Development of Ship Maintenance Performance Measurement Framework to Assess the Decision Making Process to Optimise in Ship Maintenance Planning

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List of Abbreviations

SMPM	Ship maintenance performance measurement
KOTC	Kuwait Oil Tanker Company
RCM	Reliability centred maintenance
TPM	Total productive maintenance
HSE	Health and safety executive
MTBF	Mean time between failures
CBM	Condition based maintenance
RE	Reliability engineering
CE	Control engineering
OEE	Overall equipment effectiveness
GT	Gross tonnage
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
RORO	Roll-on/roll-off
BSF	Black Sea Fleet
PI	Performance indicator
KPI	Key performance indicator
MTTR	Mean time to repair
MPM	Maintenance performance measurement
SMM	Strategic maintenance management
BPM	Business performance management
R&D	Research and development
MTTF	Mean time to failure
HS&E	Health, safety and environment

TMSA	Tanker Management and Self-Assessment
OCIMF	Oil Companies International Maritime Forum
M&R	Maintenance & rehabilitation
GAMS	General algebraic modelling systems
LCC	Life cycle cost
CU	Chillier unit
PM	Preventive maintenance
VLCC	Very large crude carrier
FAD	Fuzzy axiomatic design
CSP	Constraint satisfaction problem
CBR	Constraint-based reasoning
GA	Genetic algorithm
TOC	Theory of constraints
KLTT	Kuwait Livestock Transport and Trading Company
GRC	Gulf Rocks Company
MS	Management science
OR	Operation research
LPP	Linear programming problem
IPP	Integer linear programming problem
KPC	Kuwait Petroleum Company
ISM	International safety management
AMD	Assistant manager director
GMSM	Gulf Maritime Shipping Management Company
MPI	Maintenance performance indicator

List of Publications

- Alhouli, Y., D. Ling, R. Kirkham, T. Elhag (2009). On the Factors Afflicting Maintenance Planning in Mercantile Industry. COMADOM. San Sebastian Spain.

- Alhouli, Y., D. Ling, R. Kirkham, T. Elhag (2009). Dry Docked Maintenance Scheduling of Commercial Shipping Vessels in Kuwait Using An Integer Programming Methodology. The 42^{nd} Annual Conference on Statistics, Computer Science and Operation Research. Cairo University, Cairo, Egypt.

- Alhouli, Y., D. Ling, R. Kirkham, T. Elhag (2010). Performance Measurement of Marine Vessel Maintenance Operations: A Case Study of Kuwaiti Shipping Companies. 5^{th} Annual Conference Liverpool BEAN. Liverpool John Moores University, Liverpool, UK.

Abstracts

Effective maintenance planning is essential and important in any organisation that is responsible for procuring and managing complex assets. In the marine shipping industry maintenance planning is very significant due to its complexity and the obligations on shipping organisations to comply with certain regulations and requirements. Moreover, improper planning can reduce the ship's availability, which may in turn, be reflected in the revenue of the company. Another issue that requires attention in this field is the cost of maintenance, since improper or inadequate planning could result in breakdowns that could increase the cost of maintenance.

This research aims to identify the key factors that affect ship maintenance planning and to provide a framework that can help the decision maker to identify and choose optimum decisions regarding ship maintenance. The research is divided into four stages in order to achieve its objectives and to address the research problem.

The first stage is the review of the literature to identify the need for maintenance and to select the key factors that affect maintenance planning. The findings indicate that: maintenance scheduling, selection of maintenance strategy, ship construction, crew compensation, and shipyard selection are the most important factors.

The second stage is to evaluate maintenance performance measurements for the marine shipping industry by conducting case study and interviews with professionals involved in the mercantile industry. Semi-structured interviews were conducted with six senior staff experts from three different organisations. The results show that: dry docking scheduling, maintenance costs and budgets, customer satisfaction, employees' satisfaction, classification requirements, and the ship's maintenance requirements are the main factors that have great influence on maintenance planning.

The third stage is to develop new methodology to measure the maintenance performance in the marine shipping organisation which is the ship maintenance performance measurement (SMPM) framework. The developed method was validated to assist managers in making the right decisions in ship maintenance planning. The framework was developed based on ten thematic criteria that can be used as indicators for potential organisation growth, i.e., maintenance strategy; dry docking scheduling; budget and costs; the ship's equipment; customer satisfaction; employees; health, safety and environment; learning and growth; classification requirements; and the ship's operation and demands requirements. Interviews were conducted with key personnel from the Kuwait Oil Tanker Company (KOTC) to validate the framework.

The fourth stage demonstrates that an optimised schedule for the dry docking of ships for routine maintenance has been constructed. This is accomplished on the basis of one measured criterion, dry docking scheduling, by using an integer programming model to maximise the ship's availability within the company fleet. The model is defined by three constraints: the maintenance window, maintenance completion, and the ship's limit. The model was validated using data from KOTC, and the results depict an optimum solution for maintenance scheduling, maximising the ship's availability to 100% and not less than 92%.

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Chapter 1: Introduction

1.1. *An Overview*

Effective maintenance is widely regarded as one of the major challenges facing any organisation, especially if its goal is to provide services or products at a higher competency level than its competitors. This challenging issue has forced many ambitious, industrial organisations to place a high priority on preventive maintenance. In modern industrial organisations, maintenance departments have important roles because of their ability to have an economic balancing effect (Dekker 1996). From that viewpoint, good managers have tried to run their business in an optimal manner, including maintenance. However, the importance of effective maintenance is related to availability and performance, and it may also be concerned with issues related to the safety-critical nature of mercantile industries (Artana et al. 2005).

In many cases, management does not speak the same language as the staff in the maintenance department, and they may have different understanding over many conflicting issues. This indicates that there is a requirement to understand the respective views of maintenance and the consequences that may result if improper maintenance decisions are made. In many cases in actual practice, serious accidents and interruptions in many industries are related to poor maintenance, or, more specifically, to poor maintenance planning (Reason and Hobbs 2003). To understand this issue, one such case was selected from the marine industry for the purposes of this study.

The marine industry faces unique challenges in the execution of scheduled and unscheduled maintenance; the mere fact that ships spend significant periods at sea impacts upon supply-chain management (e.g., labour and availability of resources) (Rustenburg et al. 2001).

A ship at sea is isolated from onshore repair and maintenance facilities, and, if a failure occurs during the passage, the required replacement parts may not be available on board. The rising cost of ship operation is a problem, since the failure of a vital piece of equipment can be very expensive and may put the whole ship at risk. Added to this is the cost of downtime, when the ship is out of service (off hire). Other problems are the ship's safety and environmental effects, as poor maintenance can result in dangerous operation and environmental damage (Rothblum 2000).

Therefore, maintenance is a crucial factor in a ship's performance and, in turn, can affect the shipping company's revenue. There should be a balance between maintenance cost and over-maintenance. Thus, a good framework with which to measure maintenance performance and to plan maintenance policy for the shipping marine organisation is of vital importance.

Questions are: What factors influence the performance of the shipping marine organisation? What are the issues related to developing a ship maintenance performance framework (SMPM)? How can such a framework be validated and implemented?

1.2. Research Significance

Many organisations from different industries are incurring exorbitant costs for maintenance. The marine organisation is one such industry, and it spends huge amounts of money on maintenance. In fact, approximately 40% of the operation costs in a marine shipping organisation is attributable to maintenance (Alhouli et al. 2009).

Poor maintenance planning can result in serious incidents (Reason and Hobbs 2003). Therefore, it is important to study this issue and find the most important factors that can optimise maintenance expenditures and also reduce the occurrence of serious incidents.

In general, this research is intended to highlight the importance of measuring the maintenance performance of a marine organisation and its influence on the organisation's revenue. An evaluation of the importance of dry docking maintenance scheduling of ships in any maritime transportation organisation is then conducted.

The research is based on identifying the factors that have an influence on maintenance planning. This can be achieved by assessing the measurement of maintenance performance and identifying the need for that assessment in order to optimise maintenance planning for the mercantile industry.

The research has proposed new methodology to measure the maintenance performance of the marine shipping organisation. This method is named as SMPM framework, which is the ship maintenance performance measurement framework.

1.3. Research Aim and Objectives

In order to keep the ship operating at the lowest possible operation cost and for safety and efficiency, ship maintenance is a must, due to many factors. Moreover, ship maintenance planning and its cost are significant issues, therefore it is very important to identify the factors that affect maintenance planning and that lead to the optimisation of such planning, because this can produce great savings for the mercantile industry.

The aims of the study are to identify the key factors that affect ship maintenance planning, to develop a maintenance measurement framework, and to optimise ship availability.

Accordingly, the main objectives of this research project are summarised as follows:

1. To identify the need and importance of maintenance with a specific focus on the mercantile industry; and to extract and assess the factors that affects the decision-making process for ship maintenance planning.

2. To evaluate and compare the different approaches and frameworks for maintenance performance measurement.

3. To assess marine maintenance performance indicators based on the literature and interviews.

4. To develop a ship maintenance performance measurement framework method that helps decision makers in planning ship maintenance.

5. To develop maintenance scheduling system by implementing mathematical modelling for dry docking scheduling (which schedule the ships to be maintained in ship yards).

6. To validate the framework by interviewing experts from the marine field and validate the mathematical model by using data from a marine shipping organisation.

1.4. Research Methodology

This research was conducted using the methodology shown in Figure 1-1, which shows the sequence of activities and tasks that were used in the thesis in order to achieve the objectives set out in Section 1.3.

The study of maintenance measurement and planning for the marine shipping industry began with a literature survey to identify the main concepts.

The second step was to measure the maintenance performance of the shipping industry and discuss and identify the need for a method that helps in maintenance planning for the marine industry. A case study was used to measure that performance. An abductive approach was used to analyse and discuss the literature review, case study findings, and experts' interviews.

The third step was to develop a ship maintenance performance measurement framework that helps in the decision making for planning maintenance in the marine shipping industry. Then, an operation research method was applied by using an integer programming approach to develop ship dry docking maintenance scheduling.

The last step is to validate both the framework and the developed dry docking maintenance scheduling. The framework was validated through interviews with top management and decision makers, and dry docking maintenance scheduling was validated through real data collection from the KOTC.

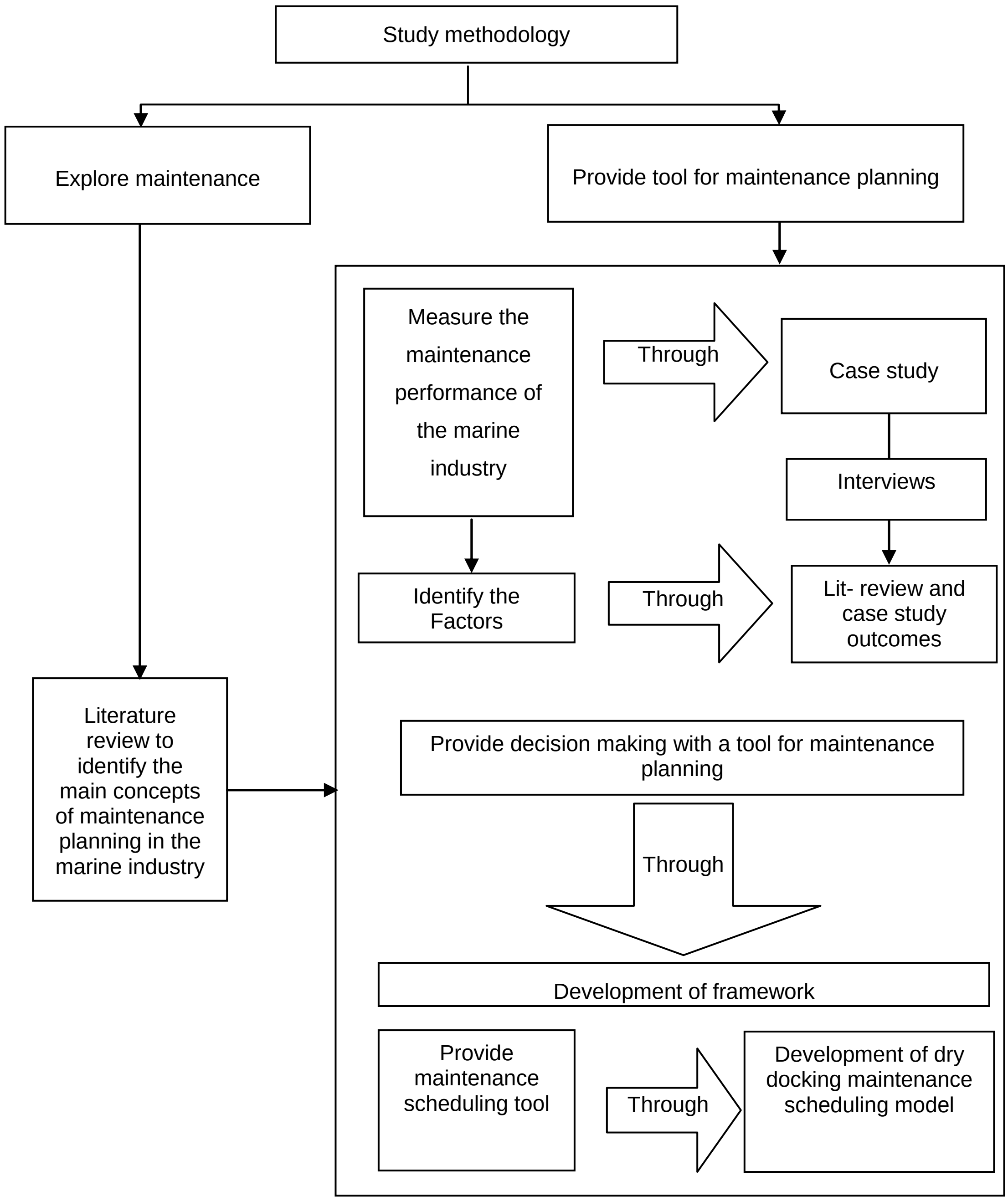

Figure 1-1: Study Methodology

1.5. Research Limitations

Maintenance measurement and maintenance optimisation is a very broad area of research, therefore the present research is planned to focus on specific theme, which is in this case the marine shipping industry.

This research was focused on developing a new method to measure maintenance performance of the marine shipping organisation, which is the SMPM framework. Also, a model was developed to schedule a ship’s dry docking maintenance times.

In view of the fact that the study discusses a general maintenance background, the study focused on the requirements and performance of ship maintenance by marine shipping organisations. Therefore, any outcomes that result from this research are limited to the marine shipping industry.

In this context, the data collected were limited; they were based on the interviews conducted with the Kuwaiti shipping companies.

Although the findings might be used for maintenance performance measurement in other organisations, attention was paid to the limitation of the nature of the case study, since it was conducted for a specific organisational and institutional context.

The dry docking scheduling model was constructed to maximise the ship’s availability with three selective limited constraints, i.e., the maintenance window, maintenance completion, and the ship’s limiting constraints. The data collected for the model are limited in that they were collected only from the KOTC.

The implementation of the framework and model on the operation stage is a lifetime process, which, obviously, cannot be accomplished during the duration of the research project. Therefore, validations of both the framework and the model were conducted based on interviewing key personnel and data collected from KOTC.

1.6. Thesis Organisation

The thesis is divided into nine chapters, starting with the broad study of the maintenance subject and its importance to the marine industry. The need for a maintenance performance measurement for the marine shipping industry is emphasised, and, then, the factors that affect ship maintenance planning are identified. After that, ship maintenance performance measurement (SMPM) framework and a ship's dry docking maintenance schedule are developed. Finally, conclusions and future work are detailed, see Figure 1-2. The chapters' outline of the thesis is presented as in as follows:

Chapter One introduces the importance of and need for maintenance in the marine industry. The research problem and the research significance are discussed. The aim and the objectives of the research are discussed in detail. The research methodology and research limitations are discussed.

Chapter Two provides an overview of maintenance management; maintenance definitions are explored, including the benefits and importance of maintenance systems, maintenance philosophies (strategies), maintenance policies, and the concepts of reliability and maintenance. The two methods of Reliability centred maintenance (RCM) and Total productive maintenance (TPM) are discussed. Then, marine background is discussed, along with ship maintenance and its costs. A description of shipping maintenance and shipyard maintenance is presented. Maintenance costs are discussed, and the differences between direct and indirect ship maintenance costs are identified; an example of ship maintenance costs and an evaluation of the costs are provided. Finally, controlled and uncontrolled maintenance planning factors are discussed.

In **Chapter Three,** maintenance performance measurement techniques are discussed, and the need for such measurement in any organisation is identified. The link between maintenance performance measurement and maintenance performance management is identified. Different approaches to maintenance measurements are discussed and selected examples used in maintenance measurements are reviewed. Maintenance performance indicators are identified and discussed, as is the appropriateness of these indicators in a management framework.

Chapter Four discusses the maintenance optimisation and gives a review of the maintenance optimisation models. It classifies the maintenance optimisation models into time-based and cost-based generic models and ship maintenance models.

Chapter Five discusses the methodology used in this research. It discusses qualitative and quantitative approaches and the strategic methods used. It discusses the case study approach that was used, and it ends with the operation research method that was used in this study.

A case study that is concerned with three Kuwaiti shipping companies is discussed in **Chapter Six**. Interviews with experts from the three companies are discussed and analysed, using an interpretive approach.

Chapter Seven shows the steps in developing a new method which is the ship maintenance performance framework. This method is the main novelty of this research which identifies the performance measurement criteria. For each criterion, the performance indicators are identified for each hierarchical level of the marine organisation. Finally, the validation of this framework is discussed by conducting interviews with key personnel from the marine organisation.

In **Chapter Eight,** a mathematical model is developed for scheduling the ship's dry docking maintenance. The model is developed as a zero-one integer programming model. The validation of this model is carried out by using data from KOTC.

Chapter Nine summarises the thesis chapters, and then the conclusions are presented. Then, the contribution of this research to the knowledge base in the marine shipping industry is discussed. The thesis ends with recommendations for future research work in this area.

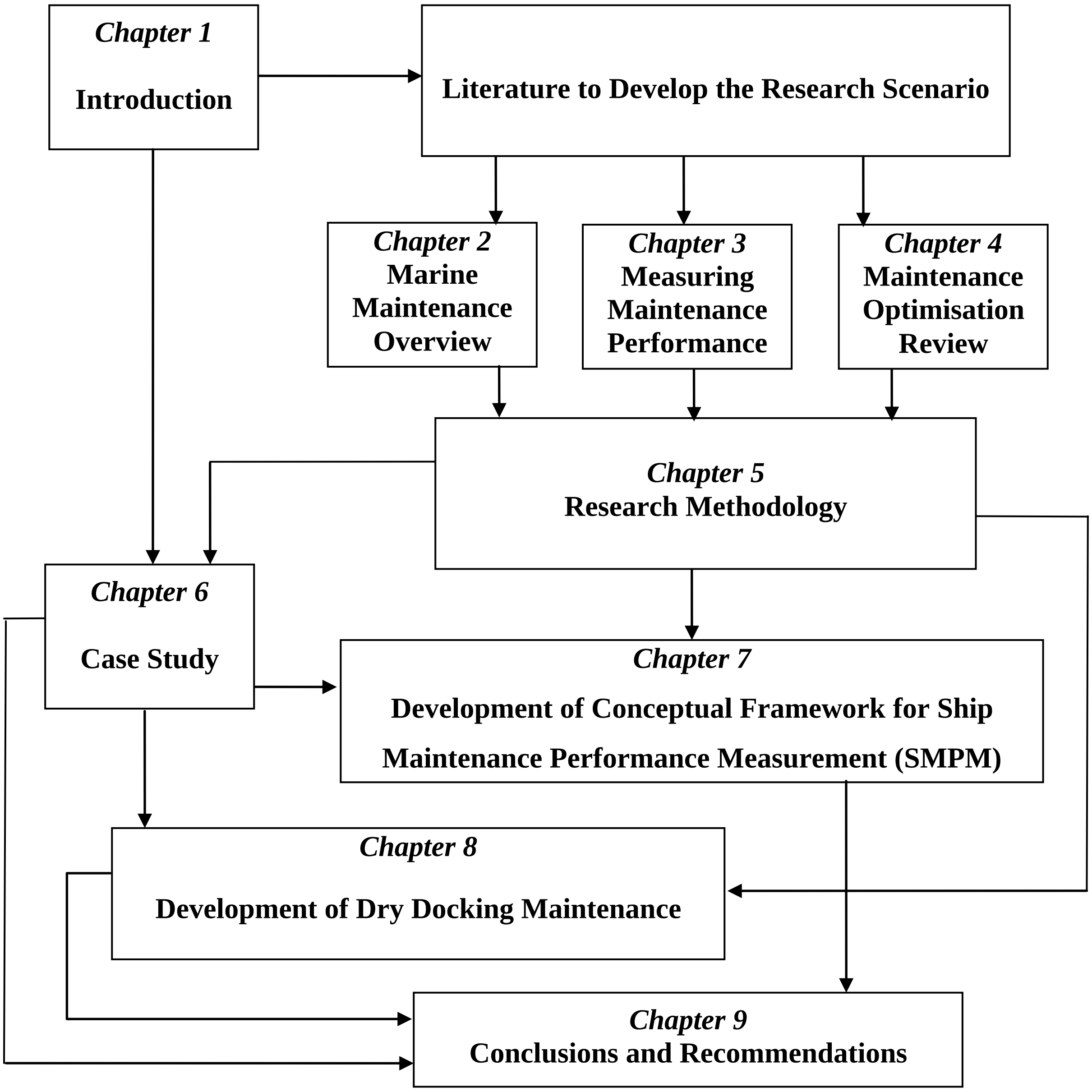

Figure 1-2: Thesis Layout

Chapter 2: Marine Maintenance Overview

2.1. Introduction

Mercantile industries operate in an environment in which safety is a critical issue; this is illustrated clearly in the health and safety executive's (HSE's) most recent accident statistics. Sound working methods along with appropriate maintenance regimes are a prerequisite to any corporate strategy; the potential consequences of poor maintenance have been illustrated in numerous shipping incidents over the years, including the Torey Canyon in 1967, the Urquiola in 1976, the Amoco Cadiz in 1978, the Betelgeuse in 1979, the Haven in 1991, the Aegean Sea in 1992, the Braer in 1993, the Sea Empress in 1996, Erika in 1999, and Terra Australis in 2002 (Parrett 2000). Therefore, it follows that robust strategies for managing the maintenance requirements of these highly complex assets are of interest to both academia and commercial organisations.

The purpose of this chapter is to explore the existing literature surrounding the design, implementation, and review of maintenance strategies in the context of: (1) general asset management theory; and (2) the mercantile sector, specifically. This critical review identifies the potential obstacles to the implementation of generic approaches to ship maintenance by examining the idiosyncratic nature of maintenance requirements in shipping vessels and suggests signposts for further research.

The review reflects upon the almost inconceivable notion that maintenance is viewed in some organisations as a non-core function (Cooke 2003). The inextricable link between effective maintenance and operational efficiency (and thus profit) has been highlighted in recent research, thereby increasing the focus on the need for effective approaches to maintenance management. At best, maintenance was seen as an unimportant sub-system of production, and, at worst, as a necessary and unplanned overhead.

During the last 30 years or so, the maintenance function has become increasingly important to profitability. This is the result of organisations' facilities increasing in sophistication and complexity. Maintenance is a vitally important feature of the national economy. Large amounts of money are allocated to maintenance each year by industrialised nations (Guignier and Madanat 1999). Failure to manage maintenance can lead to high penalty costs arising from operation downtime (Dekker 1996). However, Wireman (2005) takes an alternative perspective, focusing on the potential compromise to strategic corporate performance. Recent developments in the field of indirect work measurement have convinced management that maintenance can be subjected to the same types of analyses as operations.

It has become increasingly evident that maintenance can no longer be ignored; it must be engineered, as other plant functions are (Traister et al. 1991). The fact that the cost of maintenance labour is increasing faster than the index of total plant operation costs dictates increased prudence in spending on maintenance activities (Pintelon and Gelders 1992).

In this stage, maintenance must be defined and discussed in detailed in order to build the foundations for a theory of maintenance processes that can provide benefits to organisations. Also, a full description of marine shipping maintenance is presented to explore the understanding of that maintenance and to define the important factors that can have great influence on the organisation's performance.

2.2. Maintenance Definitions

Maintenance processes vary from one industrial field to another. For example, the maintenance of bridges requires different processes from the maintenance of buildings, and the maintenance of machine equipment differs from one unit to another. Maintenance has attained an important position as a result of modern technology, which requires frequent maintenance; such maintenance is required to ensure the performance of machines, irrespective of whether the maintenance is classified as planned or unplanned.

Due to their range of professional backgrounds, many authors have presented a wide variety of definitions of the term "maintenance," and examples of these are given below:

- "Maintenance is work that has a repeated nature to keep machines in order so we can make use of them continuously" (Lewis and Pearson 1960).
- "Maintenance is the process that enables us to prevent the cessation of production" (Moore 1969).
- "Maintenance is the work that maintains the production means at a reasonable cost" (White 1973).
- "Maintenance is the job that maintains facilities and factory machines in a continuous state of operation" (Amrine et al. 1987).
- "Maintenance is the work that keeps the machine in an operating condition" (File 1991).

These varying definitions of maintenance reveal a contextual basis. Perhaps what is more apparent is the fact that these definitions do not explicitly highlight the important role that maintenance plays in ensuring a sustainable organisation.

In the production industry, as an example, maintenance represents a very significant function within the overall production environment, which is necessary in order to increase production levels or maintain maximum production levels. However, in other organisations, such as the marine industry, the need for maintenance is based on the availability of ships in a safe condition.

2.3. The Benefits and Importance of Maintenance Systems

The maintenance system plays a very important role, as does many other systems within an organisation. The maintenance system must be considered carefully because this system can have great influence on the overall performance of the organisation.

Maintenance expenditures in the UK's manufacturing industry (as an example) range from 12 to 23% of the total operation costs (Cross 1988). Dekker (1996) reported that, in refineries, maintenance spending is about 30% of the total staffing costs. The mining industry spends between 40 to 50% of operating costs on maintenance (Campbell 1995). Alhouli et al. (2009) showed that, in a case study of data presented on a six-year-old, 75,000-ton bulk carrier, maintenance costs account for the largest proportion of operation costs (40%) based on the sample surveyed. Therefore, the issue of how to conduct maintenance optimally must be given careful consideration to reduce the great costs of such maintenance.

