which results into reduction of inter-arrival time as shown in Tables (6.6) to (6.8).

Table (6.6)
Increase of Complaints by 15% and its Effect on Inter-arrival Time

Type of complaint	Number of complaints			Muharraq arrival time (hours)		Budaya arrival time (hours)		Riffa arrival time (hours)	
	Muharraq	Budaya	Riffa	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs
Leak from main	1581	5475	6736	3.69	11.08	1.08	3.08	0.82	3.10
Leak from service line	1235	4866	5262	4.73	14.19	1.22	3.46	1.05	3.96
Leak from water meter	543	1369	2315	10.75	32.25	4.32	12.31	2.39	9.01
Leak from valve	247	1065	1052	23.65	70.94	5.56	15.82	5.27	19.82
Leak from fire hydrant	296	1217	1263	19.71	59.12	4.87	13.85	4.39	16.51
Leak from a fitting	1037	2737	4420	5.63	16.89	2.16	6.15	1.25	4.72

Table (6.7)
Increase of Complaints by 30% and its Effect on Inter-arrival Time

Type of complaint	Number of complaints			Muharraaq arrival time (hours)		Budaya arrival time (hours)		Riffa arrival time (hours)	
	Muharraaq	Budaya	Riffa	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs
Leak from main	1787	6189	7614	3.27	9.81	0.96	2.72	0.73	2.74
Leak from service line	1396	5501	5949	4.18	12.55	1.08	3.06	0.93	3.51
Leak from water meter	614	1547	2617	9.51	28.53	3.83	10.89	2.12	7.97
Leak from valve	279	1203	1190	20.92	62.76	4.92	14.00	4.66	17.53
Leak from fire hydrant	335	1375	1428	17.43	52.30	4.30	12.25	3.88	14.61
Leak from a fitting	1173	3094	4997	4.98	14.94	1.91	5.44	1.11	4.17

Table (6.8)
Increase of Complaints by 45% and its Effect on Inter-arrival Time

Type of complaint	Number of complaints			Muharraaq arrival time (hours)		Budaya arrival time (hours)		Riffa arrival time (hours)	
	Muharraaq	Budaya	Riffa	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs	Posting hrs	Non posting hrs
Leak from main	1993	6903	8493	2.93	8.79	0.86	2.44	0.65	2.46
Leak from service line	1557	6136	6635	3.75	11.25	0.96	2.75	0.84	3.14
Leak from water meter	685	1726	2919	8.52	25.57	3.43	9.76	1.90	7.14
Leak from valve	311	1342	1327	18.75	56.26	4.41	12.55	4.18	15.72
Leak from fire hydrant	374	1534	1592	15.63	46.89	3.86	10.98	3.48	13.10
Leak from a fitting	1308	3451	5574	4.47	13.40	1.71	4.88	0.99	3.74

The inter-arrival times obtained from Tables (6.6) to (6.8) are entered into the Arena model to observe the delay time needed to start serving a complaint. Table (6.9) shows the effect of the volume of complaints, and consequently the inter-arrival time on delay time.

Table (6.9)
Effect of Volume of Complaints on delay time

		Muharaq depot			Budaya depot			Riffa depot		
		% Increase in number of complaints								
		15 %	30%	45%	15 %	30%	45%	15 %	30%	45%
Delay time (hrs)	Posting hrs	0	0.0001	0.9784	0	0	1.5862	0	0.0722	1.0557
	Non posting hrs	0	0	0.7533	0	0	1.1101	0	0.0009	0.9626

6.4 Discussion of Results

In this section, the results obtained from the simulation are discussed.

6.4.1 Proposed number of maintenance teams

After running the Arena model to insure the validity of the proposed number of maintenance teams obtained in Chapter 5, and to compare it with the actual available number of maintenance teams, it is clearly obvious from Table (6.4) that currently the delay time needed to start serving a complaint in the three depots is considerably high. This will affect the following:

1. increase the total time needed to complete a complaint, (i.e. delay plus service time)
2. increase the NRW in Bahrain.
3. increase the cost of NRW.
4. wasting Bahrain natural resource.
5. developing a bad image about EWA by its customers.

When it comes to the objectives of this research and with regard to EWA strategic objectives, one of EWA main goals is to complete any complaint within 2 hours from receiving it. This cannot be maintained with the current number of maintenance teams. For example, in Budaya depot, a complaint requires an average delay time of 1.59 hours (Table (6.4)) and an average service time of 3.45 hours (Table (5.3)) to finish the remedial actions on the site. Thus, a total of 5.04 hours is needed to complete the complaint.

However, after implementing the proposed number of maintenance teams, the service time is assumed not to be more than 2 hours and the delay time becomes 0 (Table (6.4)) which give a total of 2 hours in order to complete the complaint. Thus, with the proposed number of maintenance teams, EWA strategic goal can be met.