The importance of maintenance has generated an increasing interest in the development and implementation of optimal maintenance strategies for improving system reliability, preventing the occurrence of system failures, and reducing maintenance costs of deteriorating systems.

In addition to attempting to achieve those objectives, applying an optimum maintenance system in an organisation can produce many other benefits, which can be summarised as follows:

- The asset remains in its operational state and breakdown risks can be avoided.
- The instant availability of the asset when it is required to operate.
- The increase in safety levels for the employees who operate the machinery.
- Increased reliability, leading to less lost time while facilities are being repaired, less disruption to the normal activities of the operation, less variation in output rates, and more reliable service levels.
- Quality errors can be avoided, because well maintained equipment is more likely to perform to meet standards, thereby avoiding quality problems.
- The potential reduction of operating costs if maintenance is conducted at regular intervals.
- Longer life spans for the machinery; regular care can prolong the effective life of facilities by reducing the small problems in operation whose cumulative effect causes wear or deterioration.
- Higher end value of the machinery; well maintained facilities are generally easier to dispose in the second-hand market.

The benefits of maintenance demonstrate that a well-planned and implemented maintenance system is vitally important to the organisation.

In order to keep the organisation's performance healthy and productive, it is very important to select the optimum maintenance strategy. Therefore, the types of maintenance strategies are discussed next in order to understand the different approaches and identify the need for selecting the appropriate approach for maintaining the system.

2.4. The Categories of Maintenance

In the literature, different authors categorised maintenance differently, based on the system required to maintain an ongoing process. Some authors categorised maintenance by different strategies (White 1979), and others categorised maintenance according to the policies that required maintenance to be performed in different ways (Mobley 2002) and (Ben-Daya et al. 2006).

Reliability is another category of maintenance, such as reliability centred maintenance (RCM) and total productive maintenance (TPM), depending on different applications.

2.4.1. Maintenance Philosophies (Strategies)

Maintenance levels usually differ from one operator to another, depending on their different requirements. The operator usually considers the most appropriate maintenance for his equipment. The intention is to keep the machine in an operational state such that it can deliver the required performance. The operator usually has more than one choice of maintenance options. Therefore, it is necessary to select the appropriate policy or strategy for maintenance implementation. Figure 2-1 indicates different strategic maintenance options.

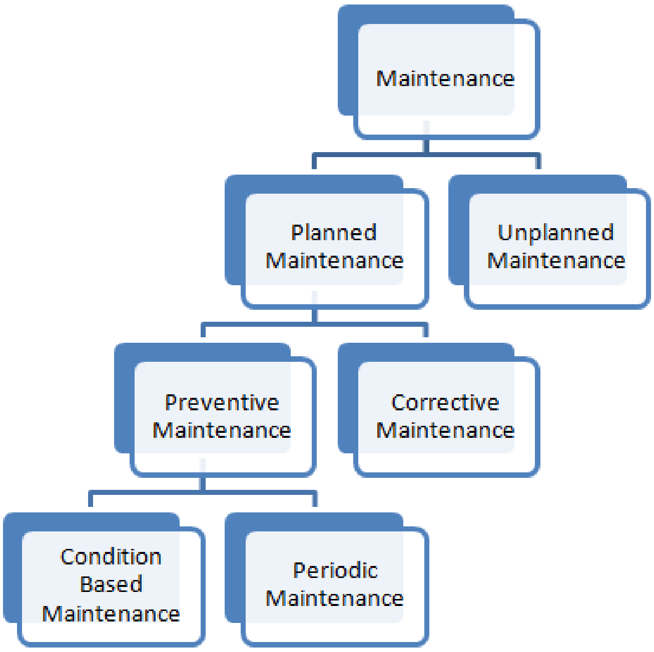

Figure 2-1: Maintenance Options (White 1979)

2.4.1.1 Unscheduled (Unplanned) Maintenance

This type of maintenance is basic and simple; it is defined as "breakdown maintenance" or "run to failure maintenance." The philosophy of this type of maintenance is "fix it when it breaks" or "if it ain't broke, don't fix it." This approach was the standard approach before the World War II (1945) when industry at that time was not highly mechanised and downtime had less deleterious effects (Mobley 2002).

In this maintenance policy, the repair or replacement is performed only when failure occurs. In other words, it is a reactive technique that is dependent upon the time taken to assess failure (Ben-Daya et al. 2006). Basic preventive maintenance, such as lubrication and machine adjustment, is applied to the system at regular intervals.

Run to failure maintenance policy can be the most expensive policy: “Analysis of maintenance costs indicates that the repair performed in the reactive mode will average about three times higher than repairs made within a scheduled or preventive mode” (Mobley 2002).

This will result in high overtime labour, high machine downtime, low production, and high inventory costs for spare parts. This policy is suitable for a system with a low or constant hazard rate and no serious cost or safety consequences. If this technique is applied, quick reaction is needed with regard to availability of spares, and, in addition, maintenance personnel should be well prepared, have the necessary skills, and be readily available to repair the equipment.

2.4.1.2 Scheduled (Planned) Maintenance

“Maintenance scheduling or planning embraces all activities necessary to plan, control, and record all work done in connection with keeping an installation to an acceptable standard” (White 1979).

Scheduled maintenance became more common after World War II (1945) when it was recognised that equipment failure can be prevented. Failing assets result in expensive repairs and costly loss of time to repair, but scheduled maintenance can prevent these high costs and the associated downtime through regular inspections and maintenance.

Four basic task types should be performed in scheduled maintenance to protect the reliability and safety of a system. These are: (1) inspection of a component to detect failure; (2) failure detection; (3) reworking and discarding of a component before its maximum age; and (4) inspecting an item to assess unseen failures (Nowlan and Heap 1978).

Scheduled maintenance can be determined by the classical approach, which is based on mean time between failures (MTBF). This approach is based on a model of the time that elapses between maintenance periods that takes into account the mechanisms of failures, which are early failure, random failure, and wear-out failure.

Maintenance scheduling includes, for example, preventive maintenance, predictive maintenance, corrective maintenance, planned overhaul, planned replacement, and spares provisioning (White 1979). The preventive and predictive maintenance policies will be discussed in detail in this chapter to provide an understanding of the need for such policies in maintenance planning.

- ***Preventive Maintenance***

Preventive maintenance usually depends on the manufacturer’s recommendations and past experience for scheduling repair or replacement time. In this policy, the maintenance is performed on a scheduled basis within scheduled intervals.

Preventive maintenance is time-driven in that maintenance is performed based on elapsed time or hours of operation. Preventive maintenance consists of actions that are designed to improve the condition of system elements before they fail (Levitin and Lisnianski 2000).

The preventive maintenance programme varies from very basic maintenance, such as lubrication, to major maintenance, such as rebuilding machines. All preventive maintenance programmes assume that the machine will degrade within a time frame typical for its particular classification. The problem with this approach is that the mode of operation and variables that are system related or specific to a given plant directly affect the operating life of the machinery (Mobley 2002).

- ***Predictive Maintenance***

Predictive maintenance one of the techniques used in preventive maintenance. The decisions in this policy are based on the current condition of the system or equipment, and the avoidance of unnecessary and unexpected maintenance by performing maintenance when required to prevent failure. Another definition of this policy is condition based maintenance (CBM). This describes monitoring the machinery and acting upon its condition. Usually, engineers record the system parameters and use their senses of hearing, sight, and smell to assess the condition of the system.

Condition monitoring comprises four steps: (1) sensor selection; (2) data measurement; (3) feature extraction; and (4) classify the condition of the machine. Different techniques are used in condition monitoring, such as visual inspection, performance monitoring, trend monitoring, vibration monitoring, thermal monitoring, lubricant monitoring, thermograph monitoring, and acoustic monitoring.

The advantages of such a policy are that unnecessary work can be avoided, thus preventing catastrophic accidents (Mobley 2002). The loss of production during scheduled machine downtime can be reduced, and components can remain in service if the machine is in good working condition.

2.4.2. Reliability and Maintenance

In maintenance, four main reliability applications are used: (1) reliability centred maintenance (RCM); (2) total productive maintenance (TPM); (3) reliability engineering (RE); and (4) control engineering (CE). These applications use different methods and policies to control reliability. RCM and TPM originate from industry practice, whereas RE and CE originate from mathematics and systems modelling. RCM and TPM applications are discussed in the next section in order to clarify the concepts and facilitate the understanding of the different approaches to reliability and how industrial maintenance is planned and controlled.

2.4.2.1. Reliability Centred Maintenance (RCM)

RCM is a structured way to determine the maintenance requirements of complex systems and assets. It was first developed in the late 1960s, and the approach was derived from the aircraft industry. In mid seventies the RCM was applied in other industries (Mobley 2002). It has been applied to military operations, the nuclear power industry, the offshore oil and gas industry, and many other industries. The marine merchant shipping industry has taken the first step in applying RCM techniques, but some difficulties have been encountered.

RCM focuses on the effect of failure with the consequences of a failure being more important than its technical characteristics. The RCM process entails asking the following seven questions about the asset or system under review (Moubray 1997).

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

From the above questions, the idea of RCM is that any physical machine or system has at least one function, and the users have performance requirements for that function. The main objective of RCM is to reduce the maintenance costs, by focusing on the most important functions of the system and avoiding or removing maintenance actions that are not strictly necessary (Rausand 1998).

RCM is a planned process that is used to determine the optimal failure management strategies for any system's reliability characteristics and the proposed operational context. RCM defines what must be done for a system to achieve the desired level of safety, environmental protection, and operation readiness at the lowest possible cost.

RCM is designed to minimise maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventive maintenance, taking into account the potential for the loss of some of the entity's operational lifetime (Vaurio 1995). RCM is considered a very successful systematic method for balancing costs and benefits in efficient maintenance programmes.

This method analyses the system's functions, identifying their safety and economic priorities in order to direct the maintenance effort towards those units that are critical from the point of view of reliability, safety, and production regularity. The approach is more qualitative than the optimisation models, and it has limited capability.

RCM can be conducted by the analysis of a sequence of activities, starting with functions and performance standard, functional failures, failure modes, failure effects, failure consequences, preventive maintenance tasks, and default tasks (Moubray 1997).

The RCM method is one of the most successful methods for establishing maintenance programmes. It is a practical approach for obtaining a cost-effective maintenance level. Application of RCM has enabled significant savings in maintenance costs and increased safety and reliability.

2.4.2.2. Total Productive Maintenance (TPM)

TPM was first developed in the 1950s by Dr. Deming in Japan (Wireman 2004). It is the systematic implementation of maintenance by all employees through small group activities.

TPM is a manufacturing-led plan that emphasises the importance of people and the importance of the production and maintenance staffs working together. It is presented as a key part of an overall manufacturing philosophy.

The benefit of TPM is that it improves the overall equipment effectiveness (OEE), which was calculated by Nakajima (1988) as:

$$OEE = Availability(\%) \cdot Performance(\%) \cdot Quality(\%) \qquad \textbf{Equation 2.1}$$

where:

Availability: is the operating time as a percentage of the total available working time.

Performance: is the ratio of the actual production to the maximum production.

Quality: is the ratio of good products to the total production.

TPM is a zero breakdown programme with zero defects, which aims to reduce equipment breakdowns, setup and adjustment slowdowns, idling and short-term stoppages, quality-related losses, and start-up/reset losses (Mobley 2002).

TPM aims to create good maintenance practice through the pursuit of “the five goals of TPM,” which are:

- Improving equipment effectiveness.
- Involving operators in daily maintenance.
- Improving maintenance efficiency and effectiveness.
- Educating and training personnel.
- Designing and managing equipment for maintenance prevention.

2.5. Discussion on Maintenance Categories

It has been observed that maintenance can be carried out by different types of strategies and that the proper strategy depends on the process and what is the most suitable approach to be used on that process.

It has been observed that unscheduled maintenance is an expensive policy, but, in some cases, it is ideal to choose this approach because other approaches might not be suitable.

Preventive maintenance can be time based or condition based. The advantage of condition-based preventive maintenance over time-based maintenance is that the condition-based maintenance can avoid unnecessary work. The preventive maintenance approach has the advantage of preventing the system or process from failing, and that can result in saving the asset from costly repair and costly downtime.

The reliability and maintenance approaches have been designed for particular systems or processes. For example, the RCM was designed mainly to maintain the aircraft industry, whereas the TPM was designed to maintain the production system.

From all those types, it is observed that maintenance can be conducted by more than one approach, and sometimes it is necessary to select more than one type of approach in order to reach the optimum maintenance result; that is the case in the marine shipping industry, because maintenance must be conducted by different maintenance approaches in order to achieve the optimum maintenance results.

2.6. Marine Background

Ships have been an important medium for trade and commerce for thousands of years. Today's maritime shipping industry carries 90% of the world's 5.1 billion tons of international trade (Hauke and Powell 2001). As world trade continues to grow, the marine shipping industry transports the biggest share of world trade, which has resulted in the expansion of the shipping industry around the globe. According to World Fleet Statistics, the number of ships of 100 GT and above has increased between the World War II (1945) and 2004 from about 24,000 ships to about 90,000 ships (Lloyd's 2005).

Shipping distinguishes between two main types of cargo: bulk (usually shiploads of a single product) and general cargos (everything else). Major dry bulk cargo includes iron ore, coal, grain, bauxite, sand, gravel, and scrap metal. Liquid bulk or tanker cargos include crude oil and petroleum products, chemicals, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and vegetable oil. Tanker cargos (mostly oil and oil products) make up about 40% of all world cargo movements by weight (Lloyd's 2005).

The general cargo vessels are classified mainly as two types, i.e., container ships and general cargo ships; container ships carry their entire load in truck-size containers, whereas general cargo ships, which include, for example, RORO (roll-on/roll-off) ships and cargo liners, carry their cargo as loose goods.

Ship owners and ship operators always seek the best performance from their ships, and this is most likely to occur when the ships are in a good working condition. To keep any ship in good condition, maintenance must be considered.

Therefore, ship owners are constantly looking to measure the maintenance performance in their organisations and improve their maintenance programmes, since ships that are out of service will adversely affect the organisation's performance, which, subsequently, has negative impacts on revenue.

2.7. Ship Repair and Maintenance

Ship maintenance is normally considered in the early stages of ship design (Shields et al. 1996). The designers and the owner review the plans for preventive maintenance with the classification society to confirm that the plans are acceptable in accordance with the classification society's requirements for surveys after construction (Thomas and Ingram 2001).

Every component in the ship is scheduled to be maintained individually within the maintenance scheduling plan to maximise the ship's availability. The ship can be available if all its major components are operational, such as propulsion, power, air-conditioning, and cargo machines. If any one of the major components is not operational, the ship will be classified as unavailable, and maintenance will be required (Deris et al. 1999).

In the marine industry, ship maintenance and ship repair can be completed in two different ways. First, they can be undertaken in the ship repair yard when the ship is due for dry docking to survey the underwater parts and when it is due for its classification survey. Second, maintenance can be conducted during the ship's day-to-day operations which can be presented in Figure 2-2.

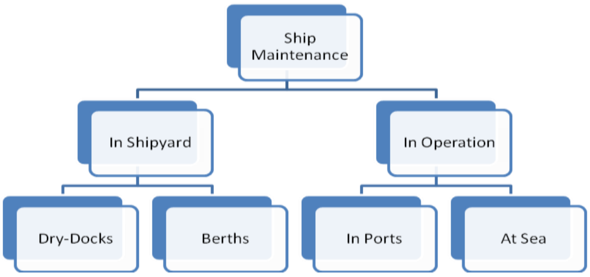

Figure 2-2: Ship Maintenance

Ship maintenance has unique features in terms of maintenance scheduling; the maintenance can be conducted in different locations, such as in the shipyard when the ship must be dry docked and major overhaul is needed, at anchorage, and in the harbour when medium maintenance is needed. In addition, different types and sizes of ships may require the use of different shipyards (Deris et al. 1999).

Ship maintenance varies since it can involve many different aspects of the ship, including engine machinery, deck machinery, the ship's body, and electrical items (e.g., navigation and communication systems). Figure 2-3 demonstrates what parts of an oil tanker generally require maintenance.

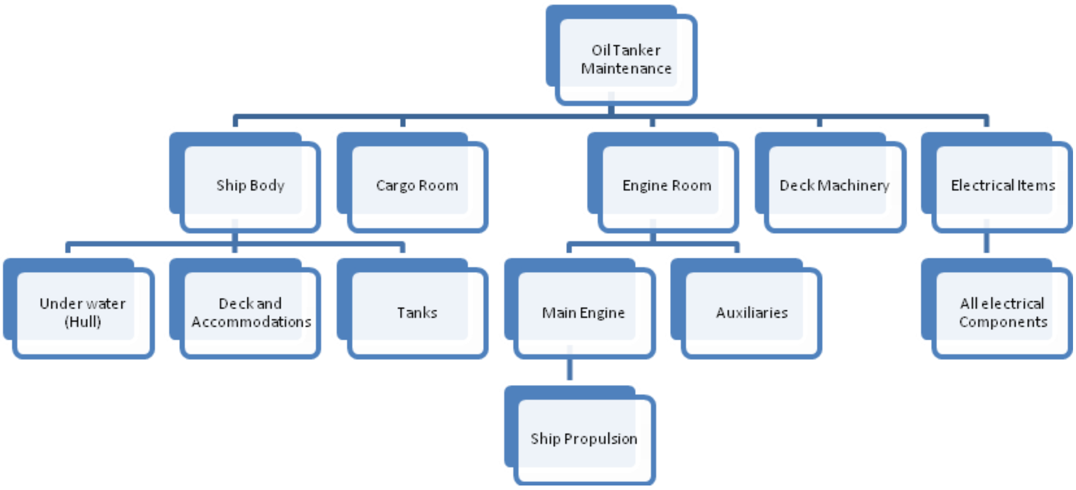

Figure 2-3: Oil Tanker Maintenance

When a ship is in operation, the crew on board the ship must conduct the maintenance. The Black Sea Fleet (BSF) Management Service Report suggests that some operator hours are spent on maintenance (Shields et al. 1996). The number of hours depends on the rank of the operators, but the figures may also vary depending on the ship type and size. Table 2-1 shows the operator's maintenance hours (Shields et al. 1996):

Table 2-1: The Ship Crew's maintenance hours (Shields et al. 1996)

Rank	Maintenance hours	Number of men
2nd Engineer	2 hr of maintenance/day	(1)
3rd Engineer	4 hr of maintenance/day	(1)
4th Engineer	4 hr of maintenance/day	(1)
Junior Engineer	8 hr (all day)	(0-2)
Electrician	8 hr (all day)	(1)
Boatswain	4 hr of maintenance/day	(1)
Mechanic	8 hr (all day)	(1-2)
Seamen or Wiper (GP)	4 hr of maintenance/day	(6-9)

From Table 2-1 it can be seen that most of the engineer officers and the seamen have a number of maintenance hours, and the number of maintenance hours depends on the officers ranking or seamen rank, the higher the rank the less maintenance hours.

Ship maintenance, like maintenance in other industries, typically employs two types of policies, i.e., breakdown maintenance and preventive maintenance. Breakdown maintenance policies are usually conducted without any preventive maintenance, except for essential lubrication and making minor adjustments. Preventive maintenance involves maintenance to reduce the number of breakdowns, and it can be time-based or condition-based maintenance.

Originally, the determination of the maintenance that was to be conducted was based on operating experience and manufacturers' recommendations. Generally, the maintenance work on any machine on the ship consists of the following four tasks:

1. Inspection: a visual examination to identify the state of the machinery.
2. Minor overhaul: involves some stripping down of machinery.
3. Major overhaul: involves the full strip down of machinery items.
4. Survey: usually is done in conjunction with a major overhaul and involves an examination of the machinery.

2.8. Shipyard Maintenance

As discussed earlier, ship maintenance can be carried out in the ship repair yard for major routine ship maintenance, which requires a dockyard to maintain the underwater part of the vessel. Ships are usually scheduled to go to the shipyard every two and a half years for an intermediate classification survey and every five years for a major classification survey. At these times, an overhaul of most of the ship's machinery takes place to maintain the ship and restore it to its original condition.

In the shipyard, typically 75% of the work involves routine ship maintenance, and the remaining 25% is for damage repair and ship conversion (Mackenzie 2004).

Ship repair work can be categorised in an increasing order of scale and cost:

- Voyage repairs (minor and continuous repairs).
- Routine docking (underwater work).
- Major repairs (typically steel).
- Damage repairs (usually steel).
- Refit and conversion.

The planning and management requirements vary according to the category of work and vessel type (Evans 2007).

Before the ship arrives at the shipyard, it is customary for detailed work specifications to be forwarded to the shipyard; this provides an opportunity to quote the price and time required. The specifications are often for spare parts, with detailed work requirements identified after the repair work has been completed. On the other hand, quite detailed specifications may be used to prepare a quote, but it is likely to change significantly after the ship arrives at the shipyard and its requirements are assessed. Items may be added or removed from the specifications (Evans 2007).

Emergency work is always a possibility. This leads to the cancellation of other work that is less urgent to ensure that the total cost of the repairs remains within the budgeted total and to maintain a firm end date. Planning must be immediate and reactive, because, typically, timescales for ship repairs are measured in days.

2.9. Ship Maintenance Costs

In the marine shipping industry, maintenance cost can be classified as one part of the ship's operating costs. In general, a ship's operating costs vary, depending on type, size, and age of the vessel. Ship maintenance and operation costs include all the costs related to equipment and materials, personnel, replacement inspection, overhaul, and repair.

Ship maintenance costs can be defined as: "those costs incurred in the organisation, execution, and control of work undertaken for safe operation of the ship"(Shields et al. 1996). Ship maintenance costs can be measured in different ways; they can be directly measurable maintenance costs and indirectly measurable maintenance costs. Moreover, some costs are controllable and some are not. A brief description of the different types of costs is presented in the following section.

2.9.1. Directly Measurable Maintenance Costs

This type of maintenance measurement can be measured by what is done directly towards the maintenance, which, in this case, includes dry docking repair, voyage maintenance repair, irrecoverable damage, and spare parts.

2.9.2. Indirectly Measurable Maintenance Costs

Direct maintenance costs are not the only costs that must be considered. These costs make up only one part of the total, with the other being indirect maintenance costs, which include the cost of some other operations. The crew always performs maintenance, and this indicates that some of the operators' time is used for maintenance. Since the personnel on board the ship are part of the maintenance function and, hence, are considered part of the maintenance cost, then part of the provision costs (store) must be apportioned to maintenance.

2.9.3. Controllable and Uncontrollable Costs

Not all costs can be controlled by the management of the shipping company, because some costs are uncontrollable. The uncontrollable costs in this industry occur under three measurable costs, which are: (1) personnel costs; (2) insurance costs; and (3) general costs.

Earlier, it was discussed that some of the personnel costs are included in the maintenance costs. This is the case to some extent, but there is a limitation. For example, there must always be a specified number of personnel on board to enable the ship to sail and berth safely. So, in this case, some of the costs are uncontrollable.

Insurance costs are uncontrollable because the broker sets them, and, therefore, the shipping company has no control over those costs. The uncontrollable general costs are, for example, the port charges that the shipping company cannot control. Damage costs are also uncontrollable because these costs are essential for the company to recover, but the company cannot control them.

However, other operating costs can be controlled, for example, by reducing overtime, minimising the crew's travel expenses, controlling storage costs, and controlling the dry docking costs, spare gear, and other maintenance repairs (Shields et al. 1996).

2.9.4. Example of a Ship's Costs

In this section, an example is given to demonstrate the ship operation costs and show how the maintenance cost is linked to the operation costs. Data were collected from *Ship Maintenance, a quantitative approach book* (Shields et al. 1996) that addresses the operating costs of a 75,000-ton bulk carrier that is six years old. The operating costs were classified into five types of directly measurable costs, as follows:

- Personnel: where the costs spent on personnel are divided between wages and leave, overtime, pensions, crew travel manning expenses, and miscellaneous
- Storing: where the costs are divided into provisions, general stores, cabin stores, and lubricating oils
- Maintenance: where the costs are dry docking repair, voyage and other repair, spare gear, and irrecoverable damage
- Insurance
- General

The costs in the example are divided into directly measureable costs and indirectly measurable costs, as shown in Table 2-2 (Alhouli et al. 2009).

Table 2-2: Direct and indirect operating costs of a 75,000-ton bulk carrier

Cost Type	Personnel	Storage	Maintenance	Insurance	General
Directly measurable costs	36%	10%	28%	23%	3%
Indirectly measurable costs	24%	8%	42%	23%	3%

In the directly measurable costs, it was very clear that the highest direct cost among the costs was the personnel cost, which amounts to about 36%, with the maintenance cost in second place at 28%, and the insurance cost in third place at 23%.

In the indirectly measurable costs, the maintenance cost is divided into two types, i.e., direct maintenance costs and indirect maintenance costs. Table 2-2 indicates that the indirect maintenance is 42% of the whole cost (which is 28% from the direct measurable maintenance cost in addition to 12% from personnel costs and 2% from storing cost). At 42%, the maintenance costs are the highest cost among all the operating costs.

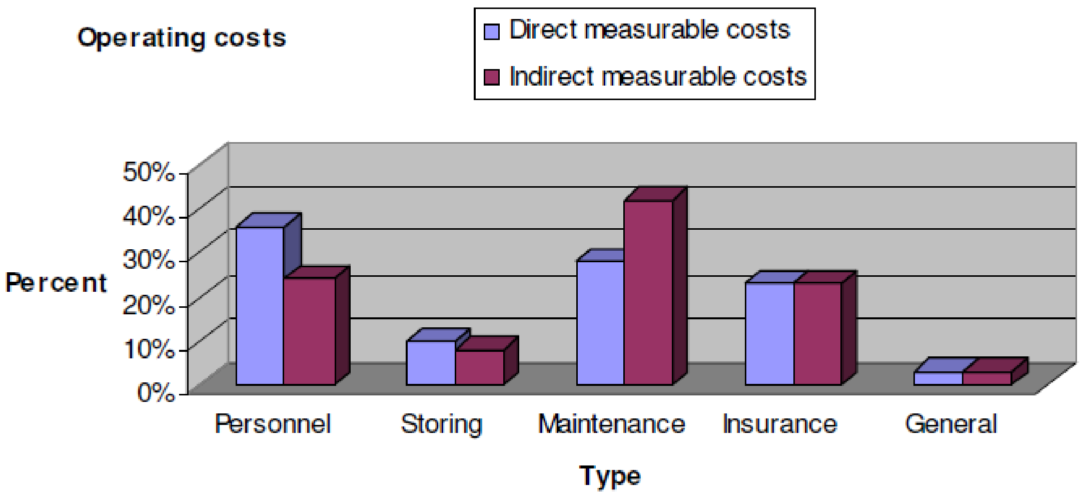

Figure 2-4: Operating costs

Maintenance costs are the largest item in the operating cost, and the majority of this cost is controllable. Therefore, attention should be focused on maintenance in order to reduce that cost for the benefit of the shipping company. Also, attention should be paid to the specifications that are sent to the shipyard; carefully prepared specifications can save a lot of money for the shipping company.

2.10. Factors That Complicate Maintenance Planning

Overhauling in terms of a major survey should no longer be the only means of maintenance today. Regular preventive maintenance is now required to allow for upgrading of the equipment and the condition of the ship.

Thus, it is very important to understand the factors that contribute to maintenance effectiveness, how these factors contribute, and to what extent they contribute.

Maintenance planning factors are divided into two main types, i.e., those factors that can be controlled so the cost can be reduced by applying an optimising technique and other uncontrollable factors for which the cost cannot be controlled but can be optimised to some degree with certain limitations. These main ship maintenance-planning factors are discussed in the next sections.

2.10.1. Controllable Factors

2.10.1.1. Maintenance Scheduling

Maintenance scheduling is one of the main factors that affect maintenance planning and costs. Since the demand on ship operations changes from one season to another, seasonal demand can vary. Therefore, it is vital to choose the most convenient time when demand for the ship's use is low to send the ship for maintenance. This factor requires close attention when setting up maintenance planning for ships.

2.10.1.2. Selecting Maintenance Strategy or Policy

In maintaining a ship, there are usually several strategies or policy options available to management, and many alternative decisions must be considered. These strategic or policy options can be outlined in two main approaches, i.e., the reactive approach (breakdown) and the proactive approach (condition-based and time-based). All types of maintenance strategies or policies could be applied to every item on the ship, but only one will yield optimal results. However, it is sometimes necessary to integrate various types of maintenance strategies or policies.

Therefore, selecting the optimum maintenance strategy or policy for the ship's machinery and items is a significant factor, and, therefore, it is very important in maintenance planning because it can have an impact on the total maintenance costs involved.

2.10.1.3. Ship Construction

Ship construction is a significant factor, and it has a key role in influencing future maintenance planning and costs. Therefore, this factor must be studied in depth to assess its importance. For example, the hull of a ship made of high-tensile steel has the advantage of light weight and thickness, but it has the disadvantage of rusting very quickly, which means maintenance will be required. Therefore, body panels must be replaced more frequently, resulting in higher costs.

Another example is the epoxy coating for cargo tanks and ballast tanks; if this coating is applied, it can result in long-lasting benefits, because it protects the surface of the vessel from early corrosion.

In addition, choosing high-quality, manufactured equipment will reduce the risk of future equipment failures. Therefore, consideration is required for maintenance planning from the construction stage to avoid any difficulties in planning maintenance for future failures.

2.10.1.4. Number of Crew and Crew Composition

The work of the ship's crew members is another factor that may affect ship maintenance planning and maintenance cost. Some ships have an extra crew member on board to undertake maintenance work. This may result in a direct increase in maintenance costs, but, on the other hand, it may result in reducing future maintenance costs, e.g., for dry docking, because some of the work has already been done by the crew.

In addition, different nationalities of crew may affect maintenance costs due to their differing productivity levels and variations in skills and pay rates, which mean a more productive crew may pay more attention to maintenance.

Another factor to be considered is crew training, since good training can give the crew more confidence when working with new machines. Therefore, maintenance planning must be considered at this stage to optimise maintenance cost efficiently.

2.10.1.5. Shipyard Selection

A further factor affecting maintenance planning and costs is the selection of a shipyard. The location of the shipyard is a very important factor when the ship requires dry docking for intermediate and major maintenance surveys. Therefore, shipyard selection is very important to all shipping companies, since this can affect both planning time and costs. The most competitive repair yards are found in the Far East, such as Singapore and China, or in the Middle East, such as Dubai.

Most shipping companies will always allocate a budget for repair yard work. So, selecting the shipyard can often depend on the price quoted by each shipyard, and this can vary between different shipyards. Therefore, shipping companies usually choose the cheapest to do the work, but location is another issue that shipping companies consider when choosing a shipyard. They always choose the yard that is located on the ship's route, because this can avoid the ships having to make an unnecessary journey and cancel its scheduled trips.

In the case of container ships, for example, the choice of repair yards is limited, because such ships are committed to fixed routes and tight schedules. In contrast, tankers have a greater choice among repair yards, since most tankers travel from the Middle East.

2.10.2. Uncontrollable Factors

2.10.2.1. Ship's Age

The ship's age is one of the main factors that affect maintenance planning. As the ship gets older, more maintenance is required to bring the ship back up to an acceptable standard. Ship owners often have to spend more when the ship passes its fourth or fifth special survey. Frankel (1991) showed that maintenance and repair costs are usually reasonable during the first year or run-in period of the ship, then they decline and start to increase again significantly at mid-life, with a very sharp increase after 20 years or so, unless an effective life extension programme is undertaken.

2.10.2.2. Ship's Size

Another factor that must be considered is the ship's size. This factor is very important because it has a direct effect on maintenance planning and cost. According to Shields et al. (1996), a comparison of the dry docking maintenance costs of two bulk carriers of different sizes, but of the same age, found that the cost of dry docking maintenance for the larger bulk carrier was higher than for the smaller one. This was due to more material being used in the replacement of the hull plates. The larger the ship's size, the more maintenance is needed, which results in higher maintenance costs. Also, the larger the ship, the larger the revenue it can generate when hired, so, when a larger ship goes out of service, the overall company revenue will be affected.

2.10.2.3. Utilisation

Utilisation is also an important factor that affects maintenance planning and cost. If the intensity of utilisation is expected to increase, it could result in higher maintenance costs. For example, a ship that charges and discharges more frequently than another means the ship is being utilised (operated) more, and it could probably incur higher physical stress. In addition, since the ship will visit more ports, there is a higher risk of an accident. Therefore, the maintenance plans for such a ship require careful attention.

2.10.2.4. Ship's Type

The ship's type is another factor that affects ship maintenance planning and maintenance costs, because different ship types have different operational procedures that may have an impact on the ship's wear and tear. This results in a wide range of maintenance costs among all types of ships. For example, container ships are required to navigate at high speed to meet their time-schedule targets, resulting in visiting more ports and having to charge and discharge more frequently. This leads to a higher level of physical stress to the ship. Another example is if the ship is charged with special cargo, such as iron ore that may damage the ship's hull; the ship's maintenance must be given greater consideration.

In addition, it is expected that ships transporting LPG, which requires the use of sophisticated technology for safe transportation, will exhibit higher maintenance costs than simpler types of ships.

2.10.2.5. Classification Societies

Classification societies are organisations that establish and apply technical standards for the design, construction, and survey of marine-related facilities, including ships and offshore structures. The classification societies have imposed obligatory intermediate and special surveys on ships. The class requirements set the general regulations for classing an existing vessel. Each society can extend its requirements and set even stricter rules. For example, Lloyds Register imposes a hull and machinery special survey every five years, dry docking every two and half years, annual hull and machinery surveys, a tail-shaft inspection every five years, and a boiler survey every two and half years. These factors may affect maintenance planning and maintenance costs because, the stricter the rules are, the more likely it is that maintenance costs will increase.

2.11. Summary

This chapter has given an introduction to maintenance terms and discussed the differences between them. Two methods of maintenance planning were discussed, planned and unplanned maintenance, with a description of different maintenance policies. Finally, maintenance reliability was discussed, and the two main reliability applications used in the industry were examined, RCM and TPM.

Also, this chapter introduced the essential need for ship maintenance and repair. The two methods of ship repair were clarified. An example of the maintenance of an oil tanker vessel was given. Crew maintenance hours were discussed based on the BSF Management Service Report (Shields et al. 1996). Shipyard maintenance was discussed, including the intermediate survey and major survey requirements.

The maintenance cost in the marine industry was discussed, with particular focus on the cost of maintaining a ship. The maintenance costs were identified within the operation costs. The operation costs were classified as controllable or uncontrollable costs, and the maintenance costs were classified as directly measurable or indirectly measurable costs.

Ship maintenance planning factors were examined, with the planning factors divided into two types, i.e., controlled factors, for which the maintenance costs can be optimised, and uncontrolled factors, for which maintenance costs cannot be controlled.

This chapter emphasises the point that maintenance is very important and essential for any organisation, especially for the marine industry; it is a supporting function in any organisation, and it can help the organisation perform better than it might perform otherwise.

Maintenance must be managed and optimised carefully to increase the benefits that can result in increased availability, safety, reliability, equipment life, and end value for equipment.

The categorisation of maintenance has shown that maintenance can be conducted in different scenarios that depend on machinery and equipment requirements. More than one maintenance type can be used for the same system to achieve the optimum scenario.

Also, it has been observed that the maritime shipping industry is responsible for the highest trading around the world today, which gives an indication of the growth of the world fleet (Hauke and Powell 2001).This growth shows the need for maintaining the world fleet to stay in good and safe working condition.

Ship maintenance can be conducted during the ship’s operations; this can give the operators some responsibility for maintenance. Thus, the shipping company can save costs and time when the ship goes to the shipyard (Shields et al. 1996).

Marine maintenance costs are identified within the operation costs, and it is the highest percentage of the total operation costs when both direct and indirect costs are considered. Therefore, maintenance costs must be optimised by planning the maintenance and finding the most important factors that can affect the maintenance plan.

Therefore, optimising ship maintenance can be achieved by controlling some factors that can have an influence on maintenance planning, such as maintenance scheduling, selecting the maintenance strategy, designing the ship with consideration of future maintenance, the number of crew members and their composition, and shipyard location. And that can be achieved by assessing and measuring the maintenance performance of the organisation to determine the effects of those factors on the overall performance of the organisation and to establish an appropriate guideline concerning how maintenance is performed in a marine organisation.

For that reason, it is important to consider the measurement of maintenance performance in order to make suitable decisions on conducting the best maintenance approach for the organisation; thus, it is important to measure the maintenance performance beforehand.

Therefore, the next chapter will discuss maintenance performance measurements to understand why they are needed, to provide a guide-line on how to measure the maintenance performance in the organisation, to identify the benefits of conducting that measure, and to explain how this can aid management in making appropriate decisions.

Chapter 3: Measurement of Maintenance Performance

3.1. Introduction

The measurement of maintenance performance has become a crucial element of strategic thinking for asset managers. For many asset-intensive industries, such as transportation and manufacturing, maintenance costs are a significant percentage of the operation costs. For example, in the marine shipping industry, maintenance costs are about 40% of the total operation costs (Alhouli et al. 2009). In addition to the high cost of maintenance, breakdowns and downtime have negative impacts on meeting the goals and objectives of the organisation, and they are also vital factors that affect health, safety and the environment.

Due to the complexities of the maintenance process and the difficulties of arranging resources, many professionals do not have the thorough understanding of the maintenance process that is required to facilitate appropriate decision making. Therefore, maintenance measurements become central in controlling and monitoring a maintenance process for taking appropriate and corrective action.

3.2. Performance Measures and Performance Management

Measurement provides the basis for an organisation to assess how well it is progressing towards its predetermined objectives, helps to identify areas of strengths and weaknesses, and contributes to decisions concerning future initiatives with the goal of improving organisational performance (Amaratunga and Baldry 2002).

The performance measurement process can be defined as a process of quantifying action, which is used to measure the efficiency and effectiveness of action (Neely et al. 1995). Historically, performance measurement systems have been developed as a means of monitoring and maintaining organisational control, which is the process of ensuring that an organisation pursues strategies that lead to the achievement of overall goals and objectives (Dixon et al. 1990).

Performance measurements provide information on what has happened to a system or a process; they do not generally include any justification of why it happened or what is the best way to react. For an organisation to make effective use of the information provided by performance measurements, the transition from measurement to management must be made.

Performance management is defined by the Procurement Executives' Association (Association 1999) as "the use of performance measurement information to effect positive change in organisational culture, systems, and processes by helping to set agreed-upon performance goals, allocating and prioritising resources, informing managers to either confirm or change current policy or programmed directions to meet those goals, and sharing results of performance in pursuing those goals".

In general organisations that do not integrate ongoing performance measurement and feed the information back into their management development programmes tend to experience lower than expected performance improvements, higher dissatisfaction, and lower turnover (Longenecker and Fink 2001).

In performance measurement, “metric,” “measure,” and “performance indicator” are terms that are often used interchangeably. However, they can be distinguished to avoid conflicts. Metric represents the unit of measure, whereas measure means specific observation characterising performance. Performance indicator (PI) represents a specifically defined variable. A performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of action (Neely et al. 2005).

Thus, performance management provides organisations with the opportunity to refine and improve their development activities. Performance management programmes provide feedback based on specifics rather than generalisations and also based on specific objectives derived from the desired outcome of performance measurement results.

There are three main approaches for measuring performance that are used in world asset management, i.e., surveys and audits, benchmarking, and in-house measures. Each of the three approaches is useful in different scenarios and situations (Jones and Rosenthal 1997).

In practice, those approaches are measuring performance against standards that are set by an individual company based on competitors’ performance or on comparable industry data. They can be different measures, such as production or maintenance measures (Al-Muhaisen and Santarisi 2002). These approaches are discussed next.

3.2.1. Surveys and Audits

This type of approach is usually completed by the auditors with the use of questionnaires and agendas that have been refined over many similar audits. Then, they are presented as a formal report to the organisation and generated for the use of the management team.

In a maintenance system, an audit will determine the efficiency and the effectiveness of the existing operation and will highlight the strengths and weaknesses of the system. Auditing maintenance management or maintenance operation can provide a methodological framework to improve maintenance effectiveness (Raouf and Ben-Daya 1995; Duffuaa et al. 1999).

The auditing survey gives an unbiased snapshot of a point in time from the auditor who has experience with many other companies. The advantages of this approach are: (1) it clarifies the process for the users; (2) it refines the process quicker than the user could have done; and (3) it shows the users how they complicate a simple process (Bititci et al. 1997). The disadvantages of this approach are the high expense of the auditors and the report format that is written specifically for senior management and is less beneficial to its subordinates (Gillett 2001).

3.2.2. Benchmarking

Benchmarking is a powerful tool to quantify and compare the gathered data with others of a similar process. Benchmarking is the process of identifying, sharing, and using knowledge and best practices. It is the measurement against defined standards. It can be used to analyse any level of detail and can be conducted internally in multisite organisations or as an agreement between “like-to-like” companies (Gillett 2001).

It not only copies or imitates others, it is also a continuous process for investigating and learning from best practice and getting useful information to improve the organisation’s performance (Barber 2004).

The advantages of this approach are that it can provide great insight into the processes that yield the results expected and that it improves the overall efficiency of the process. The disadvantage of this approach is the difficulty in collecting data, which requires careful preparation, analysis, and execution (Gillett 2001).

3.2.3. In-house Measures

In this approach, in-house measurements are taken to identify the process’ or system’s status. It can be designed as a set of performance indices or a measure of the trend of process inputs and outputs on an ongoing basis. These performance measures can depend on different data fed from the entire relevant department and can be presented at all levels of the organisation.

From the three approaches, it is found that each of them can be usefully applied to different processes, depending on the applicability. For assessing areas of strength and weakness in the organisation, audit and benchmark approaches are valuable tools, but they are not suitable for frequent tracking and reporting of life data. However, in-house measures can be used to determine the trend of the current position of the process in the organisation.

3.3. Maintenance Organisation

For any machinery, maintenance is essential to ensure the reliability and availability of the plant. A maintenance schedule for any piece of equipment could result in numerous decisions on repairing or replacing; therefore, maintenance must be organised on a systematic basis.

In the early days of industry, large companies often had either over-resourced maintenance teams or teams that could hardly cope with their workload, and money was either wasted on underutilised maintenance resources at one extreme or revenue was lost through stoppages at the other extreme.

In modern organisations, the situation has improved, and senior management and maintenance teams are investing the proper amount of money in maintenance programmes that benefit the organisations.

Maintenance organisation depends mainly on three key decision areas: (1) resource structure; (2) administrative structure; and (3) a control system. The resource structure can be made up of different elements, such as manpower, tools, and spares. The function of the administrative structure is to make the configuration of the decision in order to control the resource structure.

The control system is the most important key decision area, which can be expressed as the work planning system. It defines the way in which the work is planned, scheduled, allocated and controlled. The purposes of the control system are to ensure that the maintenance organisation is meeting its objectives and to warn management if it is not.

In any maintenance organisation, there are three steps that must be considered by the maintenance organisation or department. First, the function of the department must be clarified; second, the company's maintenance objectives must be identified; and, third, the company's output must be measured to ensure that the maintenance objectives are being met.

3.4. Setting Maintenance Objectives and Measures

In this stage, it is very important to identify what to measure and what can be achieved if solid objectives are set. Objectives are essential to modern day organisations, and they should be directly related to the corporate goals and must be understandable at the level for which they are proposed (Fernandez et al. 2003).

In a maintenance organisation, there are usually two main types of objectives, i.e., maintenance effectiveness and organisational efficiency. These two types of objectives are interwoven and constantly impact upon each other as they contribute to maintenance costs and to productive output (Kutucuoglu et al. 2001).

Maintenance effectiveness is concerned with how well the plant meets the user's requirements, and organisational efficiency is concerned with how well the resources are utilised to fulfil the strategy.

3.5. Performance Indicators

To measure any system or process and apply performance measurement approaches, it is necessary to use some indicators that evaluate the system's performance; such indicators are called performance indicators (PIs). A PI usually compares the actual condition of the system with a specific set of reference conditions. The application of PIs can find ways to reduce downtime, reduce costs, reduce waste, operate more efficiently, and increase the capacity of operational lines.

There is no fixed set of PIs; they can vary depending on current market conditions, business lifecycles, and the company's financial standards. As a rule, all PIs must be tied to the long-range, corporate business objectives.

PIs can be classified in two ways, i.e., leading indicators and lagging indicators. Leading PIs reflect a proactive condition that can give an early indication of the system's condition where problems can be avoided (Herrera and Hovden 2008). This works as a performance driver and supports the concerned head of the specific organisational unit in ascertaining the present status with comparison to a reference status. Leading PIs are metrics that are task-specific, and they respond faster than result metrics and are selected to indicate progress towards long-term objectives (Herrera and Hovden 2008).

Lagging PIs are a reactive condition, and they influence direction after the economy has and indicate the plant's condition after performance has taken place.

PIs usually refer to an indication at the shop-floor level and can be called key performance indicators (KPI) when they are used to influence the decisions of the senior management team, which considers the performance measures of a key result area.

3.6. Maintenance Performance Indicators

Maintenance PIs are used to measure the actual condition of the system or process and compare it with a set of reference process conditions. They are used to evaluate the effectiveness of conducted maintenance (Wireman 1998). They are a product of several measures and are used to measure maintenance performance.

Maintenance PIs can be defined as the means of measuring the efficiency and effectiveness of maintenance and related performance. Another definition of a maintenance PI is “a measure equipped with baselines and realistic targets to facilitate prognostic and/or diagnostic processes and justify associated decisions and subsequent actions at appropriate levels in the organisation to create value in the business process” (Liyanage and Kumar 2003).

Therefore, to measure maintenance performance, it is very important to develop maintenance PIs and implement them with the total involvement of the entire organisation.

Maintenance PIs can reflect the process or system status and can show the reduction of downtime, cost and waste, productivity level, quality, and health and safety of the system. Also maintenance PIs can differ from one industry to another.

Maintenance PIs can be used in many applications, such as financial reports, monitoring the performance of employees, customer satisfaction, health, safety and environmental rating, and overall equipment effectiveness. Examples of maintenance PIs are maintenance budget, plant availability targets, planning and scheduling, mean time between failures (MTBF), mean time to repair (MTTR), maintenance reliability, work process productivity, and downtime.

3.7. Maintenance Performance Measurement Frameworks

Maintenance performance measurement (MPM) frameworks are needed to provide an explanation for performance measurements by linking them to the organisational strategy (Parida and Kumar 2006).

The characteristics of performance measures include relevance, interpretability, timeliness, reliability, and validity (Al-Turki and Duffuaa 2003). A balanced performance measurement framework must be developed after much research to measure financial and non-financial perspectives.

Kaplan and Norton (1992) developed a balanced scorecard that works on four perspectives: (1) financial, (2) customers, (3) internal processes, and (4) innovation and learning. It covers both financial and non-financial aspects of the business process. Integration of the four perspectives into a graphical presentation has made the balanced scorecard a very useful method for measuring organisation performance.

Many researchers have developed frameworks considering non-financial measures to achieve competitive advantages (Kaplan and Norton 2001). A framework with nine performance variables was devised by Kutucuoglu et al. (2001), who recognised three performance needs, goals, design, and management. They compiled performance and strategy into a matrix.

Sinclair and Zairi (1995) involved employees in the development of a performance measurement system. Another framework was developed by Riis et al. (1997), which shows cross levels and functional integration of maintenance management and attempts to relate maintenance to manufacturing strategy.

The balanced scorecard was modified by Tsang (1998) to bring a strategic approach to MPM, and this approach consists of a mix of outcome measures and performance drivers, which indicate the outcome of past decisions and predict future outcomes.

Two new approaches were provided by Dwight (1999): (1) the system audit approach; and (2) the event analysis approach. The system audit approach concentrates on the degree of alignment between the maintenance systems and the goals of the organisation they are serving. The event analysis approach focuses on understanding the impacts of the specific actions undertaken during the period on the value of the organisations. The strategic maintenance management (SMM) approach was presented by Murthy et al. (2002) and has two elements, maintenance management and effective maintenance management. Maintenance management is a critical, core business activity that is crucial for the business's survival and success and, as such, must be managed strategically; effective maintenance management must be based on quantitative business models that integrate maintenance with other decisions, such as production levels.

Mojdeh (2005) developed a four-step process, the business performance management (BPM) framework, which can also be applied in MPM. The steps are: (1) strategise; (2) plan; (3) monitor; and (4) act and adjust.

Kumar (2006) discussed the issues and challenges associated with the development and implementation of maintenance performance systems and maintenance performance indicators for the effective management of infrastructure and industrial assets. The study was based on some of the research and development (R&D) projects being pursued at the Division of Operation and Maintenance Engineering at Luleå University of Technology in Sweden.

Parida and Chattopadhyay (2007) presented a proposed MPM framework that is balanced, holistic, and integrated and focuses on both internal and external effectiveness, considering the maintenance PIs from the multi-criteria hierarchical level of the organisation.

Muchiri et al. (2009) conducted an industrial survey of Belgian industries to explore the use of performance measurement in maintenance management. The analysis they used was based on the popularly-used KPIs and how these KPIs are sourced or chosen, as well as the influence of the manufacturing environment and maintenance objectives on the choice of KPIs and the effective use of these KPIs in decision support and performance improvement. The results show no direct correlations between the maintenance objectives pursued and the KPIs used.

Yuniarto and Osada (2009) developed a framework that enables maintenance operatives to plan maintenance actions through the identification of the root cause of failures and the quest of optimal solutions by viewing problems as a system in its entirety. It integrates between the six sigma *(which is a methodology and set of tools used to improve quality of process outputs by identifying and removing the causes of* *defects (errors)and minimizing variability in manufacturing and business processes* (Antony 2008)*)* and the system's dynamics.

An extended OEE framework that incorporates six sigma thinking and asset management strategy PIs was proposed by Gibbons (2010). The OEE framework is based around incorporating an understanding of asset management effectiveness measured against MTTF, MTTR, and MTBF into the availability element of the OEE calculation and an understanding of the process capability measured against six sigma levels into the quality element of the OEE framework.

After reviewing different frameworks, it was observed that different categories of measures show different areas of interest in maintenance performance, both in the literature and in practice.

Also, it was observed that some authors have mainly proposed lists of KPIs rather than a methodological approach for selecting or deriving the KPIs. As a result, the decision makers must decide how to select relevant KPIs for their processes.

The relevant KPIs can be drawn from different frameworks, which can be used in this study to support the construction of the new proposed framework for the decision makers of maritime organisations.

3.8. MPM in Different Industries

The need for MPM in different industries is important to measure and evaluate in order to control and improve the maintenance activities for ensuring the achievement of organisational goals and objectives. Industries are improving their performance measurements, and some organisations are working to develop specific MPM frameworks to identify the best indicators for their organisations.

The maintenance PIs are measures of efficiency, effectiveness, quality, timeliness, safety, and productivity, among other things. An example of industries that must use MPM frameworks are the nuclear industry, oil and gas industries, the railway industry, the process industry, and the energy sector. Those industries are required to apply such maintenance performance measurements because of the critical nature of their work.

3.9. MPM in the Marine Industry

The marine shipping industry has done little work on MPMs. In the marine industry, assessments and measures are concentrated on ship safety and pollution prevention. Examples of performance measurement in the marine industry are the Tanker Management and Safety Assessment (TMSA) by Oil Companies International Marine Forum (OCIMF), the Sustainable Development Strategy by Fisheries and Oceans Canada, and the Marine Safety Performance Plan of the United States Coast Guard. The TMSA will be discussed next.