In Muharraq and Budaya depots, it can be noticed that during the non-posting hours the delay time needed to start serving a complaint is zero which gives an indication that the existing number of maintenance teams is enough to maintain EWA strategic goal. While in Riffa depot, it is mandatory to increase the number of maintenance teams to meet the strategy.

6.4.2 Effect of reducing the number of maintenance teams

The proposed numbers of maintenance teams are gradually reduced and the delay time is observed and recorded. The simulation indicates the sensitivity level of the results obtained in case of any unanticipated constraint occurred that lead to reduction in the number of the proposed number of maintenance teams, such as availability of budget or transportation problems of the teams.

It can be noticed in Table (6.5) that in the three depots there is a flexibility in the proposed number of maintenance teams during the posting hours where in Muharraq depot, there is no effect on the delay time until the proposed number of

maintenance teams is reduced by 2. Where as in Budaya and in Riffa depots, there is no effect on the delay time until the proposed number of maintenance teams is reduced by 4. This flexibility will reflect the desired service level of completing 99% of received complaints, each in not more than 2 hours as introduced in the queuing model (Chapter 5).

6.4.3 Effect of decreasing inter-arrival times

For some technical reasons, the volume of received complaints might increase rapidly in one or multiple areas in Bahrain. Due to this, it is necessary to test the proposed number of maintenance teams against such increase, and to evaluate how sensitive the results are. Table (6.9) shows the delay time with the increase of volume of complaints. It can be noticed that when the complaints are increased by 15% there is no effect on the delay time for the three depots. This gives an indication that the proposed number of the maintenance teams is flexible with regard to small increases in the volume of complaints. However, when the volume of complaints is raised by 30%, in Muharraq and Budaya depot there was no effect on the delay time, and in Riffa depot there are small increases. This gives an indication that the proposed number of maintenance teams in the three depots can accommodate up to 30% increase in the volume of the complaints. This flexibility is a reflection of the desired service level of completing 99% of all received complaints within 2 hours.

When the volume of complaints is raised by 45%, the delay time increases considerably for the three depots, which means at this level of received complaints the proposed numbers of maintenance teams are not enough to satisfy EWA strategic goal of completing all complaints within 2 hours.

Chapter 7

Conclusions, Recommendations and Further Research

7.1 Conclusions

7.2 Recommendations for Muharraaq and Budaya Depots

7.3 Recommendation for Riffa Depot

7.4 Further Research

Chapter 7: Conclusions, Recommendations and Further Research

7.1 Conclusions

The main objective of this research is to minimize the service time needed to complete a complaint in any of the three depots to 2 hours by finding the optimum number of maintenance teams for each depot, and accordingly the NRW will be reduced in Bahrain. To do so, the service times for the three depots are established through a survey, the arrival times are obtained from historical data. A queuing model is developed for each depot to find the optimum number of maintenance teams that satisfy the condition of completing 99% of received complaints within 2 hours.

For the shift arrangement and the type of maintenance teams in each depot, a linear programming model is developed in order to distribute and schedule EWA and contractor maintenance teams while keeping the EWA current maintenance teams. To validate the results, Arena simulator is used to verify whether the results obtained are practical or not by ensuring that the delay time to start serving a complaint is minimized. To evaluate the robustness of the findings with the increase of the volume of complaints or the decrease of the number of maintenance teams, a sensitivity analysis is conducted to ensure completion of 99% of complaints within 2 hours.

The results obtained show that the objectives of this research are achieved, which indicate that a considerable reduction in the NRW can be maintained. In conclusion, the correct number of maintenance teams in each depot will have a

positive effect on the NRW and will save Bahrain natural resources for future generations.

During the evaluation of the current status in WDD of EWA, it is noticed that the procedures and the preparations of handling the maintenance activities in each depot are different. Moreover, during the survey held in Riffa depot the average service time needed to complete a complaint is less than the service time in Muharraq and Budaya depots even though Riffa area is having more complaints, more area to cover, more congested area than others, and more pipeline length to handle than Muharraq and Budaya depots. Neglecting the factor of the number of the maintenance teams, the justification that Riffa depot is having less service time than other depots is that they adopt a better management and maintenance style in handling the works due to the relatively advanced and automated tools used and the diversity of professional manpower.

7.2 Recommendations for Muharraq and Budaya Depots

The following points are the recommendations for Muharraq and Budaya depots:

1. With regard to the time of approaching to the location of the complaints, it is recommended to establish new sub-stations in different locations in order to minimize the time needed to approach the location of the complaint. The average time found in the survey is considered high for Muharraq and Budaya depots. For example, around 45 minutes are required to reach a complaint located in Juffair area from Budaya depots which is located in Duraz area.
2. With regard to the type of tools used by the maintenance teams, it is recommended to use an advanced automated tool rather than the basic tools

(shovels and steel rods) where it is found from the survey that the average time needed for the excavation and backfilling is considered high. For example, during the excavation in Muharraaq area which having a high ground water table, the average time needed may reach up to 1.5 hours, but, if automated equipment's are available (pumps and jack hammers) the time may be reduced to 20 minutes only.