The TMSA is a guideline to measure and assess a tanker’s operations management system developed by the OCIMF. The TMSA guidelines define 12 elements of management practices. The elements provide a checklist approach for ship operators who are aiming to achieve safety and environmental excellence. Element four relates to reliability and maintenance standards, and the main objective of this element is to establish maintenance standards so that all ships in the fleet are capable of operating safely without the risk of an incident or detention (Turker and Deha Er 2008).

3.10. Summary

This chapter introduced MPM and discussed its importance to any organisation. Next, performance measurement was defined, and, then, the transition from measurement and management was discussed. Measuring performance approaches used in world asset management were explored.

A description of the importance of the maintenance department in any industrial organisation was presented, and the objectives of maintenance in an organisation were discussed.

PIs and maintenance PIs were explained, and examples of such indicators were given. A review of selective MPM frameworks was presented, because they are needed to assist and support management to control and monitor performance aligned to the organisational objectives and strategy and to make appropriate decisions. This chapter discussed the need and importance of MPM in different industries, and an example of measurement in the marine industry was provided. The conclusion from this chapter is that the measurement of maintenance performance is very critical element for asset managers. It can draw the map for those decision makers and provide them with a clear road map for selecting the optimum maintenance strategy for their organisations.

Therefore, it is important to manage the maintenance performance measurement in order to quantify actions that are used to measure the efficiency and effectiveness of action and to assess the organisation’s effectiveness in achieving its objectives (Neely et al. 1995).

Measuring maintenance performance can result in higher organisational performance outputs, which will eventually increase the turnover for the organisation (Longenecker and Fink 2001).

Performance measurements can be achieved by applying different measuring approaches, which can be used successfully in different scenarios. Such approaches are surveys and audits, benchmarking, and in-house measures (Jones and Rosenthal 1997).

The key to measuring the performance of any system or process is to identify the correct indicators. Those indicators must be observed and monitored in order to achieve the organisation’s objectives.

Going through the literature, it was found that maintenance performance measurement frameworks are used to support the organisation’s management in achieving the organisation’s objectives. Also, different frameworks are designed for different organisations.

It was observed that the frameworks are constructed based on set of KPIs, and those KPIs are the elements used to evaluate and measure the performance of the organisation. Some KPIs are used in more than one framework.

Also, it was observed that, in some industries, the maintenance performance measurement is required and needed because of the critical nature of those industries.

Finally, the marine organisation is one of those industries that must develop maintenance performance measurement frameworks, because this can keep the organisation in good working order and protect the environment. The development of this framework can be based on some of the KPIs found in the literature.

This framework will enhance the organisation’s ability to conduct maintenance in an optimum way. Therefore, maintenance optimisation will be addressed next to review optimisation approaches and to assist in developing and planning optimum maintenance approaches for the mercantile industry.

Chapter 4: Maintenance Optimisation

4.1. Introduction

Maintenance management always measures the effectiveness of maintenance in terms of production and company profits, and it is often difficult to balance maintenance and the company's profit. Achieving an appropriate balance is known as 'maintenance optimisation' (Ben-Daya et al. 2000).

Maintenance optimisation is defined in the British Standard as finding the best procedure, policy, or maintenance interval with respect to specified criteria (Standards 1993).

One way to achieve maintenance optimisation is by producing a mathematical model in which both the costs and the benefits of maintenance are quantified and an optimum balance between both is obtained (Dekker 1996).

Maintenance optimisation has been studied extensively in the past, and many maintenance optimisation models have been developed. Therefore, in this chapter, maintenance optimisation models in general are reviewed, with emphasis on models related to maintenance schedules. The use of integer programming in maintenance is reviewed and, more specifically, marine maintenance and marine maintenance schedules are reviewed.

4.2. Maintenance Optimisation Review

In the early 1960s, maintenance optimisation was proposed and developed to solve maintenance management's problems. It was developed by researchers, including Barlow, Proschan, Jorgenson, McCall, Radner, and Hunter, who used what is called 'age and the block replacement' models in operations research (Dekker 1996).

Many authors have reviewed maintenance optimisation; they reviewed the maintenance optimisation models based on some categorisation, which helped to enhance the knowledge domain of maintenance optimisation models. Such as McCall (1964), who gave one of the early reviews in his paper, in which he surveyed the scheduling policies for stochastically failing equipment.

Pierskalla and Voelker (1976) surveyed available maintenance models that related to making an optimal decision to procure, inspect, repair, and/or replace a unit that was subject to deterioration in service.

Sherif and Smith (1981) reviewed optimal maintenance models for systems subjected to failure, Valdez-Flores (1989) reviewed the available models for single unit systems, and Cho and Parlar (1991) surveyed literature on optimal maintenance models for multi-unit systems.

Dekker (1996) gave an overview of the application of maintenance optimisation models and of tools developed to assist in maintenance optimisation, and Wang (2002) reviewed the maintenance policies for deteriorating systems.

Garg (2006) reviewed the literature on maintenance management and suggested possible gaps from the points of view of researchers and practitioners.

Van Noortwijk (2009) surveyed the application of gamma processes in maintenance, which are to model stochastic deterioration for optimising maintenance, and Shaomin (2010) provided a review in which he presented the existing preventive maintenance models and investigated their interrelationships.

It was observed from the reviews carried out in section 4.2 that the authors reviewed the developed optimisation models based on different characteristics. On the other hand, this research has reviewed maintenance scheduling in general and its application in marine organisations. Furthermore, this study reviewed integer programming models that have been used in maintenance scheduling.

4.3. Maintenance Optimisation Models

Maintenance models have been applied extensively in many industries. Some of the early models are simple and easy to apply, whereas some of the new models are complex and require highly sophisticated computers for implementation.

In this stage, a review of maintenance scheduling models is conducted based on some keywords related to maintenance scheduling and marine or ship maintenance scheduling. The keywords are maintenance, ship, scheduling, integer, linear programming.

In order to develop a maintenance optimisation model, four main aspects must be considered (Dekker 1995). First, the system must be described technically to clarify its function and importance. Second, the deterioration of the system over time and possible consequences for the system must be modelled. Third, the available system information must be described. Fourth, the objective function and optimisation techniques must be identified, which may help in finding the best solution.

Once the model is constructed, it should run and produce results (Dekker 1995). The expected results can be used to evaluate the maintenance policies and compare them with cost-effectiveness and reliability characteristics. Then, the models can assist the decision making process in considering the timing aspect. Finally, the models can help in determining effective and efficient maintenance schedules and plans.

4.3.1. General Models

Various models have been developed to help in the decision-making process for maintenance scheduling and planning. Most of these models are based on operations research methodologies. It was found that the integer linear programming technique was the most commonly used in maintenance scheduling.

Dedopoulos and Shah (1996) considered the problem of determining optimal preventive maintenance policy parameters for different items of equipment in multi-purpose plants. They explored mixed-integer, non-linear programs and mixed-integer, linear programs. The model is involved in the formulation of long-term combined production/maintenance procedures to overcome the process planning problem.

Ashayeri et al. (1996) developed a mixed-integer linear programming model to plan preventive maintenance and production in a process industry environment in which maintenance planning was extremely important. The model schedules production and preventive maintenance jobs, while minimising the costs associated with production, backorders, corrective maintenance, and preventive maintenance.

Chen et al. (1999) used a shortest-path method to solve the integer non-linear programming problem and presented a model for the minimisation of total maintenance cost subject to system state probability requirements for the next mission.

Wang et al. (2003) established an integer linear programming model to select a set of candidate projects from the highway network over a planning horizon of five years. They used two optimisation objectives: (1) maximisation of the total maintenance and rehabilitation (M&R) effectiveness; and (2) minimisation of the total M&R disturbance cost over the planning horizon. The model is subject to the constraints of available annual budgets and minimum requirements on pavement conditions.

Mongeau and Bes (2005) introduced a mixed-integer linear programming model and reported encouraging computational results in experiments on historical data. The model is to address the problem of assigning forces to jacking positions in order to weaken stress at points where aircraft maintenance is conducted. The model is used as a maintenance decision-analysis tool for the Airbus industry.

Qassim et al (2007) developed a mixed-integer linear programming model to optimise jointly the maintenance of a capacity-constrained resource, it feed machine/operation, and inlet buffer size. They used a machining example to illustrate the application of the model.

Singh et al (2008) designed an optimal preventive maintenance policy for a system of N items that minimises the total expected maintenance cost. They assumed that the preventive maintenance budget is limited. They considered constant inter-preventive maintenance times for every item and used a binary integer program and computational results to reformulate the non-linear optimisation problem.

Fu et al. (2009) introduced a real-time optimisation model that can be used by maintenance managers to develop and evaluate alternative resource allocation plans for road maintenance operations during the winter months. They considered a wide range of road and weather condition factors in the model and used the model to analyse a realistic case to illustrate the potential impact of improved information on winter maintenance operations.

4.3.2. General Maintenance Scheduling Models

Khatib (1979) proposed one of the first stochastic methods for power systems planning. Two Markov process states were used to produce a maintenance schedule for 23 generator units. The author claimed that this schedule both minimised risk and accounted better for generation costs.

Mixed-integer programming was used to solve the maintenance scheduling problem by Mukerji et al. (1991). They discussed a number of different optimisation goals and optimisation techniques in their production of maintenance schedules for the Wisconsin Power and Light Company. Their solution used an integer-programming approach to find a schedule that attempted to level the generating reserves throughout the planning horizon.

Vatn et al. (1996) presented an approach for identifying the optimal maintenance schedule for the components of a production system. Safety, health, and environmental objectives, maintenance costs, and costs of lost production were all taken into consideration, and maintenance was optimised with respect to multiple objectives. Three decision nodes were used to estimate the overall cost. For simplicity, downtime cost, shutdown cost, accident costs, and maintenance costs were considered in the analysis. The overall cost function included safety costs, environmental costs, material costs, production losses, and maintenance costs.

Ahmad and Kothari (2000) developed an optimal maintenance scheduling model for generating units in a power system with transmission network representation. The optimisation model was achieved by using the integer linear programming method. The model uses the minimisation of system cost (production cost plus the undelivered energy cost) as the objective criterion, whereas the reliability objective function used is the minimisation of undelivered energy.

Ding and Feng (2004) presented a unique methodology for global generator and transmission maintenance scheduling based on the generalised Benders decomposition. The method breaks down the large-scale, non-linear, mixed-integer stochastic programming problem into two problems:

1- A deterministic multi-objective integer programming master problem.

2- A stochastic, linear operation sub-problem.

Matsuoka and Muraki (2007) presented a mathematical programming model with network constraints. They proposed a mixed-integer linear programming model to optimise short-term maintenance scheduling of utility systems. An example was given to evaluate the model.

Alardhi and Labib (2008) constructed an integer linear programming model to schedule the preventive maintenance for co-generation plants. The model was to maximise the system availability subject to system constraints, which include the crew constraints, maintenance window constraint, and time limitation constraint.

Bohlin et al (2009) developed and implemented a software decision support tool for the maintenance planning of gas turbines. The aim of this tool was to reduce the direct maintenance costs and the production losses that are often costly during maintenance downtime.

Morais et al (2010) implemented a mixed integer linear programming in general algebraic modelling systems (GAMS) to operate a wind turbine, a solar unit, a fuel cell, and a storage battery in optimum ways. The model was applied to a real case study in Budapest Technology and demonstrates the effectiveness of the model for solving the optimal isolated dispatch of the DC micro-grid renewable energy park.

In reviewing the aforementioned general maintenance scheduling models, it was observed that all of the models aim to maximise the availability of the system or process in order to achieve maximum profit or revenue. In addition, optimum maintenance scheduling can also result in maintenance cost savings, reducing breakdown risks, keeping the process in good working order, and protecting the environment.

4.4. Marine Maintenance Optimisation Models

Marine maintenance and replacement optimisation have multiple, conflicting objectives, which can be achieved by using interactive techniques involving the decision-maker throughout the optimisation process (Inozu and Karabakal 1992).

In the marine industry, many models have been developed for preventive ship maintenance optimisation. In this study, a review of some selected models on system maintenance and replacement, relevant to marine maintenance, was conducted. Then, marine or ship maintenance scheduling optimisation models were reviewed. The reviewed models will be categorised into generic ship maintenance models and ship maintenance scheduling models to cover all related models in the marine shipping industry.

Based on the general maintenance scheduling review and the marine maintenance scheduling review, a dry docking scheduling model was developed. Based on that review, a suitable maintenance scheduling method was selected and the model was constructed.

4.4.1. Ship Maintenance Models

Jambulingam and Jardine (1986) surveyed reliability central maintenance (RCM) and lifecycle cost (LCC) models. The study demonstrated the two concepts on a 75-ton chillier unit (CU) on board a destroyer. The objective of the study was to determine whether the CU requires a preventive maintenance (PM) inspection or adjustments and, if so, whether the optimal PM interval between the CU's major overhauls is required to minimise the expected maintenance manpower cost over the refit period, which reduces the maintenance cost.

Perakis and Inozu (1991) developed reliability-based replacement models to enhance current winter lay-up practices of marine diesel engines used on the Great Lakes. Two systems were considered, i.e., one for a ship equipped with a single engine and one for a ship with two engines. A semi-Markov competing process approach is used in the model, in which the age-dependent system failure behaviour is treated as a race among the engine components. However, a one-set competing process model is implemented and extended to two sets of competing processes. A recursive iteration procedure was used in the expected cost calculation. Computer codes were developed using the above models and several examples were examined. Sensitivity analyses were performed for several parameters to see the influence of their variation on the expected cost and corresponding winter lay-up policies.

Inozu and Karabakas (1994) reviewed past replacement models, with applications to the marine industry, to determine the optimum maintenance strategy, and, then, a new deterministic model approach to group replacement under budget constraints was presented. The model is applicable to ship fleet or single ship components' maintenance and replacement. The decision environment is characterised by the following assumptions: (1) the service under consideration is provided by number of components, each of which competes for a fixed budget in each period for maintenance or replacement; (2) all cash flows and budgets are deterministic; (3) the decision-makers objective is to minimise the total discounted cost of replacements and major maintenance actions over a finite planning horizon; and (4) maintenance and replacement costs are dependent only on the component's age and time of component installation.

Boer et al. (1997) discussed the basic framework and algorithm of the decision support system, which enhances the process and capacity planning at a large repair shop. They concentrated on the planning and execution of maintenance projects and gave an outline of the characteristics of a standard database that was developed to support process planning and thereby deliver input to both aggregate and detailed capacity planning. A formulation and solution methodology was given in order to enable a sound order-acceptance procedure.

Pillay et al. (2001) studied the maintenance of fishing vessels' equipment by using time-delay analysis. In the study, a model was proposed to optimise the inspection period of the vessels' equipment. Data were gathered from fishing vessels, and assumptions and expert judgments were made on the incomplete information. A normal distribution and the Weibull distribution were used to demonstrate the time-delay concept for the study.

Sasajima (2001) studied the lifecycle cost (LCC) of a ship in the fabrication phase in the shipyard. The analysis was focused on the hull structure as the main item of the fabrication cost and maintenance cost for a very large crude carrier (VLCC). The data were acquired from the shipyard and ship owners.

Bitros and Kavussanos (2005) introduced an econometric model to explain the determinants of expenditures for ship maintenance and repair. The study data were acquired in 1999 for 112 vessels from two different Greek companies. A semi-log, linear model was estimated on the methodological plane to find the best functional form. The results showed that maintenance expenditures are related positively to utilization, age, and size. Moreover, the model was extended to include the additional factors that were found, such as ship type, the country where the ship was registered, classification society, and the yard where the survey and maintenance took place.

Oke (2006) redefined the expression that defines the period-dependent cost function for preventive maintenance scheduling activity. The approach involves transforming the preventive maintenance cost function that is expressed in terms of several variables into a more precise framework. A case study from the shipping industry was presented.

Celik et al (2009) investigated a systematic evaluation model on shipyards' docking facilities to provide a decision aid for technical ship managers to perform their responsibilities in an efficient manner. They used a multi-criteria fuzzy axiomatic design (FAD) approach for selecting the most suitable shipyard.

4.4.2. Ship Maintenance Scheduling Models

Deris et al. (1999) modelled ship maintenance scheduling as a constraint satisfaction problem (CSP) to maximise the availability of a ship, squadron, or fleet for operations that satisfied maintenance requirements, dockyard availability, and operational requirements. The variables used in the model were based on the start times, and the domain values were the start and the horizon of the schedule. Application of this model was made to the Royal Malaysian Navy. Constraint-based reasoning (CBR) was used, which required the start times of the first activities of the maintenance cycles, and, then, a genetic algorithm (GA) was used to find the start times of the first activity.

Manti et al. (2003) applied a theory of constraints (TOC) project management method, and approach developed by Drs. Goldratt and Cox (1984). The application is on the operation and maintenance scheduling of a research vessel to reduce the project period and make it efficient. They presented a case study on a marine geology research project for the purpose of operations and included repairs on the repairing dock projects for the maintenance of vessels.

Baliwangi et al. (2006) developed ship maintenance scheduling management integrated with a risk evaluation and Lifecycle cost (LCC) assessment approach. The approach was proposed to establish optimal maintenance scheduling in several steps, which includes determining component function, generating the time predicted and possible component combinations, analysing associated alternatives and uncertainties, and selecting the best alternative using a criterion LCC.

Charles-Owaba et al. (2008) established a new approach for evaluating the sensitivity of a preventive maintenance scheduling model that is based on an integrated operations maintenance activity schedule in a resource-constrained environment, and they tested it on a shipping company. Their results show that some shipping maintenance scheduling parameters are sensitive and could, therefore, be manipulated for the best performance of maintenance scheduling models.

Jessop et al. (2008) presented a condition-based maintenance (CBM) decision support software tool that leverages real-time current and future health condition information to optimise maintenance resources, tasking, and planning in order to maximise the readiness of the system or process. The decision support tool is a multi-sweep optimisation algorithm that is tuned to the maintenance scheduling problem.

4.5. Summary

In this chapter, a maintenance optimisation review was presented. The literature was outlined, which was based on different categories, e.g., the method of solution, information availability, and unit type. An integer linear programming method was used as a solution method, which was the keyword for the maintenance optimisation review of this chapter. The review of the models was categorised into general maintenance models and general maintenance scheduling models. The marine maintenance optimisation models were reviewed and classified into ship maintenance optimisation models and ship maintenance scheduling models.

In reviewing the literature for maintenance optimisation models, it was found that maintenance optimisation models are important for achieving the optimum balance between maintenance times and costs.

From previous models, it was also concluded that the maintenance optimisation models can aid the decision making process to plan the maintenance program in advance, and that could result in reduction of overall maintenance costs and the reduction of the risk of failures or breakdowns.

One way of achieving maintenance optimisation is by optimising the maintenance scheduling times. Maintenance scheduling can be obtained by developing a mathematical model that can be used to determine the result of maximising the equipment's availability.

The integer programming models showed success in developing an optimum maintenance scheduling plan, therefore they were selected to develop the optimum maintenance scheduling plan for the marine shipping organisation.

In the marine shipping industry, optimisation models are required to achieve the organisation's objective, which is to increase the overall marine organisation's profits. The previous studies on marine shipping maintenance showed that one way of optimising maintenance is by developing a maintenance scheduling plan, which can result in maximising the ships availability and keeping the ships working in a safe and healthy environment.

Based on the previous reviews, a mathematical model to schedule the dry docking maintenance plan was developed to achieve one of the project's objectives. And, therefore, an integer programming model was developed to maximise the ship's availability. This development is presented in Chapter 8.

Chapter 5: Research Methodology

5.1. Introduction

To assess the decision-making process of a marine shipping organisation, measuring the performance of the organisation is very important. Thus, the maintenance performance is one of the main measures that must be considered in order to achieve a good performance measure.

Therefore, this study is focused on measuring the maintenance performance of the marine shipping organisation to aid the decision-making process so that appropriate decisions can be made concerning maintenance planning.

To achieve a good maintenance performance measure, it is important to develop a suitable conceptual framework that can be used in the decision-making process. Thus, it is important to identify how this conceptual framework will be developed and what a suitable method would be for this framework.

Also, this study is focused on taking one element of this framework and showing how this element can help the decision-making process in planning the maintenance process in an optimum way. And, therefore, identifying how to achieve an optimum dry docking scheduling planning is discussed.

An optimum dry docking maintenance planning model was constructed to maximise the ship's availability within the fleet. Thus, it is important to study the methodology that can be used in optimising dry docking maintenance planning and to justify the suitability of that methodology.

Different approaches can be used to formulate the purpose of the research study, and they are often related to each other. Two main approaches were identified, a qualitative approach and a quantitative approach. Each approach can be achieved by different methods of research, because the qualitative approach is descriptive in nature with the findings described by words or pictures, whereas the quantitative approach is defined by numerical findings.

Figure 5-1 shows some of the possible methodologies that might be selected for this research.

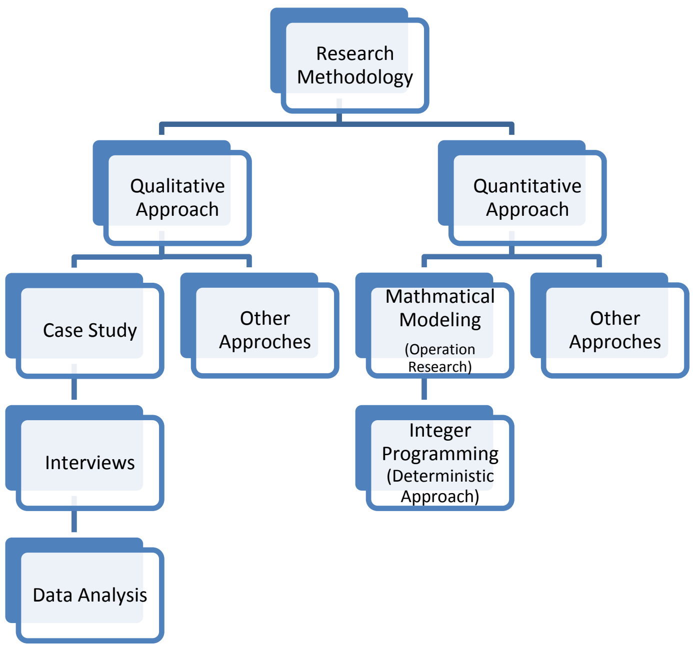

Figure 5-1: Research Methodology

In this chapter, the methodology approaches used in this thesis are defined. The purposes of this research are to identify suitable qualitative and quantitative approaches for developing an appropriate framework and/or model by applying a suitable method to measure the maintenance performance of the marine shipping organisation and to develop a mathematical model for scheduling a ship's dry docking maintenance.

5.2. Qualitative and Quantitative Approaches

These two approaches to research use different types of measurements. The quantitative approach deals with numerical measurements where the information is converted to numbers. Quantitative research emphasises the measurement and analysis of variables and relationships, and it also identifies the causal relationships between variables (Denzin and Lincolin 2000). Quantitative approaches aim to test hypotheses and then identify numerical differences between groups.

The qualitative approach is a complex approach that deals with people's understanding, and it uses pictures and words to describe what the researcher found during her or his study. Therefore, qualitative research may be seen as descriptive and holistic (Taylor and Bogdan 1984).

Qualitative research is concerned with finding the answers to questions which begin with the words Why, How, and in what way, whereas quantitative research is more concerned with questions such as, How much, How many, How often, To what extent, (Hancock et al. 1998).

5.3. Research Strategy

In general, the direction of the research is identified by the research strategy, and it can include the process by which the research is to be conducted. In this research, the strategy is to measure the maintenance performance of a marine shipping organisation by implementing a case study and developing a conceptual framework.

The case study is based on three Kuwaiti marine shipping companies, i.e., Kuwait Oil Tanker Company (KOTC), Kuwait Livestock Transport and Trading Company (KLTT), and Gulf Rocks Company (GRC); an interview approach was chosen in this case study to find the need of developing such a framework. The interview approach was chosen because the research study was conducted at the strategic level, and the best way to get data from decision-making personnel is by conducting interviews. Face-to-face interviews with senior managers are often the best way to collect data, because the interviewer can obtain information about the direct experience of the interviewees.

Then a mathematical model was developed for optimising the scheduling of a ship's dry docking maintenance based on: (1) the case study; (2) data collected from a marine organisation; and (3) the developed framework. Scheduling a ship's dry docking maintenance was modelled to optimise and maximise the ships availability within the fleet. The dry docking scheduling problem is a constraint-optimisation problem in which the objective is to maximise the ship's availability.

From the literature, it was found that the integer linear programming method is often the best method for optimising maintenance scheduling. Although other methods may be used, the integer linear programming method is used because the model uses discrete values, which necessitates integer programming (Winston and Goldberg 1987).

5.3.1. Case Study

A case study is an empirical enquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and its context are not clearly evident (Yin 2003). Case studies use multiple sources of data to provide rich analyses of the phenomenon being studied. The case study can be presented in different ways, which are a form of evidence for the research; it can be presented, e.g., as a questionnaire, interview, artefact, or outcome of action.

A case study can be considered as an intensive and holistic description and analysis of a restricted phenomenon (Merriam 1988).

In general, it is preferable to use case study methodology to solve a descriptive research question when the investigator has little control over events and when the focus is on a contemporary phenomenon within some real-life context.

Case studies are appropriate for obtaining real data and/or collecting information through interactive methods to achieve the objectives. In a case study, one tries to illuminate a decision or set of decisions, including why they were taken, how they were implemented, and what the results were (Yin 2003).

In this research, empirical evidence and theoretical evidence have been collected and analysed, and the empirical evidence has been collected through the case study, while the theoretical evidence was collected through a literature survey.

The research study used for this thesis was based on a case study that was conducted on shipping companies by conducting interviews with some experts from those companies.

5.3.2. Interviews

Documentation, archival records, interviews, observations, and surveys are methods that can be used in a case study for data collection (Yin 2003). Interviews are a very important source of information for the case study. They provide a two-way conversation that gives the interviewer the opportunity to participate actively in the interview (Yin 2003). The aim of any interview is to collect valid information reliably in a socially reactive situation (Goldie and Pritchard 1981).

Conducting interviews with senior managers can be intimidating even for an experienced researcher. The interview can focus more directly on areas that are of interest, at the same time being insightful and providing causal inference.

There are different types of research interviews, e.g., face-to-face or one-to-one interviews, group interviews, and telephone interviews.

In this research study, face-to-face interviews were used; the interviews were semi-structured with limited questions, which gave the interviewees the freedom and time to articulate their own responses.

This type of interview was used because the interviews were conducted with top management personnel whose knowledge and experience were very beneficial for achieving the research objectives. Such interviews also gave the researcher the freedom to explore unanticipated themes. The interviews provided a lot of valuable information, and the analysis of the information obtained was conducted using an interpretive approach.

5.3.3. Data Analysis

Qualitative data analysis consists of three main activities, i.e., data reduction, data display, and drawing conclusions (Miles and Huberman 1994). Three general strategies can be applied in a case study, i.e., data collection through theoretical propositions, development and testing of rival explanations, and development of a descriptive framework for organising the case study (Yin 2003).

Narrative text is the typical mode of data display in qualitative research. Narrative text is sometimes considered as a weak form of display, but it is an attractive approach that can bridge the gap between theory and practice (Czarniawska 1999).

The interpretive approach is one method of data analysis that can be used as a tool for understanding the reality experienced by the people who are being interviewed. The interpretative approach was used in this study to analyse the case study, because this approach describes and explores the understanding of the expert’s knowledge.

The abductive approach was used to combine the findings of the literature review and the interviews to develop a conceptual framework that can measure the maintenance performance of the ships in the marine shipping organisation.

A mathematical model was constructed to optimise dry docking maintenance planning and to maximise the ship's availability within the fleet. One approach in achieving an optimum solution for maintenance scheduling is by implementing a suitable operation research technique.

5.4. Operation Research

There are two main approaches in scientific management that are utilised in solving organisational problems, i.e., management science (MS) and operation research (OR). Management science tends to favour the approach of the social scientist and economist, whereas operation research uses the approach of physical scientists and engineers (Shields et al. 1996).

Operation research was first used by the British military at the beginning of World War II, when a team of scientists joined the military to analyse military operational activities.

After the war ended, it was recognised that operation research methods can be applied to other industries to improve efficiency and to increase the profits of the industry.

Operation research is used to explain the application of advanced methodical techniques, such as mathematical modelling, statistics, and algorithms, in achieving better decision making to solve complex, real-world problems. This is what is known as the 'scientific method' in solving problems.

5.4.1. Definition of OR

Various definitions of operation research have been provided as the subject has developed. Kalavathy (2002) listed the various definitions given by different experts which reproduced next for clear understandings:

- OR is a scientific method of providing executive departments with a quantitative basis of decisions regarding the operations under their control (Morse and Kimbal, 1946).
- OR is the scientific method of providing an executive with an analytical and objective basis for decisions (Balckett, 1948).
- OR is the art of giving bad answers to problems, to which otherwise worse answer are given (Saaty, 1958).
- OR is a systematic, method-oriented study of the basic structures, characteristics, functions, and relationships of an organisation to provide the executive with a sound, scientific, and quantitative basis for decision making (Arnoff and Netzorg, 1965).
- OR is a scientific method to problem solving for executive management (Wagner, 1969).
- OR is a scientific knowledge through interdisciplinary team effort for the purpose of determining the best utilisation of limited resource (Taha, 1976).

From these definitions, it is very clear that they are based on the application of operation research in order to achieve a solution for a certain problem.

In this study, the operation research method can be defined as the method that can provide the optimum solution to aid the decision-making process in planning.

The operation research approach is characterised by several features, such as its universal nature in solving several systems and models and the requirement for the optimal solution for a specific function, known as the objective function. It also involves teamwork rather than individual work.

The scientific method is made up of five phases of research, i.e., definition of the problem; constructing the model; solving the model; validation of the model; and implementation of the solution see Figure 5-2.

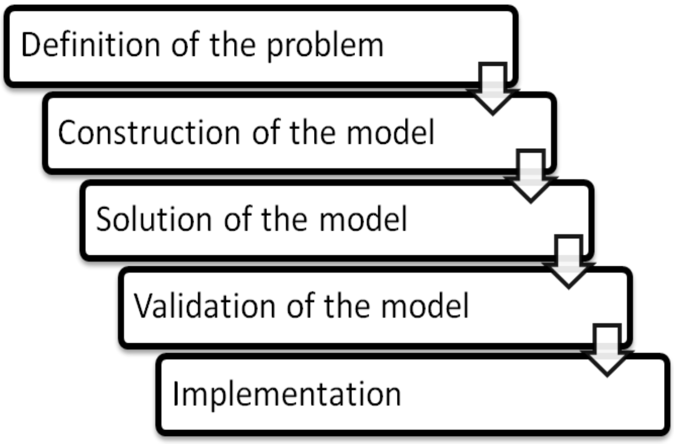

Figure 5-2: Phases of the scientific method (Taha 2003)

5.4.2. Operation Research Scientific Methods

The aim of operation research is to give an outline for constructing a mathematical model in order to make a decision to solve a certain problem. Then, the result can be implemented to solve the problem. This can be done in phases or via methods that are an important step of the operation research approach (Hillier and Lieberman 2001). The operation research phases will be discussed in the following sections.

5.4.2.1. Definition of the Problem

Usually, the first step of any study is to identify the problem, or the fact of the problem, which is of concern to the decision maker. In this phase, the problem is defined by measuring the performance of the maintenance function, and the decision variables that can be used to manipulate the maintenance function are identified.

At this point, it is very important to identify the problem clearly. This can involve good communication skills to clarify what is required and an ability to distinguish the most important part of the problem from the peripheral considerations.

In addition, it is also important to determine what information is available and how reliable it is. The importance of the problem to the decision maker and the priority the problem has been assigned must also be determined.

Three principal elements of the decision problem are identified in this phase, the description of the decision variables, determination of the objective function, and specification of the limitations or constraints (Taha 2003).

The mathematical model is used to relate the variables, constraints, and objective function to obtain results in this phase. Then, the solution of the model yields the values of the decision variables that can optimise the value of the objective function, while satisfying all the constraints.

5.4.2.2. Constructing the Model

The subsequent translation of the problem is presented as a mathematical relationship. There are different techniques that can be used in constructing the mathematical model, such as symbolic analytical presentations and simulation models. If the mathematical relationships are too complex to allow the determination of the analytic solution, then a simulation model can be used, or a combination of mathematical and simulation models may be required to solve the decision problem (Taha 2003).

The construction of a mathematical model involves the compilation of logical and mathematical relationships that represent features of the real world, as revealed by the undertaken study. Models describe important relationships between variables and include an objective function with which alternative solutions are evaluated. There are also constraints that restrict solutions to feasible values (Shields et al. 1996).

In choosing the appropriate mathematical model, it is important to choose on the basis of the cost and difficulties involved in constructing the model, the information required, the ease of communication with decision makers, and the ability to conduct a sensitivity analysis on the parameters of the model.

5.4.2.3. Model Solution

After the model has been constructed to solve the problem, the procedure that must be followed to obtain a solution from the model is developed in this phase. This is the simplest phase, because it uses one of the standard algorithmic computer software packages to find the problem solution after the model is formulated (Winston and Goldberg 1987).

The theme of the model is to obtain the best optimum solution. However, for a real-world problem, obtaining the optimum solution cannot be guaranteed, because there are too many uncertainties and unknowns associated with a real problem. Therefore, great care must be exercised in locating pertinent data and selecting the data to be used in acquiring a solution.

5.4.2.4. Model Validation

In this phase, the model is tested to identify whether or not it does what it is supposed to do. The user must evaluate whether the solution offered by the model makes sense. In other words, the model is examined to validate the given data.

In general, the output of the model is compared with historical output data. The model can be validated if the results it produces in the test agree with past performance when the input conditions were identical.

Usually, the model's validity is based on careful examination of past data, but, if the model represents a new system and no historical data are available, simulation must be used as an independent tool for verifying the output of the mathematical model (Taha 2003).

5.4.2.5. Implementation

This is the last phase in which the solution of a validated model involves the conversion of the results into operational instructions to be issued in a clear form to those who will manage the system.

Implementation is part of the operation research study, because any operation research study is conducted to provide the basis for the implementation of some action to achieve some desired result.

Many factors can affect the implementation; for example, communication between the operational researcher and various parties can play an important role in successful implementation. With good resources, the implementation can succeed, and complicated procedures may be counterproductive. Before proceeding with the action, it must be determined that the projected gains and benefits from the action exceed the cost and time associated with the implementation of the action. Good skills developed in the operation research study can lead to successful implementation (French et al. 1986).

5.4.3. Operation Research Techniques

There are many techniques used in operation research to manipulate and solve models that represent the problem, including linear programming, dynamic programming, queuing theory, goal programming, inventory models, neural network models, and integer linear programming (French et al. 1986).

The operation techniques can solve different types of problems. Operation research is not confined to a specific type of problem but can be applied to a wide range of problems to produce best solutions.

There are some so-called ‘off-the-shelf models,’ and their solutions are available to solve the related problem. Examples of such problems are stock control, product scheduling, waiting-time processes, competitive processes, replacement processes, and frequency of preventive maintenance (Kalavathy 2002).

Maintenance scheduling is a typical, constrained, optimisation problem that reflects the nature of the power system under study. The problem of scheduling maintenance can be described as determining the optimal starting time for each preventive maintenance outage in some time period in advance, while satisfying system constraints and maintaining system reliability.

In the next section, the operation research techniques that have been used in maintenance scheduling planning in general are discussed.

5.4.3.1. Linear Programming

Linear programming involves the planning of activities to obtain optimum results (Hillier and Lieberman 2001). In more detail, it is a technique that uses a form of a mathematical model that includes all the solutions for the designed problem based on the available resources and imposed constraints and indicates the region of optimal solution. Frequently, it is referred to as a technique that deals with the optimisation of the objective function, which is subject to some constraints.

Generally, the procedure for mathematical formulation of the linear programming problem (LPP) involves the following two steps. First, the decision variables of the problem are written and formulated linearly into the objective function that is to be optimised. Second, the conditions of the problem, such as resource limitations and market constraints, are identified (functional constraints) and added together with the non-negative restriction by LPP (non-negativity constraints). As a result, the LPP is formed from the objective function and the defined sets of constraints and restrictions. The standard form for formulating any LPP is summarised below, as illustrated by Kalavathy (2002). The value of n decision variables x_1, x_2, ... x_n to maximise or minimise the objective function is determined by:

$$z = c_1x_1 + c_2x_2 + ... + c_nx_n$$ **Equation 5. 1**

which are subjected to the following m-constraints:

$$\begin{aligned}
&a_{11}x_1 + a_{12}x_2 + ... + a_{1n}x_n (\leq = \geq) b_1 \\
&a_{21}x_1 + a_{22}x_2 + ... + a_{2n}x_n (\leq = \geq) b_2 \\
&\vdots \\
&a_{i1}x_1 + a_{i2}x_2 + ... + a_{in}x_n (\leq = \geq) b_i \\
&\vdots \\
&a_{m1}x_1 + a_{m2}x_2 + ... + a_{mn}x_n (\leq = \geq) b_m
\end{aligned}$$ **Equation 5.2**

The above constraints may be in the form of inequalities ($\leq or \geq$) or even in the form of an equation (=).

The decision variables must satisfy the non-negativity constraints below, which is a requirement by LPP to exclude any decision variable that does not have any physical meaning.

$$x_1 \geq 0, x_2 \geq 0....x_n \geq 0$$ **Equation 5. 3**

Solving linear programming problems can be applied to different methods, e.g., (1) to the graphical method in which the problem consists of only two variables and only two dimensions can represent the problem and (2) the Simplex method in which the optimal solution is determined algebraically.

The advantages of using linear programming are as follows (Hillier and Lieberman 2001):

- The quality of decision-making is improved by this technique because the decisions are made objectively and not subjectively.

- By using this technique, wasting resources, such as time and money, can be avoided.

- It helps in attaining the optimum use of productive factor.

- It helps in providing better tools for adjustments to meet changing conditions.

- It allows modification of its mathematical solution.

- It highlights a bottleneck in the production process, which is the strictest constraint in the production process due to its lowest capacity machine.

5.4.3.2. Integer Linear Programming

Integer programming is a linear programming approach that uses a linear programming model in which the objective functions and constraint functions are linear. However, in integer programming, some or all of the variables are required to be integers or discrete values (French et al. 1986).

If all the variables in the optimal solution are required to take an integer value, then the integer linear programming problem (IPP) can be called 'pure integer linear programming'. When only some of the variables are required to take integer values and the rest are free to take any value, then integer linear programming is called 'mixed integer programming'(Winston and Goldberg 1987).

If all the variables in the solution are allowed to take values of only 0 or 1, they are called 'binary variables,' and the problem is called a 'zero–one programming problem' or a 'binary programming problem' (French et al. 1986). Integer programming can be applied to many problems in business and industry.

The main methods used in solving integer programming problems are gemory's cutting plane method and the branch and bound method. In gemory's cutting plane method, the IPP is first solved as an ordinary LPP by ignoring the restriction of integer values, and, then, a new constraint called fractional cut or gomorian is introduced to the problem. The problem is then revised using the simplex method until the integer solution is obtained (Schrijver 1998).

The branch and bound method is an enumerated method in which all feasible integer points are enumerated. The feasible region in this method is divided into smaller subsets that eliminate parts that contain no feasible integer solution (Schrijver 1998).

5.5. Summary

This chapter discussed the research methodology used in this thesis. It discussed the purpose of the research study, identified qualitative and quantitative methodologies, and discussed their applicability to this research.

The chapter discussed the case study methodology and focused on using an interview approach for collecting data. It also justified the selection of the interview and discussed the data analysis approach.

The operation research (OR) method was discussed for the optimisation of maintenance scheduling planning. Then, the OR was defined, and the phases of the OR scientific methods were discussed. The integer linear programming was explored and proved to be the most appropriate method for use in scheduling ship dry docking maintenance; and in this study its utilisation will be one of the first applications to the marine maintenance scheduling.

Chapter 6: Analysis and Discussion of Case Study

6.1. Introduction

This chapter describes a case study that was based on three Kuwaiti shipping companies, i.e., the Kuwait Oil Tanker Company (KOTC), the Livestock Transport and Trading Company (KLTT), and the Gulf Rocks Company (GRC). The maintenance objectives and the importance of maintenance to the three marine shipping companies are discussed. The key maintenance performance indicators are identified and explored, and the factors that affect maintenance planning are considered. The study data are based on interviews undertaken with six experts in those companies; the interviews provided valuable information that was used to evaluate maintenance requirements and maintenance performance in the maritime industry. An introduction to the three companies follows.

6.2. Kuwaiti Marine Shipping Companies

6.2.1. Kuwait Oil Tanker Company (KOTC)

The Kuwait Oil Tanker Company (KOTC) is one company within the Kuwait Petroleum Company (KPC) group, and it is involved mainly in the ownership and management of tankers engaged in the transport of crude oil, refined petroleum, and liquefied petroleum gas (LPG). KPC is an integrated oil company that enjoys international recognition in the petroleum industry; it is one of the largest companies among the Kuwaiti government's operations in the petroleum sector.

In 1961, KOTC took delivery of the first 49,000-metric-ton crude oil tanker, *Kazimah*. It was the vanguard of oil tankers flying the Kuwaiti flag, and, in those days, it was considered to be a super tanker.

By 1975, the fleet had expanded to transport over one million metric tons of crude oil, but, due to the expansion of refinery capacity in Kuwait, product tankers and liquefied petroleum gas (LPG) carriers were also acquired (KOTC 2009).

KOTC now owns a fleet of 24 tankers that can transport a total capacity of 3.2 million metric tons. This fleet comprises crude/product carriers, crude carriers, product carriers, and gas carriers (KOTC 2009).

KOTC uses the Task Assistant software platform, which was originally launched in 1998, as part of a joint development venture between Ulysses Systems, Ltd. and Lyras Shipping. The main feature of Task Assistant is its capability of incorporating company information with matching documentation and procedures relating to the implementation of the International Safety Management (ISM) Code. Task Assistant also includes modules for purchasing, planned maintenance, fleet management, crew management, quality, and safety.

6.2.2. Kuwait Livestock Transport and Trading Company (KLTT)

The Kuwait Livestock Transport and Trading Company (KLTT) is a Kuwaiti public shareholding company established in 1973 and is one of the major pioneering international companies that transport sheep. The company owns a fleet of four modern, technically-sophisticated sheep carrier vessels to transport sheep from Australia to the Arabian Gulf area (KLTT 2009).

The company has a marine fleet department that comes under the Assistant Manager Director (AMD). The marine department has a fleet manager, a deputy fleet manager, one technical superintendent, and one operational superintendent. The ships' maintenance is the technical superintendent's responsibility, and maintenance is arranged manually, based on defect reports. The superintendent also arranges the dry docking times, based on the ships' due dates.

6.2.3. Gulf Rocks Company (GRC)

The Gulf Rocks Company (GRC), incorporated in Kuwait in 1997, is a publicly traded shareholding company that was initially listed on the Kuwaiti stock market in March 2004. GRC is considered to be one of the region's largest producers and traders of aggregates, which are used for building and road construction. The company owns a fleet of three Handymax bulk carriers.

The Gulf Maritime Ship Management Company (GMSM), a Kuwaiti company that specialises in handling technical issues, fleet personnel, and operations for shipping companies, manages the daily operations of the GRC fleet, including scheduling dry docking maintenance. The GRC has special engineering and operation departments that employ experienced engineers and officers.

6.3. Interviews

The interviews were planned with decision makers from marine shipping organisations to obtain their understanding of how maintenance is planned in their organisations and their perspective concerning the most important factors that influence maintenance planning.

KOTC, KLTT, and GRC are leading marine shipping companies in Kuwait. Therefore, the three companies were selected on that basis as well as on the basis of their considerable data sets; and their kind agreement to make that data available and accessible for this research. The interviews were conducted in December 2009.

The personnel interviewed were the Manager of the KOTC Fleet Engineering Group; the Team Leader of Marine Affairs and Risk Assessment at KOTC; the Deputy General Manager of GRC; the Chief Executive Officer of GMSM, which provides technical management for GRC; the Deputy Manager of the Fleet Department at KLTT; and the Technical Operation Superintendent of the Fleet Department at KLTT.

The plan was to interview selected key, responsible personnel from KOTC, KLTT, and GRC concerning the subject of maintenance planning. As discussed earlier, these three companies have different trade interests, and the objective of the interviews was to acquire an in-depth understanding of the organisations' stakeholder needs, maintenance processes, and existing maintenance performance measurement systems. Thus, interviews and discussions were conducted at the strategic/corporate and tactical/managerial levels of the three companies, using the interview questions given in Appendix 1.

6.4. Analysis of the Interviews

In this chapter, an interpretive approach was used in order to analyse and identify the present status of the maintenance organisation of these three marine shipping companies. The findings from the interviews are presented in the following sections.

6.4.1. The Importance of Maintenance

As discussed earlier, the importance of maintenance has produced an increased interest in the development and implementation of optimal maintenance strategies for improving system reliability, preventing the occurrence of system failures, and reducing the maintenance costs associated with deteriorating systems. In the marine industry, maintenance is very important, since the failure of a major mechanical system can put the whole ship at risk.

From the interviews, it was noted that all the interviewees agreed that maintenance is a very important issue in the marine industry. It is of primary importance to conduct maintenance to ensure that the ship is operating in a safe environment. Additionally, well-planned maintenance will maximise the ships' availability, which maximises the ships' revenues.

There were some other factors the interviewees thought should be considered regarding the importance of maintenance. The first factor is to satisfy the classification requirement, since every ship must undergo surveys to be certified and remain in service. Scheduling is another important factor, because good scheduling can maximise the shipping company's transportation and trade. The human factor also is important when conducting maintenance; as the Technical Operation Superintendent of KLTT's Fleet Department said, *'If a substandard crew carries out the maintenance, it could result in poor maintenance, which increases the probability of failure'.* Also, the availability and quality of spare parts are important. Safety is also an important factor, since poor maintenance can put the ship in considerable danger.

6.4.2. Maintenance Strategies

In the marine industry, a combination of maintenance strategies is used. Usually, the combination consists of corrective and preventive strategies, and some condition monitoring is also applied. From the interviewees, it was noted that the three companies use a corrective maintenance strategy as their first choice, which is very clear for small companies for which the budget is important and their ships are old, whereas, in large companies, preventive maintenance is essential to avoid any breakdown during the ships' operation, although condition monitoring is implemented to some degree in these companies because their ships are new.

The manager of KOTC's Fleet Engineering Group said, *'The Company uses a combination of strategies. We use hourly-based, planned maintenance, some condition monitoring for some equipment, and dry docking scheduling'.*

So, it is true that a combination of maintenance strategies is already in use in the marine shipping industry. That is an advantage to the marine industry in which using a balance between the strategies can optimise the planning of ship maintenance.

6.4.3. The Maintenance Objectives

From interviewing the experts, it was noted that the objectives of conducting maintenance in all the companies was almost the same; they all mentioned that they want the ship to be ready for operation at all times, with due consideration for the safety of the crew and the ship.

The interviewees identified the maintenance objectives in their organisations as described next.

The Deputy Manager of KLTT's Fleet Department said, *'The main objectives of the company to carry out maintenance are to keep the ships running in good condition and to be in line with the classification society standard as regards safety and to keep trade as efficient as possible'.*

The Technical Operation Superintendent of KLTT's Fleet Department said, *'The main objectives of the company to carry out maintenance are to keep the ships and their machinery running continually in an efficient way'.*

The Chief Executive Officer of GMSM identified the maintenance objectives as follows, *'Our objectives as technical manager of the ships are the safety of the ship and their safe operation (safety of life, ship, and cargo). But, as we are not the ship's* *owners, the ship owner is after profit and has no connection with the people. What he wants is his asset, which is the ship'.*

The Deputy General Manager of GRC said, *'The most important is to have a seaworthy ship, and we need the ship to be maintained to the safety standards for the ship, crew and cargo'.*

The Manager of KOTC's Fleet Engineering Group pointed out that the objectives that the company is applying, in providing its maintenance programme, are based on the Tanker Management and Self-Assessment (TMSA). He said, *'TMSA has 12 elements and element four is the reliability and maintenance standard, and this is the relevant element that needs to be monitored, and that can be done by having the right KPIs (Key Performance Indicators) in place'.*

The Team Leader of KOTC's Marine Affairs and Risk Assessment said, *'The objective of maintenance is to reduce the off-hire time of the vessel and keep the vessel ready, and reduce the cost of unexpected maintenance'.*

Therefore, the objectives of conducting maintenance in all three companies are important to consider, since it is those objectives that can make companies implement and optimise the maintenance strategies by using these strategies in order to achieve those objectives.

It can be concluded that the main objectives of conducting maintenance in any marine shipping organisation are to maximise the ship's availability and to operate in safe environment.

6.4.4. Coordination and Ship Demand

The coordination between the planned maintenance programme and the ship's operation is very important because maintenance has an effect on ship scheduling. Therefore, good coordination between the maintenance plan and ship scheduling can maximise the ship's availability, which, in turn, can maximise the ship's revenue. Good coordination can help in selecting the best time window for conducting maintenance jobs, for example, when demand for the ship's usage is low. To achieve good coordination between the maintenance programme and ship operation, all departments within the marine organisation must coordinate in a positive way; that is, the engineering department, which is responsible for ship maintenance work, must coordinate with the operation department, which is responsible for ship operation and scheduling, and with the financial department, which is responsible for setting the maintenance budget.

All the marine industry experts who were interviewed agreed that choosing the best time for the maintenance window is the main issue in this coordination, which can, therefore, maximise the ship's output.

The Technical Operation Superintendent of KLTT's Fleet Department remarked on this issue; he said, *'Maintenance, operation and finance departments are hand-in–hand, working together to make the decisions on carrying out all maintenance work. Operation gives the window for maintenance when ship demand is low, and for repair and spares it's the maintenance department's responsibility'.*

So it is very clear that maintenance should be conducted on an appropriate time schedule or in a correct time window, i.e., when demands for the ships is low. This can be achieved by monitoring the operation from previous years and so avoid conducting any maintenance or sending the ship to the shipyard for maintenance during high-demand period.

6.4.5. Maintenance Forecasting

Another issue considered in this study was maintenance forecasting in the marine industry, i.e., how the shipping companies forecast the maintenance needs for their fleets of ships. Forecasting of maintenance is very important in order to provide a well-planned maintenance system.

The Chief Executive Officer of GMSM pointed out that, *‘Maintenance forecasting is undertaken mainly by the personnel involved in maintenance, based on their personal experience’.* Also, the Technical Operation Superintendent of KLTT’s Fleet Department mentioned that, *‘The information recorded and the records’ availability can provide good maintenance forecasting’.*

6.4.6. Failures and Breakdowns

On every ship, failures and breakdowns are recorded by some means, either by manual logs/records or by a computerised information system. The personnel on board conduct the recording of such events. As the Manager of KOTC’s Fleet Engineering Group said, *‘Failure records are very important for our database, which is usually stored at the Head Office, either as hard copies or in electronic* *format'*. Therefore, this is very important information for any ship or shipping company, because it provides full information for future prediction.

From the interviews, it was noted that all of the companies have failure or breakdown records, and these records are used for future reference to react faster in the event of such a breakdown. They also pointed out that there are monthly defect reports, which are sent to the head office, where all the records of the breakdowns and failures are monitored and analysed. Then, the records are archived for future reference.

The interviewees added that they use all these information to analyse the root cause of such breakdowns. As the manager of the Fleet Engineering Group at KOTC stated, *'We analyse the root cause of such breakdowns and put measures in place to prevent their recurrence'*.

Also KLTT's Technical Operation Superintendent of the Fleet Department said, *'You learn from every incident. Every time you have a breakdown you will learn more and you will have better experience for preventing that breakdown'*.

This matter of experience can improve the reaction when a failure or breakdown occurs. Since failures and breakdowns occur and since the personnel learn from such breakdowns, it is important to keep records of every incident.

6.4.7. Budget and Costs

Maintenance costs and budgets have always been important in the marine shipping industry. They usually come under ship operation costs, which vary depending on different factors, such as age, size, and type. Shipping companies always budget for the fleet and for individual ships within the fleet, and the budget also varies, depending on the same factors. Ship maintenance costs can be defined as 'those costs incurred in the organisation, execution, and control of work undertaken for safe operation of the ship' (Shields et al. 1996).