3. With regard to the skills of the manpower in each maintenance team, it is recommended to hire a professional skilled manpower in the maintenance teams in order to minimize the replacement time needed. The diversity of skills is highly recommended as well where the plumber is good in plumping work not excavation works and the excavator is good in excavation works not reinstatement works. The correct and right diversity will reduce the time needed to complete complaints rapidly. Further investigation need for this point as well.

Considering the above recommendations will have a positive effect on the service time, and accordingly on the NRW.

7.3 Recommendation for Riffa Depot

In Riffa depot there is a recommendation with regard to the distribution of the sub-stations in the covered area where most of the sub-stations are placed in Very Important People (VIP) areas and less are placed in other areas. The recommendation is to distribute the substations based on the volume of complaints.

7.4 Further Research

In order approach to a comprehensive and durable solution for the NRW in Bahrain, it is recommended to have further researches on the following areas:

1. The analysis of current procedures of handling complaints to ensure its effectiveness, i.e. to make necessary modifications in the current procedures.
2. The distribution of the substations and its locations over Bahrain to minimize the transportation time to the location of the complaints.
3. The right number of manpower in each maintenance team and the correct skills required by the manpower. i.e. the number of manpower to be present in the maintenance team and the occupation of these manpower might have an effect on the processing time of completing the complaint.

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Appendix A: EWA CEO Presentation

Appendix B: Water Distribution Directorate Strategic Goal

Appendix C: Sample of Muharraaq Depot Survey

Appendix D: Sample of Budaya Depot Survey

Appendix E: Sample of Riffa Depot Survey

ملخص الدراسة

لقد استثمرت مملكة البحرين الكثير من الاموال منذ وقت طويل في تقنين المفقود من المياه في شبكات توزيع المياه التابعة لهيئة الكهرباء والماء ليتسنى لها المحافظة على ثروات مملكة البحرين للأجيال القادمة. ومن خلال الابحاث الخاصة بالمفقود من المياه في الهيئة، تبين بأن كمية المفقود تساوي 21,535 مليون جالون سنوياً بتكلفة تقارب 71 مليون ديناراً بحرينياً مما يؤشر على الحاجة لإجراء المزيد من البحوث والدراسات في مجال تقنين المفقود من المياه في شبكات هيئة الكهرباء والماء. وكإجراء عاجل، وضعت هيئة الكهرباء والماء إستراتيجية لتقنين المفقود من المياه والتي تتمثل بإكمال 99% من جميع البلاغات الواردة في ما لا يزيد عن الساعتين للبلاغ الواحد.

لجمع المعلومات المطلوبة، تم عمل دراسة استقصائية للطلبات الواردة في مراكز الصيانة الثلاث التابعة للهيئة وهي مركز المحرق و مركز البديع و مركز الرفاع. تتمثل المعلومات التي تم جمعها كالآتي:

متوسط الوقت المطلوب لإكمال البلاغ الواحد في جميع مراكز الصيانة.

انواع البلاغات الواردة لجميع مراكز الصيانة.

النسبة الواردة لكل نوع بلاغ من النسبة الكلية.

نسبة ورود البلاغات في الفترة الصباحية والفترة المسائية.

لتحقيق (Queuing model) لمعرفة العدد الأمثل المطلوب لفرق الصيانة في كل من المراكز، تم تطبيق نموذج الطوابير إستراتيجية الهيئة المتمثلة في إكمال 99% من البلاغات الواردة في ما لا يزيد عن الساعتين للبلاغ الواحد. وبسبب (Linear programming) إختلاف توافيت النوبات في كل من مراكز الصيانة، تم تطبيق نموذج توقيتات البرمجة الخطية ليتم توزيع فرق الصيانة بالشكل الذي يتيح تحقيق اقل تكلفة. ولكي يتم التحقق من صحة النتائج، تم استخدام (model) لدراسة مدى فعالية النتائج في محاكاة الطبيعة الواقعية والعملية لعملية (Arena Simulator) برنامج ارينا للمحاكاة تصحيح البلاغات الواردة إلى هيئة الكهرباء والماء. ولتقييم مدى مرونة النتائج في حال تقليل عدد فرق الصيانة أو في حالة زيادة عدد البلاغات الواردة إلى الهيئة، تم إجراء دراسة لتقدير مدى حساسية النتائج في حال تغيير هذين العنصرين. أوضحت جميع النتائج تحقيق اهداف البحث المتمثلة باكمال 99% من البلاغات خلال ساعتين وإيجاد الاعداد المثالية لفرق الصيانة وبالتالي تقليل المفقود من المياه.

قسم الهندسة الميكانيكية

جامعة البحرين

كلية الهندسة



تقليل فاقد المياه في خطوط الانابيب لمملكة البحرين

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير في
الإدارة الهندسية

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