From interviewing the experts in the field, it was noted that companies usually have an operation budget, and maintenance is only one part of that budget. Also, the maintenance budget cannot be fixed, because there are many factors that influence maintenance expenditures. As the KOTC Team Leader for Marine Affairs and Risk Assessment said, *'Every vessel has an operating budget of various codes and the maintenance budget is part of that budget. This budget is not fixed because it depends on many factors, such as type and status of the vessel'.* So the budget cannot be fixed, because it depends on many factors, such as age, type, and status of the ship.

In order to reduce maintenance costs, the experts had two different opinions, i.e., four of them said good maintenance scheduling and planning could reduce the maintenance budget; the other two said that to reduce maintenance costs you should have good people on board. Therefore, it is important to focus on these issues in order to minimise maintenance costs.

6.4.8. Crew and Staff

As discussed earlier, the BSF Management Service Report suggested that some of the operating hours of the operators go on maintenance, and the hours spent on maintenance depend on the officer's rank (Shields et al. 1996). Therefore, some of the ship's maintenance is done by the people on board, which make up a part of the maintenance costs.

The company experts confirmed this by reporting that the ship's staff usually conducts the maintenance they are equipped to deal with. However, the Manager of the KOTC Fleet Engineering Group said, *'In certain areas of maintenance, it has been identified that the most effective maintenance is done by a specialist'.* That is true, because the specialist conducts maintenance in a more professional way due to her or his more extensive experience with the machines and equipment on board.

They added that a substandard crew can prevent maintenance from being successful and cause huge problems. The Chief Executive Officer of GMSM said, '*If you have good staff, you will have no problem'.*

Therefore, the quality of the crew is a very important factor in measuring maintenance performance, because members of the crew can provide good or bad maintenance, depending on their knowledge and skills.

6.4.9. Maintenance Measure

All the companies have some sort of measurement for maintenance performance. In the smaller companies, i.e., KTTL and GRC, the experts insisted that the most important measure is the maintenance budget, because the budget can give a good indication of how well the maintenance has been done for the fleet they own. However, at KOTC, the Tanker Management and Self-Assessment (TMSA) system is applied, specifically element 4, which deals with reliability and maintenance.

KOTC wants to be recognised by TMSA, so it has a key performance measurement looking for the percentage of outstanding jobs on a yearly basis and a daily basis.

The KOTC Manager of Fleet Engineering Group reported, '*Apart from KOTC identifying this critical area, it is also a requirement on what level we assess ourselves with regard to maintenance reliability. We have a key performance measure looking at the percentage of outstanding jobs on a yearly and daily basis and, depending on the level achieved, as indicators this dictates where we are at, what level we are, which 1–4 TMSA measure. And we are now at level 2 on all of the 12 TMSA measures and we [KOTC] are trying to achieve level 3'.*

The key performance indicators listed below identify the maintenance measurements for the marine shipping industry. These indicators were acquired from the literature, as illustrated in Table 6-1 below:

Table 6-1: Maintenance Performance Indicators

Performance Indicators	Source
Reliability	(Gillett 2001)
Maintainability	(Gillett 2001)
Availability	(Gillett 2001), (Parida and Kumar 2006)
Failure (MTBF, MTTF)	(Kutucuoglu et al. 2001)
Downtime	(Parida and Kumar 2006), (Kutucuoglu et al. 2001)
Maintenance budget	(Parida and Kumar 2006)
Safety and environments	(Parida and Kumar 2006)

From the interviews, the indication of the weight of the measuring indicators of maintenance performance in the marine organisation is given in Appendix 1, question 34. The indicators were ranked from 1 to 10, and the highest rank represents the most important indicator. The safety and environment indicator scored the highest (8.2 out of 10), followed by cost and budget at 7.5; reliability, maintainability, and failure at 7.3; downtime at 6.7; and, finally, availability at 6.0 (See Figure 6-1).

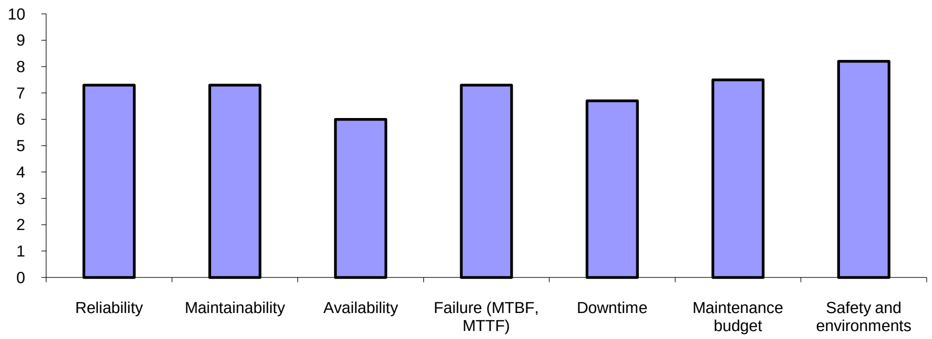

Figure 6-1: Maintenance measure ranking

From the above results, it can be concluded that the seven indicators, which were ranked in the range between 6.0 to 8.2, are almost equally significant and should be considered in maintenance planning.

The experts who were interviewed added that there are other key indicators that must be considered in maintenance planning, including quality of work, volume of communication, the ship's operation, personnel's efficiency, and customers' satisfaction.

6.4.10. Maintenance Planning Factors

As discussed earlier, maintenance planning can be done in an optimum way to reduce the maintenance costs and to maximise the ship's availability, which will eventually maximise the shipping company's revenue. So, to achieve good maintenance planning, it is very important to identify factors that influence that planning. From the literature, some factors were discussed in Chapter 2, and the factors were categorised as controlled factors and uncontrolled factors. During the interviews, the companies' experts were asked to rank the following 10 controlled and other general maintenance factors in order of importance:

- Ship maintenance scheduling.
- Selecting the maintenance strategy.
- The value (quality) of maintenance.
- Considering the maintenance from ship construction.
- Number of crew and crew composition.
- Selecting ship repair yard and its location.
- Lifecycle of the equipment.
- The recommendation from the manufacturing company.
- The average time for operating the machine.
- Maintenance costs and budget.

The experts' indications of the weight of the maintenance planning factors in a marine organisation are given in Appendix 1, question 36. The factors were ranked from 1 to 10, with the highest rank representing the most important planning factor. The ship maintenance scheduling and the quality of maintenance scored the highest (8.8 out of 10), followed by budget and maintenance strategy at 8.2; considering the maintenance from ship construction at 7.8; the ship repair yard and its location at 7.5; the recommendation from the manufacturing company and average time for operating the machine at 7.2; and the number of crew and crew composition and the lifecycle of the equipment at 6.8 (see Figure 6-2).

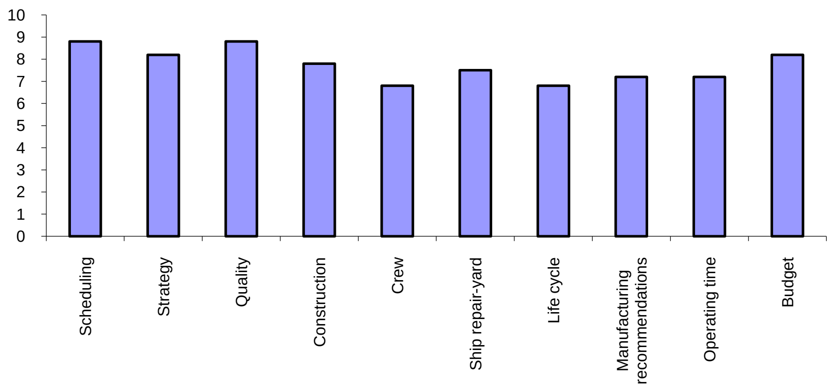

Figure 6-2: Maintenance planning factors ranking

From the above results, it can be noted that all of the factors are important, but maintenance scheduling and the quality of work are the highest among them. Therefore, good maintenance scheduling for the ships or for equipment on the ship can give good optimisation results. In addition, the quality of the work or maintenance conducted is very important. Therefore, improving the quality of maintenance can save money and time.

6.5. Summary

This chapter discussed and analysed the interviews with the experts from three Kuwaiti marine shipping companies. The discussion includes the importance of maintenance, the strategies used in maintaining ships in the marine industry, the objectives of companies that conduct maintenance, the important of coordination between the planned maintenance programme and the ship's operation, the shipping companies' maintenance forecasting, the companies' reaction to failures or breakdowns of a ship or its equipment, the companies' maintenance budget and whether it is independent or part of the operation budget, the importance of staff conducting maintenance, and the effect of substandard staff. Then, the interviews discussed maintenance performance measurement, the key maintenance performance indicators, and the importance of these indicators. Finally, the factors that control maintenance planning were discussed.

6.6. Conclusions Based on the Interviews

From the case study and by reviewing the interviews with experts from the three shipping companies, the findings and conclusions are as follows:

- Maintenance is very important to all the shipping companies since a good maintenance plan can increase the ship's availability as well as the safety of the ship's operation.
- The shipping companies interviewed use more than one maintenance strategy at the same time, and a combination of maintenance strategies is used to optimise maintenance planning.
- The maintenance objectives for all the shipping companies are similar; they all aim to have an available ship with a safe environment.
- The objective of coordination between the departments for planning maintenance within the shipping organisation is to achieve the best maintenance window that has the least effect on the ship's availability at high-demand times.
- The maintenance forecasting for the three shipping companies was based on personal experience.
- Breakdown records can help in preventing similar failures in the future, which will help to improve future performance of the companies.

- The budget is very important to the shipping companies, especially the smaller companies, and maintenance is considered as one part of the budget.

- A good experienced crew on board can reduce the maintenance costs since the members of such a crew can conduct some maintenance work, whereas a crew with limited experience can cost more due to errors and inadequate maintenance.

- Measuring maintenance performance is important because this performance can affect the performance of the whole organisation.

- Maintenance planning is very important to any industry, especially the marine industry, because good maintenance planning can maximise ships' availabilities, which will maximise the companies' profits. This can be achieved by very carefully considering the factors that affect the need for maintenance and carefully selecting the factors used in maintenance planning.

Chapter 7: Development of Conceptual Framework for Ship Maintenance Performance Measurement

7.1. Introduction

Measuring ship maintenance performance is very important to keep the ship working in a good and efficient manner. Identifying ship maintenance performance measurement criteria is very important since it affects the development of the maintenance performance measurement (MPM) framework.

Each criterion can be measured by different maintenance performance indicators (MPIs), which are a set of measurements of the impact of maintenance on process performance (Wireman 1998).

From the literature, many authors have suggested that, to develop an effective maintenance performance framework, the following questions must be answered:

- Why is measurement required? (Purpose).
- What should be measured? (Finding factors that are important).
- How should it be measured? (Methods).
- When should it be measured? (Timing and time frame).
- Who should measure it? (Owner of the process versus independent party).
- How should the result be used? (Assessment, improvement purposes).

So, in developing an SMPM framework, some related questions must be investigated, i.e., What is the purpose of the maintenance measurements?, What method can be used to measure the maintenance performance?, and How will the result of that maintenance measurement be assessed and used?

The purpose of developing this new methodology SMPM framework is to assess how well the organisation is progressing toward its maintenance objectives; it will also help the decision maker to react to that assessment in order to improve the overall performance of the organisation. And that can result in increased safety, increased market share of the organisation, increased profits, and enhanced recognition within the industry.

The maintenance performance measurement will be based on multiple criteria that can evaluate and achieve the purpose of the new methodology which is the SMPM framework.

Once the new method is achieved and the framework has been developed, it must be assessed by being implemented and validated by one of the marine shipping companies.

In this case, practical implementation of the framework would be difficult, since it would require the approval of the top management of the marine organisation. It would also be difficult because of the time that would be required, which cannot be achieved within the limited time span of this research. Therefore, a more appropriate validation approach would be to conduct interviews with key personnel from a marine shipping company; thus, such interviews were arranged with the KOTC for the purposes of this study.

In this chapter, the multiple hierarchical levels of the marine organisation are covered. The various maintenance performance measurement criteria are discussed and used in the new methodology to develop a conceptual framework for ship maintenance performance measurement (SMPM). The performance indicators for each criterion are indicated. The SMPM framework is developed and presented. The effectiveness of the developed framework is discussed. Finally the validation of the framework is conducted.

7.2. Marine Organisation Hierarchical Levels

Every organisation has multi-hierarchical levels, and, at each level, certain decisions must be made concerning the performance indicators (PIs) that can be used to guide the decision-making process. In general, the strategic planning level is the top hierarchical level, followed by the tactical or managerial level, and, finally, the functional or operational level. The maintenance indicators at the functional level are integrated and linked to the tactical or middle level to help management conduct analysis and make decisions at the strategic or tactical levels (Parida and Chattopadhyay 2007).

In a marine shipping organisation, there can be four hierarchical levels. The first (top) level is the strategic level, which is the top management level; the second level is the strategic/tactical level, which is the middle management team or the superintendent’s team; the third level is the tactical/operational level, which is the ship’s captain and chief engineer; and the fourth level is the operational or functional level, which is the ship’s crew. Figure 7-1 shows the four levels of the marine shipping organisation.

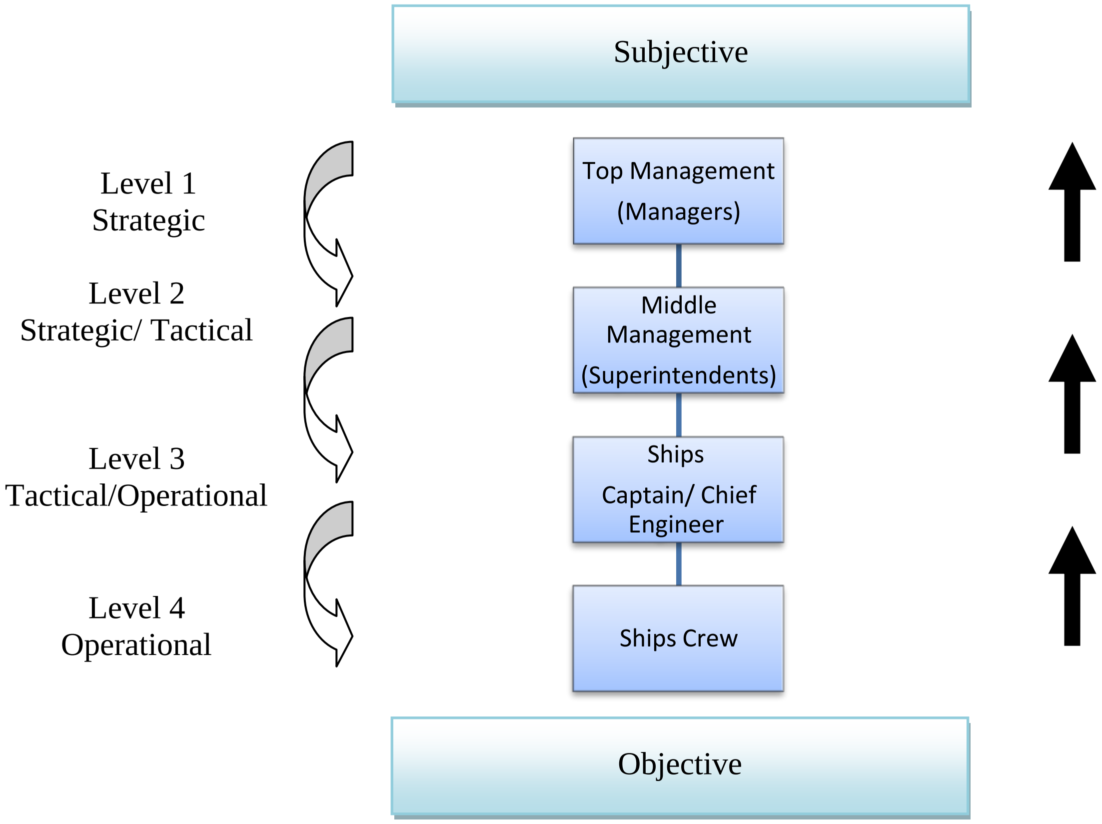

Figure 7-1: Hierarchical levels of the marine shipping industry.

The framework is designed from different criteria structure under four hierarchical levels. Analytical and conceptual approaches will be used to identify the maintenance performance indicators (MPIs). In addition, it is important to identify and analyse the external and internal stakeholders' needs.

MPIs must be integrated from the top-down, and there must be information flow from the bottom-up, so the strategic goals should be subdivided into objective targets for operating maintenance managers, who can then apply them as performance drivers for the maintenance group. Subjectivity increases when the objective outcomes from the operating level are linked to the key performance indicators for strategic goals (see Figure 7-1).

7.3. Framework Criteria

Ship maintenance performance measurement criteria are captured based on the abduction research approach which combines a literature review finding from Chapter 2 and Chapter 3, and the interview results from Chapter 6.

Ten different criteria were developed and used in the SMPM framework to measure the maintenance performance of the marine shipping organisation, as shown in Figure 7-2.

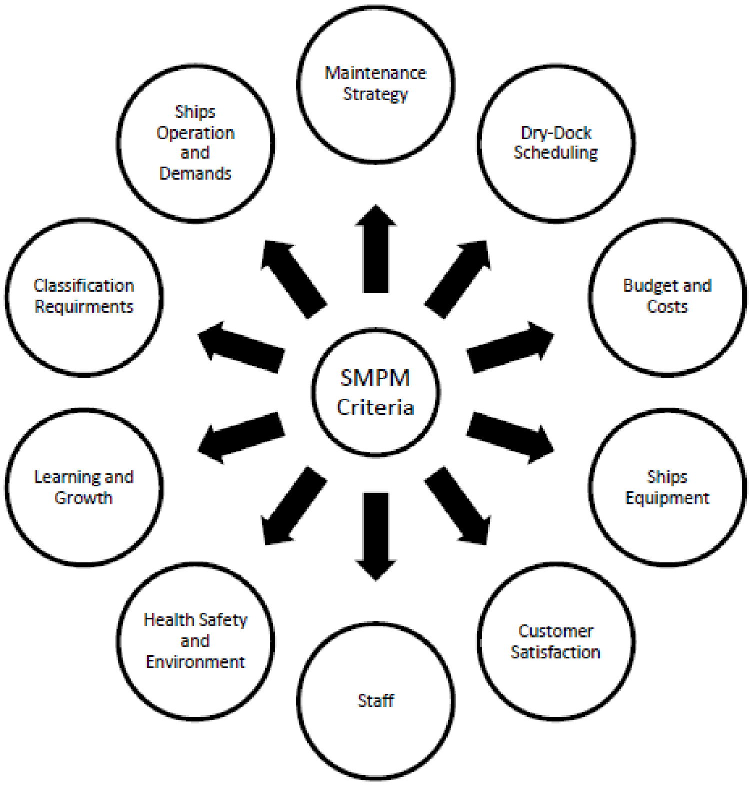

Figure 7-2:Ship Maintenance Performance Measurement (SMPM) Criteria

In the development of SMPM framework, identifying the maintenance performance indicators for each criterion is a significant issue; those indicators must be considered from the viewpoints of the organisation's vision, objectives, and strategy, bearing in mind the requirements of the external and internal stakeholders.

Three criteria were based on Kaplan and Norton's (2001) balance scorecard, and the rest were chosen from other performance measurement frameworks and from the interviews that were conducted. Six criteria were developed from the literature survey for use in the ship maintenance performance measures:

1. Financial/cost related (Kaplan and Norton 2001).
2. Customer satisfaction (Kaplan and Norton 2001).
3. Learning and growth (Kaplan and Norton 2001).
4. Employee satisfaction (Sinclair and Zairi 1995).
5. Equipment related (Kutucuoglu et al. 2001).
6. Health, safety, and environment (Parida and Kumar 2006).

The six criteria developed from the interviews that can be used in measuring the ship maintenance performance are as follows:

1. Maintenance strategy.
2. Costs and budgets.
3. Dry docking scheduling and maintenance scheduling.
4. Employees' skills.
5. Classification society requirement.
6. Customer satisfaction.

It is observed that some of the criteria were from both sources, i.e., from the literature and the interviews, such as employee satisfaction and customer satisfaction. That is an indication of the importance of these factors in measuring the maintenance performance of the marine shipping organisation.

7.4. *Framework Maintenance Performance Indicators*

Ten criteria were used in developing the SMPM framework, and those criteria can be expressed in terms of different measuring performance indicators. As discussed earlier, the indicators are measured under different hierarchical levels of the organisation.

For each MPI it is necessary to identify the reason for the measure, the aim of that measure, the method of calculating that measure, the target level of that measure and whether it is achievable or not, the frequency of measurement, the source of data for that measure, the personnel responsible for collecting those data, and how that measurement is going to be analysed and used. The selected criteria, along with their measuring performance indicators, are listed in Table 7-1 which follows:

Table 7-1: Criteria with the ship maintenance measuring performance indicators

Criteria	Source	Maintenance Performance Indicators
Maintenance strategy.	Interviews.	Maintenance strategy costs. Planned maintenance. Unplanned maintenance. Emergency maintenance.
Dry docking scheduling.	Interviews.	Dry docking costs. Dry docking time. Selection of ship yard. Ships availability
Budget and costs.	Literature review.	Maintenance budget/operation budget. Maintenance budget. Maintenance cost.
Ships equipments.	Literature review.	Downtime. Availability. Breakdowns. Spare parts.
Customer satisfaction.	Literature review.	Customer complaints. Customer penalties. Customer satisfaction. New customer addition.
Staff (employees).	Literature review.	Staff retention. Staff complaints.
Health, safety and environment (HS&E).	Literature review.	Number of accidents and incidents. Number of legal cases. Compensation paid. HS&E complaints.
Learning and growth.	Literature review.	New idea generation. Skill improvement training.
Classification requirements.	Interviews.	Classification satisfaction. Expired certificates. Certificate dates.
Ships operation and demand.	Interviews.	Shipment delays. Port authority penalties. Ships readiness.

Detailed discussions of all the selected criteria with their indicators are as follows:

7.4.1. Maintenance Strategy Indicators

In this section, the influence of maintenance strategy indicators on maintenance performance is discussed. The discussion covers three tasks: (1) planned maintenance tasks, in this task maintenance is quantified either as the number of tasks undertaken or in terms of the time/cost required to conduct the maintenance; (2) unplanned maintenance tasks; again, maintenance is quantified either as the number of tasks undertaken or in terms of the time/cost required to conduct the maintenance; and (3) emergency maintenance tasks; in these tasks, the maintenance is quantified by the number of emergency tasks conducted and also by the cost of those tasks.

Then, these maintenance strategy indicators are measured over the four hierarchical levels of the marine shipping organisation, as shown in Figure 7-3 to demonstrate how the criterion indicators are defined in the marine organisation.

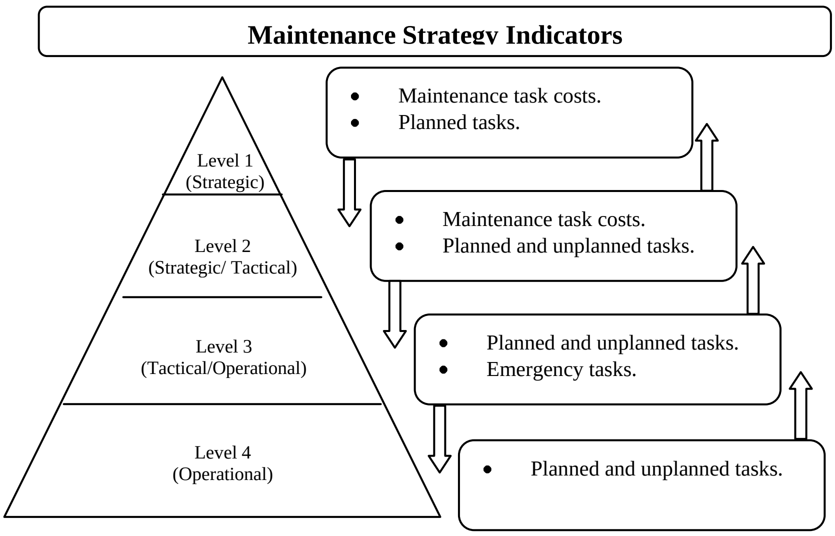

Figure 7-3: Maintenance strategy indicator over the four hierarchical organisation levels

7.4.2. Dry docking Scheduling Indicator

Dry docking scheduling is a very important aspect of performance because it can indicate how well the shipping company is organised. Dry docking is an important task that every shipping company must consider, because bad dry docking scheduling can affect the company's revenue. Dry docking scheduling is determined by the number of ships available in the time window to carry out the company's operational commitments, so it can affect a ship's availability. The cost of dry docking is another factor that must be considered in addition to the time spent in dry dock. Also, the selection of the dry dock yard can give an indication of this criterion.

7.4.3. Budget and Costs Indicators

This criterion can be measured by three indicators i.e., maintenance budget as a proportion of the operational budget, the maintenance budget, and maintenance costs. Most shipping companies set an operational budget with maintenance as only one part of that budget, so this indicator presents the ratio of maintenance component of the budget to overall operational budget. The maintenance budget indicator identifies the level of maintenance to which the organisation is committed.

7.4.4. Ship Equipments Indicators

From this criterion, there are four performance indicators that can affect maintenance performance i.e., downtime, availability, breakdowns, and spare parts. Downtime refers to the time the equipment or system is unavailable. It can be used as an indicator to measure the equipment status. It can be measured as a percentage of the time that the equipment is unavailable. Obviously, equipment downtime can affect a ship's operational schedule.

Availability is a performance indicator that can be expressed as the percentage of ship's availability for conducting shipping operations. This can be presented as the ratio of mean time to failure (MTTF) to the total time. Breakdowns are also an indicator that can identify the equipment status. Breakdowns can be measured by the number of times that the equipment fails or breaks down over a given time period. Spare parts are an important indicator that also can affect the status of the equipment; this indicates how efficient the equipment is. It can be measured by the number of times the equipment has required spare parts and by the cost of the spare parts.

7.4.5. Customer Satisfaction Indicators

In any organisation, the satisfaction of the customer is crucial because it can impact on the performance of that organisation. It can also provide insight concerning the success of the organisation in providing services to the marketplace. Customer satisfaction is a measure of how services supplied by a company meet or surpass customers' expectations.

Measuring customer satisfaction is a difficult task because this measure can differ from person to person and from company to company. The measurement of customer satisfaction as a criterion is based on the number of customer complaints, customer retention, customer satisfaction surveys, and the number of new customers.

7.4.6. Employees Indicators

This criterion can give an indication of employee satisfaction in the organisation. It can be measured by employee complaints and employee retention, which are the two main indictors. Employee complaints are an objective indicator that can be measured by the effectiveness of human resource management. The employee retention indicator can present the employee satisfaction and the effectiveness of the organisational work culture.

7.4.7. Health, Safety and Environment (HS&E) Indicators

Four indicators can define this criterion i.e., the number of accidents, the number of legal cases, the number of compensation cases, and the number of HS&E complaints. The number of accidents is an objective indicator that can be measured in the organisation to give an indication of the safety factors. The number of legal cases is also an objective indicator that can be used to measure the performance of the safety factors in an industrial set-up. The indication of the number of compensation cases is measured by comparing it with the amount of compensation paid. And the number of HS&E complaints can indicate compliance with the HS&E guidelines on the part of the management of the organisation.

7.4.8. Learning and Growth Indicators

This criterion is one of the four perspectives of the balanced scorecards. It can be measured by two main indicators, i.e., new idea generation and skills improvement training. The new idea generation indicator is an objective indicator; it can be measured by the number of new ideas generated and implemented in the organisation that require the employees' participation and motivation. Skills improvement is a subjective indicator that can be measured by the amount of money spent on employee training, the number of training programs conducted per training year, and how the skill is used to upgrade the competency level of the employees.

7.4.9. Classification Requirements Indicators

A classification society is an organisation that conducts regular surveys on service ships to ensure that the ships are compliant with a set of standards. This criterion can be measured by the society satisfaction indicator and the classification certificates indicator. Classification society satisfaction can be measured based on the surveys conducted and the number of outstanding surveys. The classification society certificates indicator is measured based on expired dates and the due dates for the surveys.

7.4.10. Ships Operation and Demand Indicators

The ship operation and demand criterion can give an indication as to how the maintenance is conducted and what its effects are on maintenance performance. The measurement indicators are shipment delays and associated fines, the port authority's penalties, and the readiness of the ships.

The maintenance performance measuring indicators must be tested and implemented in a marine shipping organisation in order to achieve the required objectives of such indicators.

7.5. The Development of SMPM Framework and its Effectiveness

The effectiveness of the ship maintenance performance measurement method is intended to satisfy the requirement of the maintenance process in a marine organisation. That can be achieved by scrutinising the ship maintenance performance measurement from different perspectives.

The ship maintenance performance measurement methodology can be achieved by developing a framework that can represent the status of maintenance in the marine shipping organisation.

The developed SMPM framework must have the following three characteristics: (1) all the criteria included in the framework are applied in parallel to measure the maintenance performance without predefined preference between them; (2) these criteria were chosen to complement each other to cover major aspects affecting the maintenance performance of the entire organisation without overlap or duplication; and (3) the framework considers the entire organisation system as a whole in order to understand how its different aspects are interrelated. In addition, the framework must link the organisation strategy with the total maintenance effectiveness and maintenance criteria as shown in Figure 7-4:

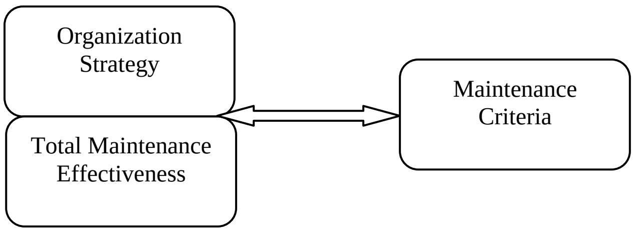

Figure 7-4: Linking Organisation strategy, total maintenance effectiveness, and maintenance criteria.

As discussed earlier, the SMPM framework also must be developed from multiple criteria under four hierarchical levels and must consider the internal and external features before deciding on the relevant criteria at those levels. Those features are part of the front-end process and back-end process (see Figure 7-5).

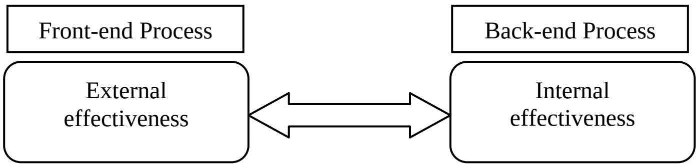

Figure 7-5: Front-end to back-end processes

The front-end process can be derived from external stakeholders' needs, which represent the shareholders or owners, financers, customers, suppliers, and regulating authorities. This process includes the HS&E rating, timely delivery, and availability.

The back-end process represents the internal aspects, such as employees' requirements, the organisation's climate, and skill enhancement. It can measure cost reduction, employee retention, and innovation.

Figure 7-6 shows, in general, the ship maintenance performance measurement (SMPM) framework; it shows that the external and internal features must be analysed before selecting the different maintenance criteria.

Front-end process	External effectiveness	SMPM	Internal effectiveness	Back-end process
• Availability • HS&E issues	• Customer/ stakeholders • Compliance with regulations		• Reliability • Efficiency • Growth & innovation	• Stability • HS&E issues

	Level 1	Level 2	Level 3	Level 4
	Strategic	Strategic/Tactical	Tactical/Operational	Operational
Maintenance Strategy indicators	• Maintenance task costs. • Planned tasks.	• Maintenance task costs. • Planned and unplanned tasks.	• Planned and unplanned tasks. • Emergency tasks.	• Planned and unplanned tasks. • Emergency tasks.
Dry docking scheduling indicators	• Ships availability. • Cost of dry docking. • Duration of dry dock. • Dry dock yard selection.	• Ships availability. • Cost of dry docking. • Duration of dry docking. • Dry dock yard selection.	• Ships availability. • Duration of dry docking.	• Ships availability. • Duration of dry docking.
Budget and costs indicators	• Maintenance budget of the operation budget. • Maintenance budget. • Maintenance costs.	• Maintenance budget of the operation budget. • Maintenance budget. • Maintenance costs.	• Maintenance budget of the operation budget. • Maintenance budget.	• Maintenance budget of the operation budget. • Maintenance budget.
Ships equipments indicators	• Availability. • Downtime.	• Availability. • Downtime. • Breakdown.	• Downtime. • Breakdown. • Spares. • Equipment operation.	• Breakdown. • Spares. • Equipment operation.
Customer satisfaction indicators	• Customer complaints. • Customer satisfaction. • Customer retention. • New Customer addition.	• Customer complaints. • Customer satisfaction. • Customer retention. • New Customer addition.	• Customer complaints. • Customer satisfaction.	• Customer complaints. • Customer satisfaction.
Employee indicators	• Employee complaints. • Employee satisfaction. • Employee retention.	• Employee complaints. • Employee satisfaction. • Employee retention.	• Employee complaints. • Employee satisfaction.	• Employee complaints. • Employee satisfaction.
Health safety and environment (HS&E) indicators	• Number of accidents & incidents. • Legal cases. • Compensation paid. • HS&E complaints.	• Number of accidents & incidents. • Legal cases. • Compensation paid. • HS&E complaints.	• Number of accidents & incidents. • HS&E complaints.	• Number of accidents & incidents. • HS&E complaints.
Learning and growth indicators	• New idea generation. • Skills improving. • Training.	• New idea generation. • Skills improving. • Training.	• New idea generation. • Skills improving. • Training.	• New idea generation. • Skills improving. • Training.
Classification requirement indicators	• Society satisfaction. • Classification certificates. • Certificates expired dates.	• Society satisfaction. • Classification certificates. • Certificates expired dates.	• Classification certificates. • Certificates expired dates.	• Classification certificates. • Certificates expired dates.
Ships operation and demands indicators	• Shipment delays & fines. • Port authority's penalties. • Ships readiness.	• Shipment delays & fines. • Port authority's penalties. • Ships readiness.	• Shipment delays & fines. • Port authority's penalties. • Ships readiness.	• Shipment delays & fines. • Port authority's penalties. • Ships readiness.

Figure 7-6: The Proposed Ship Maintenance Performance Measurement (SMPM) framework

7.6. SMPM Framework Validation

This section presents the results of the validation of the developed framework by conducting interviews with five experts from KOTC to obtain their opinions and views of the framework.

Interviews were conducted with the manager of the Fleet Engineering Group, the team leader of the Fleet Engineering Group, the team leader of the Fleet Engineering Group's dry docking division, the team leader of the Fleet Engineering Group's electrical division and acting manager of Fleet Personnel Group, and the team leader of the Fleet Personnel Group. The interview questions are given in Appendix 2.

The interviews were analysed and discussed by implementing an interpretive methodological approach. The findings from the interviews are discussed next.

In going through the interview questions, the interviewees discussed whether the company has any maintenance performance measurements. It was shown that the KOTC has established an overall organisation performance measure in order to comply with international standards for ship safety and pollution prevention. The maintenance performance measure is only one element of the Tanker Management and Safety Assessment (TMSA). Therefore KOTC does not have any other maintenance performance measurement that indicates that maintenance performance measurement is an important measure for the organisation.

Identifying the maintenance performance measurement indicators was very interesting for the interviewees. They identified some indicators based on their work experience, and they identified various indicators, including those associated with customer satisfaction, employees, budget, breakdowns, safety, classification requirements, and dry docking scheduling.

The manager of Fleet Engineering identified some maintenance performance indicators as follows, *'In my opinion, the most important indicators are those that reflect on customers' needs; other indicators are related to employee satisfaction and budget'.*

After identifying the maintenance performance indicators, the interviews proceeded into discussions of the hierarchy levels of the organisation and how maintenance is arranged in these levels. The results of these discussions are presented next.

The interviewees divided the hierarchy levels into three and four levels, starting with the top management level, followed by the management/operational level and the operational level.

The interviewees identified the stakeholders in a marine shipping organisation to be those who can have benefit from the company's operations. Such stakeholders are the customers, employees, and the owners. As the team leader of the Fleet Personnel Group said, *'The main stakeholder of our company is Kuwait Petroleum Company (KPC), which charters KOTC vessels to transport its petroleum products'.*

In general terms, the interviewees were very interested in reading the developed framework, and their comments were positive, reflecting their appreciation of the ability to read every criterion and measure it with the key performance indicators described.

As the team leader of the Fleet Engineering Group's electrical division said, *'The implementation of this framework is ideal; it can provide us, the decision makers, a guide for measuring the maintenance performance of our company'*.

Since the interviewees found the framework easy to read, it can be a good guide for measuring the maintenance performance in a marine shipping organisation.

The interviewees did not comment much on the criteria, and they did not add or remove any criteria; however, the manager of the Fleet Engineering Group said, *'I would call the criteria "elements," and each element can be measured by different key performance indicators'*.

The implementation of this framework requires the availability of data and the approval of the management team. As the team leader of the Fleet Engineering Group said, *'The implementation of this framework is possible, but it will require some time before we make decisions concerning how and when can we implement this framework'*.

In improving the framework, they could use their experience and, with the aid of this framework, good maintenance performance measurement can be achieved. As the team leader of the Fleet Engineering Group's dry docking division said, *'Using our experience with this framework can help us in providing a good maintenance performance measurement in our organisation'*.

Therefore, the interviews indicated that the framework is valid, and the validation of the framework is based on the interviewees' experience. Finally, the validation encouraged the author to plan the implementation of the framework as future work.

7.7. Summary and Conclusions

In this chapter, the purpose the new method of developing a conceptual ship maintenance performance measurement (SMPM) framework was discussed. The multi-criteria approach was used to measure the maintenance performance of a marine organisation. Different criteria for the framework, along with their performance indicators, were explained. The marine organisation hierarchical levels were explored, and the indicators were classified according to those hierarchical levels.

The effectiveness of the framework was discussed, i.e., it can aid the decision maker to make the correct decision and satisfy the requirement of the maintenance process in a marine organisation. Before developing the framework, the external and internal aspects of a marine organisation were discussed. The presented framework predicts total maintenance effectiveness by individually applying each criterion and collectively utilising the results to produce a comprehensive measure of the maintenance performance in a marine shipping organisation.

The validation of the framework showed that it is a successful tool for measuring maintenance performance in a marine shipping organisation. It can aid the decision making process in measuring the maintenance performance of the organisation, which can result from the overall measure of the organisation.

In the next chapter (Chapter 8), the scheduling criterion will be studied to provide a model that can improve the scheduling of dry docking in any marine shipping organisation.

Chapter 8: Development of Dry Docking Maintenance Scheduling Model

8.1. Introduction

Efficient scheduling of ship maintenance that requires dry docking is a vital component in the overall strategic management of a merchant shipping fleet; when this process is managed well, significant revenue and efficiency gains can be made, since downtime is, in theory, minimised. Ordinarily, ships are scheduled to undergo maintenance at a shipyard every two and a half years for an intermediate classification survey and every five years for a major classification survey (Elkhouly 2001). Usually, shipping companies attempt to conduct only the five-year major surveys with the classification societies, especially for their new vessels. This is possible because the specifications required for new ships require a much higher standard of construction than was previously the case. For example, the Kuwait Oil Tanker Company (KOTC) has proved to the classification society that ships built since 2007 only need to undergo five-year dry docking inspections and maintenance (KOTC 2009).

In dry docking, a ship is removed from the water to enable work to be performed on the exterior of the vessel, which is ordinarily below the waterline. The owners usually plan and schedule their ships for dry docking based on the dates of previous maintenance and on the latest date by which the classification society's inspection requirements must be met. The problem is that such scheduling is not planned to provide the optimum solution; therefore, optimum scheduling is needed to maximise the availability of ships while ensuring safe operation. In this chapter, an optimum scheduling solution for the five-year major surveys is presented by a mathematical formulation developed for the scheduling of the dry docking maintenance of ships. The mathematical technique used is an integer model in order to formulate the relationship between the variables and solve the resultant scheduling problem. A branch-and-bound algorithm was used to solve the resulting integer programming model.

8.2. Problem Description

In any merchant shipping company, dry docking maintenance is very important for ensuring that the ships are seaworthy and ready to conduct the required operations. This can only be guaranteed if effective planning and management of maintenance are achieved.

In the current situation, dry docking maintenance is conducted based on two factors i.e., previous dry docked maintenance and the due date for the classification society survey. However, it is clear that other factors must also be considered in order to optimise the dry docking maintenance of ships, including factors such as the demand on a ship's operations and dockyard availability.

As emphasised previously, the availability of vessels is paramount to commercial shipping companies; corporate risk management strategy is based on this availability, and, therefore, unanticipated or long-duration maintenance operations are likely to have a significant negative impact on revenue and profitability. Therefore, dry docking maintenance should be scheduled in an optimum way; this could be achieved by applying a mathematical approach to identifying the best possible solution to scheduling. In order to this a numerical solution to the problem using a zero-one integer linear programming model has been used.

8.3. Mathematical Model Formulation

A mathematical model of ship maintenance scheduling is presented in this section, using zero-one integer programming.

The first step after identifying the problem in model formulation or construction is to establish the decision variables, which are the controllable parameters, i.e., parameters that have values the decision maker can control and that affect the functioning of the system, i.e., zero-one values. Then, an objective function is identified that should satisfy all constraints on the decision variables. The objective function for this model is to maximise the availability of the ships. The constraints to which the model is subjected have limited values.

A shipping fleet typically contains various different types of vessels, with each type comprised of several classes of ships. The fleet maintenance planning horizon is usually around five years (60 months). The aim is to schedule the dry docking maintenance tasks for different types of vessels (t = 1, ….., T), with each type consisting of different classes (c = 1, ….., m) and ships (s = 1, …….., n) in order to maximise each ship’s availability over the planning period (k), subject to ship maintenance constraints. Figure 8-1 shows the indices used in this model.

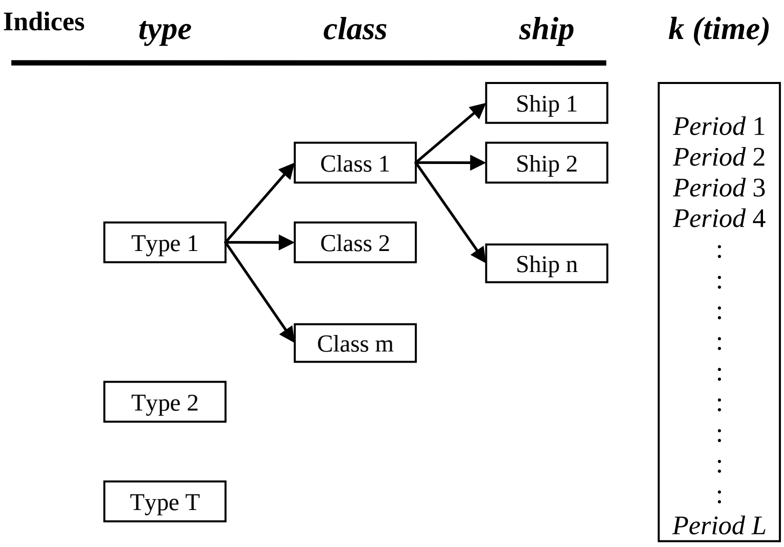

Figure 8-1: Model indices

8.3.1. Decision Variables

The first step in constructing the mathematical model was to identify the decision variables that may be controlled and serve to determine the outcome of the maximisation or minimisation decisions. The development of such values will provide the optimal solution. The decision variables for dry docking ship maintenance scheduling problems are designed as follows:

$$x_{tcsk} = \begin{cases} 1 \\ 0 \end{cases} \qquad \textbf{Equation 8.1}$$

where 1 is the ship s of the class c in type t during the period k in operational status, otherwise, 0

Also, define

$$y_{tcsk} = \begin{cases} 1 \\ 0 \end{cases} \qquad \textbf{Equation 8.2}$$

where 1 if ship s of the class c in type t is not in maintenance during period k, otherwise 0

where:

t represents the type $t = 1,2,3,\ldots\ldots,T$

c represents the class $c = 1,2,3,\ldots\ldots,m$

s represents the ship $s = 1,2,3,\ldots\ldots,n$

k represents the number of the planning horizon period $k=1,2,3,\ldots\ldots,L$

The decision variable x_{tcsk} can be set to 0 in two situations:

When the ship s in class c of type t is undergoing maintenance work during period k,

($y_{tcsk} = 0$).

When it is idle, ($y_{tcsk} = 1$).

Thus, when the ship is not under maintenance ($y_{tcsk} = 1$), this does not necessarily imply that it is in operation ($x_{tcsk} = 1$), since it could simply be idle. Therefore, the following constraints are needed to link variables x_{tcsk} with variables y_{tcsk} .

$x_{tcsk} \leq y_{tcsk}$ for all $t,c,s,$ and k.

8.3.2. The Set of Constraints

The ship maintenance scheduling problem is one of constraints optimisation. The objective function has to be maximised or minimised according to certain constraints. In this model, the following constraints will be considered:

- Maintenance window.
- Maintenance completion.
- Ships limit constraints.

8.3.2.1. Maintenance Window

According to the requirements of the classification society, a ship must go into Dry docking for maintenance regularly (every five years for a major survey and key maintenance) in order to keep the ship's efficiency at a standard level. This can be achieved by specifying the latest time that the ship can be operating without maintenance and the earliest time it can be idled for maintenance. Mathematically, the maintenance window can be expressed as follows:

$$y_{tcsk} = \begin{cases} 1 & \text{if } k < E_{tcsk} \text{ or } k > B_{tcs} \\ 0 & \text{if } E_{tcs} \le k \le B_{tcs} \end{cases}$$ **Equation 8.3**

where:

E_{tcs} = Earliest time that ship *s* of the class *c* of type *t* can be taken for maintenance

B_{tcs} = Latest time that ship *s* of the class *c* of type *t* can be taken for maintenance

Thus y_{tcsk} is fixed at 1 before the earliest and after the latest times to allow for the starting period for maintenance of ship *s* in class *c* of type *t* and can be 0 or 1 between those times.

8.3.2.2. Maintenance Completion

The purpose of this constraint is to ensure that the maintenance time (dry docking period) for each ship occupies the required duration without interruption. This means that, once the ship is in dry dock for maintenance, the work must be conducted without stopping until the maintenance is finished and the ship is returned to operation.

To model this constraint, a zero-one decision variable should be introduced to represent the start of a ship's maintenance period.

Therefore, let

$$Z_{tcsk} = \begin{cases} 0 \\ 1 \end{cases}$$ **Equation 8.4**

where 0 applies if a ship s of class c in type t starts its maintenance on period k; otherwise 1 applies.

Therefore, the maintenance completion constraint will take the following form:

$$y_{tcsk} = 1 - k + \sum_{q=1}^{k} Z_{tcsq}$$ **Equation 8.5**

for $E_{tcs} \leq k \leq E_{tcs} + D_{tcs} - 1$

$$y_{tcsk} = 1 - D_{tcs} + \sum_{q=k+1-D_{tcs}}^{k} Z_{csq}$$ **Equation 8.6**

for $E_{tcs} + D_{tcs} \leq k \leq B_{tcs}$

$$\sum_{k=1}^{B_{tcs}-D_{tcs}+1} Z_{tcsk} = B_{tcs} - D_{tcs}$$ **Equation 8.7**

$$\sum_{k=1}^{B_{tcs}} Z_{tcsk} = B_{tcs} - E_{tcs}$$ **Equation 8.8**

where, $D_{tcs} =$ duration of maintenance for ship s in class c of type t .

The first equation ensures that a job will be completed once work begins on any ship *s* in period *k*. The other two equations ensure that in period ($B_{tcs} - D_{tcs}$) and onwards, no new maintenance job will be started, but that, in these periods the maintenance jobs which have been started can be completed.

8.3.2.3. Ship Limit Constraints

There are always a maximum number of ships which can go for maintenance during certain periods without the shipping company experiencing an unacceptable loss of fleet carrying capacity or revenue earning potential. A limited number of ships of one type in each class can, therefore, be sent for maintenance work, and the remaining ships must stay in operation. Therefore, this constraint is used to limit the number of ships of one type in one class that can be sent for maintenance at any one time. The mathematical representation of such a constraint can be presented as follows:

$$\sum_{c=1}^{n} x_{tcsk} \geq n - r$$ **Equation 8.9**

where *k* runs across all time intervals: *k* = 1,2,3,…..,*L* and *r* is input data which indicate the maximum number of ships that are allowed to be maintained in period *k*.

8.3.3. Objective Function

The objective function of the model can be presented as follows:

$$\text{Max.} \sum_{t=1}^{T} \sum_{c=1}^{m} \sum_{s=1}^{n} \sum_{k=1}^{L} x_{tcsk}$$ **Equation 8.10**

where x_{tcsk} represents the number of ships *s* available in class *c* of type *t* throughout the maintenance planning period *k*.

Subject to:

$$x_{tcsk} \leq y_{tcsk}$$ **Equation 8.11**

and equations (8.5) – (8.10)

8.4. Validation and Results

In order to validate the methodology, a scheduling of dry docking maintenance for Kuwait Oil Tanker Company's (KOTC's) ships has been produced. The scheduling was conducted using data obtained from the KOTC fleet, which consists of 24 vessels and includes three different types of tankers ($t = 1$ for crude oil tankers, $t = 2$ for product oil tankers, and $t = 3$ for gas tankers), with each type having two different classes and a planning horizon of 60 months.

The maintenance constraints are the maintenance window, maintenance completion, and ship limits. For the maintenance window, the earliest and latest maintenance limits can be determined from the previous experience of ships' engineers (information based on expert judgment rather than a mathematical approach); the maintenance period usually starts at the earliest chosen time, which is month one $E_{tcs} = 1$, and the end of the latest chosen time, which is month 60, $L_{tcs} = 60$. On average, the maintenance period takes two to three months; in this example, a three-month maintenance period was chosen. The completion constraint was chosen to ensure that, if a ship is in dry dock, it has to complete the docking time without any interruption to the work. The ship limit constraint ensures that the minimum number of ships is in the dockyard for maintenance during the same period. In the example, the maximum number of ships in the fleet allowed to be in dry dock is two. An integer programming approach has been used to solve the model by using LINGO modelling and optimisation package (Schrage 1999). The results are presented in Table 8-1 and Figure 8-2 shown below, which identifies the dry docking period for every ship in the KOTC fleet.

Table 8-1: KOTC fleet dry docking maintenance scheduling

Type	Class	Ship	Period
T1	C1	S1	5-7
T1	C1	S2	36-38
T1	C1	S3	50-52
T1	C1	S4	44-46
T1	C2	S1	20-22
T1	C2	S2	53-55
T1	C2	S3	39-41
T1	C2	S4	12-14
T2	C1	S1	55-57
T2	C1	S2	42-44
T2	C1	S3	29-31
T2	C1	S4	24-26
T2	C2	S1	58-60
T2	C2	S2	9-11
T2	C2	S3	39-41
T2	C2	S4	17-19
T3	C1	S1	4-6
T3	C1	S2	1-3
T3	C1	S3	12-14
T3	C1	S4	31-33
T3	C2	S1	8-10
T3	C2	S2	27-29
T3	C2	S3	57-59
T3	C2	S4	18-20

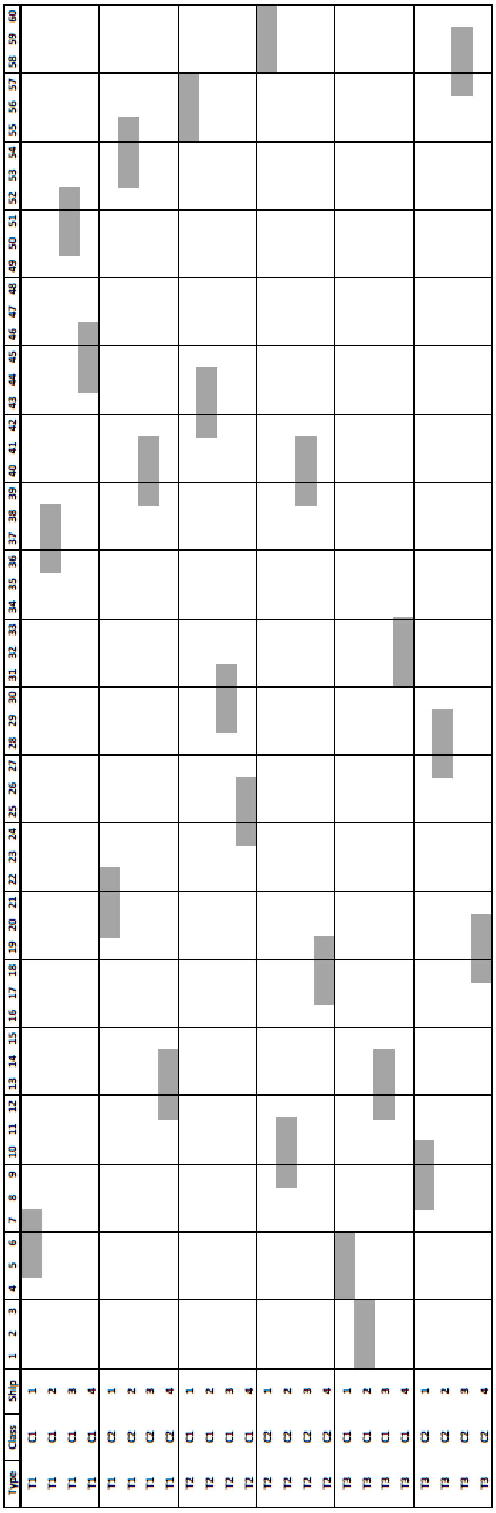

Figure 8-2: KOTC fleet dry docking maintenance scheduling

The results from the example show that dry docking maintenance is scheduled between months 1 and 60. The example also shows that once the dry docking maintenance task starts, it will continue until it is completed, which, in this case, is three months. The example shows that the maximum number of ships scheduled for the shipyard to carry out dry docking maintenance is two. Therefore, the model used in the example offers successful results, as shown in Figure 8-3.

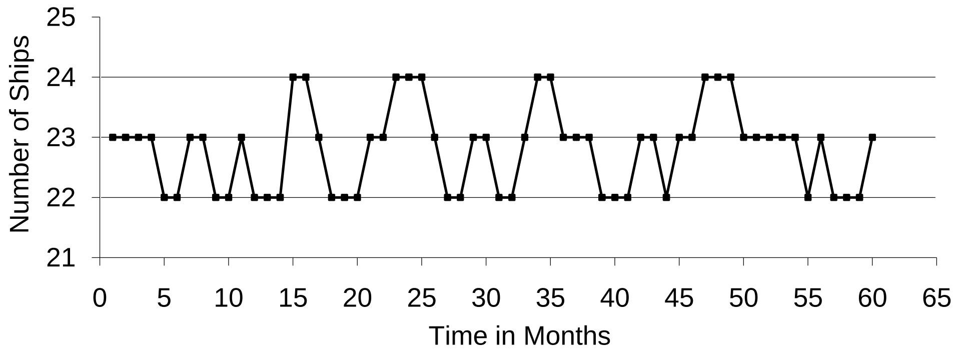

Figure 8-3: Ships availability

From Figure 8-3 it can be seen that the model has maximised ships availability during the total time of 60 months. That means for 16.7% of that period all of the 24 ships are available (100% availability of ships). On the other hand, for 46.7% of that period only one ship is out of service for maintenance, which means that 23 ships are available (96% of the ships are in service). Then, for 36.7% of that period only two ships have been removed from service for maintenance, indicating that 92% of the ships are still in service.

8.5. Summary and Conclusion

Dry docking scheduling is one of the most important aspects that decision makers must consider carefully, because the decision makers want the fleet to be seaworthy and want to ensure that the ships are ready to conduct any required operations.

Therefore, the decision making process requires a tool to optimise the fleet and maximise the ships' availabilities. The development and use of a mathematical model can optimise the ships' availabilities. In this chapter, an optimisation approach for dry docking maintenance scheduling using a mathematical model to develop the scheduling methodology is described. The basic constructs of the model illustrate a zero-one integer programming problem; mixed integer programming techniques have been shown to be a useful approach to scheduling maintenance tasks.

The objective function of this model is to maximise the ships' availability subject to three constraints, i.e., maintenance window, maintenance completion, and ships' limit constraints. Then, real data from the KOTC fleet were used to validate the model.

The validation of the model proved the applicability of the method to the scheduling of a merchant shipping company's dry docking maintenance activities. The model was able to achieve 100% ship availability during certain periods, with 92% or more of the ships available at all times.

The intention of the model is to help decision makers in planning and scheduling maintenance work; it could also aid operations researchers in understanding the relationships between the different processes.

Chapter 9: Conclusions and Recommendations

9.1. Summary

The aim of this thesis was to develop a framework to aid decision makers in the marine shipping industry to optimise maintenance planning for their organisations.

The thesis consists of nine chapters, starting with the introductory chapter, which gave an overview of the research study. This chapter also discussed the significance of the research, its aim and objectives, the methodology used, and the research limitations.

The literature review was then covered in Chapters 2, 3, and 4. In Chapter 2, a general overview of ship maintenance was presented, followed by a discussion of marine maintenance and repair. Then, maintenance performance measurements were discussed, and selected maintenance performance measurement frameworks were reviewed to identify the need for and importance of maintenance performance measurement in any industry and, specifically, in the maritime industry. Maintenance optimisation was reviewed in Chapter 4, and the review was categorised into general models and marine maintenance optimisation models.

Chapter 5 considered the research methodology; it discussed the case study methodology and focused on the use of the interview approach for data collection. Then, the operation research methodology was reviewed; the integer programming approach was explored in detail, since this approach has been used to develop dry docking maintenance scheduling for the marine shipping industry.

Experts from three Kuwaiti marine shipping companies were interviewed to obtain information concerning their opinions and their potential use of a maintenance scheduling protocol to minimise the maintenance downtimes for their fleet of ships. The interviews were aimed at acquiring information that could be used for model development and to encourage appropriate maintenance decision making at the strategic management level.

In the interviews, different aspects of the issue were discussed, including the objectives of each company in conducting maintenance, the maintenance strategies that the companies are using, the effect of maintenance on ship availability, the effect of failures or breakdowns on the companies, the maintenance budget and how it is controlled, the ship's staff and what maintenance they can provide, maintenance measurement and the most important key performance indicators, and, finally, maintenance planning factors.

A ship maintenance performance measurement (SMPM) framework was presented in Chapter 7; new methodology was used to develop the conceptual framework which will allow decision makers to make appropriate decisions in maintenance planning.

The developed framework was based on selecting 10 criteria that can measure the performance of a marine shipping organisation and identifying potential performance indicators for each criterion.

Dry docking scheduling was one such criterion and this issue was explored in Chapter 8; dry docking scheduling was modelled to find the optimum maintenance scheduling for a fleet of ships. An integer programming approach was used to develop dry docking maintenance scheduling for the KOTC fleet.

9.2. Conclusions

Going through the literature, it was found that maintenance is very important in any organisation, that it cannot be ignored, and that it must be managed in an optimum way. This approach can result in significant savings and can reduce the risk of breakdowns. Also, there are many other benefits of conducting maintenance in an optimum way, i.e., system availability is increased, the safety level for the people involved is increased, the reliability of the system is increased, the life spans of the systems are increased, and high end-of-life values are maintained for the equipment, machinery, and systems.

It was observed that many researchers divided maintenance into types or categories, which were based on the system or process operation. Maintenance was categorised based on the strategy used for maintenance planning; which are: (1) run to failure; (2) preventive maintenance; and (3) predictive maintenance.

Another category was the classification of maintenance that represents the status of the process after maintenance. The application of the reliability and maintenance was also categorised, such as RCM and TPM.

As in other industries, ship maintenance is one of the most important aspects that should be given more attention. And, from the literature, it is apparent that ship maintenance plays a very important role in the maritime industry and that planned maintenance can maximise the shipping companies' revenue as well as the safety of the ship, its crew, and its cargo.

The costs of ship maintenance can vary depending on many factors that require attention in order to achieve an optimum maintenance plan. Those factors can have direct or indirect relationship with the costs of maintenance. Also, those factors can be controlled to some degree, or they may be uncontrollable. The controllable factors include, setting the maintenance schedule, selecting a suitable strategy for maintenance, designing the ship with consideration of maintenance planning from the construction stage, selecting the ship's staff, and selecting the shipyard where the ship will be dry docked.

As a result, ship maintenance should always be considered in the early stages from ship construction, given a high priority in shipping companies' decision-making, and always studied carefully.

So, making decisions on maintenance is a difficult task because the ship maintenance process is very complex; therefore, maintenance performance measurement is essential in controlling and monitoring the maintenance process.

Measuring the maintenance performance in any organisation can help draw the map of how maintenance is progressing in the organisation, and this can help the decision making process. It can aid the decision maker to make appropriate decisions concerning planning the maintenance of the fleet.

Therefore, selecting performance indicators (PIs) or key performance indicators (KPIs) for any industry is the main contribution of maintenance performance measurement.

Therefore, the aim of this thesis is to provide a tool to help the decision-making process to measure maintenance performance in marine shipping organisations. This is important because there has been little work done on measuring maintenance performance in the marine shipping industry.

Developing a maintenance performance measurement tool for the ships in a marine shipping organisation was one of the main objectives of this research. And this was satisfied through the development of a suitable framework that can assist marine shipping organisations in planning their maintenance in an optimum way.

Thus, the method of choosing the suitable data was selected by conducting interviews with decision makers from marine shipping companies that have the appropriate experience. The interviews were conducted with key personnel from Kuwaiti marine shipping companies, and the results, along with the literature review, were used to establish the framework for maintenance planning.

The ship maintenance performance measurement (SMPM) framework was developed based on using an interpretive approach to identify the criteria that are used to measure performance in marine shipping organisations.

The outcomes of the interviews with the experts from Kuwaiti shipping companies gave a clear vision on selecting the criteria for use in the development of the framework. From the interviews, it was concluded that maintenance planning is very important for any marine shipping organisation, especially for those larger shipping organisations. Also, the maintenance budget, a good crew, good maintenance scheduling, and coordination between ships' staffs and company management can have a very beneficial effect on maintenance performance.

Also, it was noticed that some maintenance performance measurement has already been undertaken by some marine shipping organisations, such as the Kuwait Oil Tanker Company, which has adopted the TMSA to ensure that the Company is measuring its maintenance performance and its overall performance.

The maintenance performance measurement indicators for the marine organisations selected shows that they have scored an average of 67% to 82%. This can indicates that they are almost equally important indicators, and therefore the study has considered them all equally.

The developed framework was based on 10 criteria with their associated indicators; the criteria are maintenance strategy, dry docking scheduling, budget and costs, ships' equipment, customer satisfaction, employee satisfaction, heath, safety, and environment, learning and growth, classification requirements, and ships' operation and demand. All criteria were measured equally, because they all have an almost equal effect on the overall maintenance performance of the marine organisation.

The indicators were identified for four hierarchical levels of the marine shipping organisation. The 10 criteria were applied in the framework to complement each other, parallel to each other, and as a whole; which can help to understand how the different aspects of the maintenance performance measurements are interrelated. In addition, the framework was constructed to link the organisation's strategy with its total maintenance effectiveness.

The framework was validated by interviewing experts from KOTC, and it was concluded that this framework could be a good measuring tool for maintenance performance of a marine shipping organisation.

Dry docking scheduling was one criterion of the ship maintenance performance measurement (SMPM) framework, and, therefore, the scheduling was solved as an example by using an integer programming methodology approach.

The selection of the integer programming methodology was based on data selected from the marine shipping industry. This methodology showed that it was a useful approach to the scheduling of dry docking maintenance tasks.

As a result, when the model is validated with data from KOTC, the model output has maximised the ships availability. It showed that the each ship is scheduled for dry docking maintenance once every five years. The maximum numbers of ships which can carry out dry docking maintenance at the same time are two, which is only 8% of the total fleet, which leaves 92% of the fleet is available and ready for operations.

9.3. Achievements of Research Objectives

The aims of the research were to identify the key factors that affect ship maintenance planning, to develop a maintenance measurement framework, and to optimise ship availability. These aims were achieved by identifying these factors that affect maintenance planning and then developing a ship maintenance performance measurement (SMPM) framework. Finally, a mathematical model was designed and built for scheduling dry docking maintenance.

This research project has six objectives as illustrated in Chapter 1. The following paragraphs review the achievements of these objectives. ***The first objective*** was to identify the need and importance of maintenance with a specific focus on the mercantile industry; and to extract and assess the factors that affect the decision-making process for ship maintenance planning. The objective was achieved as described in Chapters 2 and 4, which gave an overview on maintenance, a broad study of the literature, and identified the need for maintenance in the marine shipping industry. The review showed that maintenance is a very important aspect for marine organisations and that it must be considered from the early stages of planning, because this can have significant positive influence on the overall expenditures and on health, safety and the environment.

The factors which influence the decision-making process for ship maintenance planning were presented in Chapter 2 based on literature review. The results indicated that the most significant factors are: (1) selecting maintenance strategy; (2) maintenance scheduling; (3) setting the maintenance plan beginning with the ships' construction; (4) number of crew and crew composition; and (5) selecting the shipyard and its location.

The second objective was to evaluate and compare the different approaches and frameworks for maintenance performance measurement. This objective was achieved, as described in Chapter 3, by reviewing maintenance performance measurement frameworks in general and, specifically, for marine organisations.

The third objective was to assess marine maintenance performance indicators based on the literature review and interviews. The objective was achieved as described in Chapters 2 and 4 for the literature review and in Chapter 6 for the case study, which was based on conducting interviews with key experts from Kuwaiti shipping companies. It was found that in the literature review that the significant factors are financial/cost related, customer satisfaction, learning and growth, employee satisfaction, equipment related, maintenance strategy, maintenance scheduling, and health, safety, and the environment. From the interviews conducted with experts in the field, it was concluded that the major factors to be considered are maintenance strategy, costs and budgets, dry docking scheduling and maintenance scheduling, employees' skills, classification society requirements, and customer satisfaction.

The forth objective was adopting a new method to develop ship maintenance performance measurement framework to assess decision makers in ship maintenance planning. This objective was achieved as described in Chapter 7 by the developed framework. The framework was constructed based on 10 thematic criteria, i.e., maintenance strategy, dry docking scheduling, budget and costs, ships' equipment, customer satisfaction, employee satisfaction, health, safety, and environment, learning and growth, classification requirements, and ships' operations and demands.

The fifth objective was to develop an example of maintenance scheduling. This objective was achieved as described in Chapter 8, which developed a dry docking maintenance scheduling model to maximise ship availability. The model uses an integer programming methodology, which resulting in maximising the ships' availability at 92% or greater.

The sixth objective was to validate the developed framework and the scheduling model. This objective was achieved, as described in Chapter 7, by conducting interviews with experts from KOTC, and the model was validated by using data from KOTC to schedule the dry docking of the fleet.

9.4. Contribution to Knowledge

The contribution to knowledge in this thesis consists of three important components: (1) the identification of factors that affects maintenance planning in the mercantile industry; (2) the development new methodology of a framework for maintenance performance measurement; and (3) the development of a methodology for scheduling dry docking maintenance.

The ship maintenance planning factors were obtained by a combination of two approaches: (1) by studying the literature review for maintenance in general and specifically for ship maintenance; and (2) by conducting a case study on marine shipping organisations and interviewing key experts in the field. The selection of those factors has contributed to the knowledge.

In the new methodology for maintenance performance measurements, the framework developed is a contribution to knowledge, because this framework is new method to the marine shipping industry and can assist the decision-making process in maintenance planning. The framework provides the decision maker with a tool to measure the maintenance performance of a mercantile organisation. The framework was constructed from 10 equally important criteria to give an overall assessment of maintenance in the organisation.

In maintenance scheduling, constructing a dry docking model for fleets of ships is contribution to existing knowledge. The model provides a method for optimum scheduling of preventive maintenance in a dry docking plan using an integer programming technique. The model has maximised the ships availability over a 60-month time window. The model results showed a maximisation of the ships' availability, increasing the availability to 92% or greater.

9.5. Recommendations and Future Research

Overall, the results of this research study have identified the main features that affect maintenance planning for marine shipping organisation. Also, it has provided decision makers with a means of measuring the maintenance performance for their organisations. It explored one criterion, which was dry docking scheduling, to show how this criterion can be optimised in maintenance planning.

As the results were limited in some respects, recommendations for follow-up work are as follows:

- The framework criteria should be studied individually to aid and optimise maintenance planning for marine shipping organisations.
- The framework should be tailored for specific marine shipping organisations, such as oil tanker shipping companies, container shipping companies, and fishing shipping companies.
- The dry docking maintenance scheduling model should be extended to include more constraints, such as maintenance budget constraints and

demand constraints. It could also introduce fuzzy parameters to these constraints.

- Further research should be done to integrate optimisation models into a simulation model and to compare the two.

- The framework should be implemented for different marine shipping organisations to illustrate the range of applicability of this framework. This can be a useful tool for marine shipping organisations since it can measure the maintenance performance in advance and aid decision makers in making appropriate decisions.

- The implementation of dry docking scheduling should be conducted in different marine shipping organisations in order to provide the organisations with an optimised dry docking maintenance plan.

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Appendices

Appendix 1

This section presents the questions asked during the conducted interviews of the participated shipping companies.

A. General strategic questions:

1. In your opinion can you explain how the maintenance is important concern to the organisation management of the company?
2. Please give the reasons for your opinion:
3. What is the organisation chart of the company?
4. Is there any co-ordination between maintenance department and other departments e.g. (operation, finance), and how they are achieved?
5. What are the maintenance strategies that the company is using? Can you give me your opinion on how efficient is the used strategies?
6. How the co-ordination between the plan maintenance program and the schedule for ship operations is achieved in the company?
7. What are the effects on the ship demand if ship carrying maintenance?
8. What are the objectives that the company applying in providing maintenance program?
9. Can you give examples of types of maintenance plan used in the company?
10. What is the company forecasting in the maintenance field?

11. What type of forecasting is used?

    Personal, Experience, Statistically or Other

12. Does the company use any maintenance planning model or software? (Yes - No) If yes, what model they use?

13. Does the company use any technique for Dry docking maintenance scheduling? (Yes - No) If yes, what technique they use?

14. Which department is responsible to send the ship to shipyard for maintenance? Is it only one department or its decision of more than one department?

B. Failure and breakdown questions:

15. Could you explain how the condition monitoring is implemented in the company? And how the company is using and analysing this information?

16. Does the company record any failure or breakdown? (Yes - No)

17. If yes, what type of record? And how often this record is taken?

18. What are the decisions made when staff found a breakdown?

19. Fix it, go back for senior decision, report for head office and wait for decision.

20. Does the company have any mechanisms in respect to improve the equipments performance and reduce the breakdown results? Can you explain these mechanisms?

C. Costs and budget questions:

21. Could you explain how the maintenance expenditure is controlled?

22. What type of maintenance budget that the company implements?

23. Is it independent budget or it include other / is it fixed or variable.

24. What is your opinion could be done in order to reduce the cost effectiveness of the maintenance?

D. Safety and environment questions:

25. Does the company take any precautions which reduce the danger of any unexpected breakdown and major maintenance jobs? (Yes - No) If yes, what precautions?

26. Does the company have any rule to avoid any environment damage if poor maintenance applied? (Yes - No) If yes, what rules?

E. Staff and employee training questions:

27. Does the company have a maintenance staff on board a ship, or any staff which can carry out maintenance work? (Yes - No) If yes, can you give me a measure of maintenance staff?

28. Is there any problems related to the staff that prevents the maintenance from being successful? (Yes - No)

29. Does the company have any training programs for the maintenance staff? (Yes - No) If yes, how the training is carried out for the staff?

F. Maintenance information questions:

30. Does the company have records for maintenance works? (Yes - No)

31. Do these records provide useful information that's needed for the maintenance job? (Yes - No)

32. Does the company have computerised maintenance information system? (Yes - No)

G. Maintenance performance measurement questions:

33. Does the company have system to evaluate the progress of the maintenance job? i.e. maintenance performance measurement. (Yes - No)

34. What do you think about the following maintenance key performance indicators? And can you rank them from 1-10 the higher is the most important.

    - Reliability.
    - Maintainability.
    - Availability.
    - Failure (MTBF, MTTF).
    - Downtime.
    - Maintenance budget.
    - Safety and environments.

35. Can you list any other maintenance key performance indicators?

H. Maintenance planning factors questions:

36. What do you think of the following factors which affect maintenance planning? And can you rank them from 1-10 the higher is the most important.

    - Ship maintenance scheduling.
    - Selecting the maintenance strategy.
    - The value of maintenance carried out.
    - Considering the maintenance from ship construction.
    - Number of crew and crew composition.
    - Selecting ship repair yard and its location.

- Life cycle for the equipment’s.
- The recommendation from the manufacturing company.
- The average time for operating the machine.
- Maintenance costs and budget.

37. Can you list other factors which affects or influence on the ship maintenance?

38. Finally what do you think about the interview questions? Can you add any other useful information?

Appendix 2

(Framework Validation Questions)

1- Is there any mean of measurement for the maintenance performance in your organisation?
2- In your opinion what are the steps in measuring the maintenance performance?
3- What are the maintenance performance indicators in your opinion?
4- In your opinion what are the hierarchy levels of you organisation?
5- Who are the stakeholders in your opinion in your organisation?
6- What are the stakeholder's expectations in your opinion?
7- See the figure 1 (framework) and give me your opinion on it and if you can read it? And is it useful?
8- Do you consider these criteria as a measuring maintenance performance tool?
9- Can you comment on each criterion?
10- Do need to add or remove any criteria from the figure?
11- Do you think it is easy to implement this framework in your organisation?
12- How can you improve this framework?
13- Finally can you give me your opinion on the framework?

Appendix 3 (Lingo Model)

```
Model :

Title Preventive Maintenance Scheduling of Ships using Integer

   Programming Method;

! mathematical model of ship maintenance scheduling ;
DATA:
! The total number of type;
number_of_type= 3;
! The total number of class;
number_of_class = 2;
! The total number of maintenance period;
period_month = 60;
! the total number of resource needs for maintenance ;
!number_of_resource = 2;

ENDDATA
sets:
type/1..number_of_type/;
class /1..number_of_class/:  ;
ship : number_of_ship;
period /1..period_month/ ;


!resource /1..number_of_resource/:;
links (type,class , ship , period ): X,Y,Z ;
links2 (type,class , ship):ET,LT,D;
links3(type,ship, period ): ;
links4(type,ship,period): ;
links8(period): ;


ENDSETS

data:
! the maximum ship that allowed for maintenance in period k ;
u =22;
!ship 1,2,3;
number_of_ship  = 1 2 3 4;
! earliest time ship s in type t in  class c can be taken for maintenance(the total number of ET = the number of type t
*the number of class c* the number of ship s) ;
!    s=1   s=2     s=3 ;
! t= 1;
ET =  1,    1,      1,    1,
     1,    1,      1,    1,

! t = 2;
     1,    1,      1,    1,
     1,    1,      1,    1,

! t = 3;
     1,    1,      1,    1,
     1,    1,      1,    1;
```

```
! latest time ship s in type t  in class c can be taken for maintenance(the total number of LT = the number of t *the number of c* the number of s)  ;
!   s=1   s=2    s=3 ;
! t=1;
LT = 60,  60,     60,  60,
    60,  60,     60,  60,

! t =2;
    60,  60,     60,  60,
    60,  60,     60,  60,

! t =3;
    60,  60,     60,  60,
    60,  60,     60,  60;


! duration of maintenace for ship s in type t in  class c (the total number of D = the number of t *the number of c* the number of s) ;
!   s=1   s=2    s=3 ;
 !t=1 ;
D =  3,   3,    3,  3,
    3,   3,    3,  3,

!t = 2 ;
    3,   3,    3,  3,
    3,   3,    3,  3,

!t = 3 ;
    3,   3,    3, 3,
    3,   3,    3, 3;

enddata

! the objective function of the model will be given by (xtcsk) where x(tcsk) represent the total operating time for all plants ;


 max =  @SUM( links(t,c,s,k ): X(t,c,s,k ));

! subject to ;
! ###### 1
constraint which link variabls xtcsk with varribls ytcsk ;

  @FOR( links(t,c,s,k) :[link_variables] X(t,c,s,k) <  Y(t,c,s,k));

! ###### 2;
! set of constraint for maintenance window and maintenance completion;

 @FOR( links(t,c,s,k)| K #GE# ET(t,c,s) #AND#  K #LE# ET(t,c,s) + D(t,c,s)  -
1 : Y(t,c,s,k) = 1 - k +   @SUM(links(t,c,s ,q)| q #GE# 1 #AND# q #LE# K
:Z(t,c,s,q)));
```

```
! ###### 3;
! set of constraint for maintenance window and maintenance completion;

  @FOR( links(t,c,s,k)| k  #GE# ET(t,c,s) + D(t,c,s)  #AND#  k #LE# LT(t,c,s)
: Y(t,c,s,k)  = 1 - D(t,c,s) + @SUM(links(t,c,s, q)| q #GE# k + 1 - D(t,c,s)
#AND# q  #LE# K  :Z(t,c,s,q)));

  ! ###### 4;
! set of constraint for maintenance window and maintenance completion;

@for(links2(t,c,s):
    @SUM( links(t,c,s,k) | k #GE# 1  #AND#  k #LE# LT(t,c,s) - D(t,c,s) + 1 :
Z(t,c,s,k))= LT(t,c,s) -D(t,c,s);
);


! ###### 5;
! set of constraint for maintenance window and maintenance completion;
 @for(links2(t,c,s):
 @SUM( links(t,c,s,k) |k #GE# 1  #AND# K #LE# LT(t,c,s)   : Z(t,c,s,k))=
LT(t,c,s)-1;
);



@for(links8(k):
 @SUM( links(t,c,s ,k ) |k #GE# 1  #AND# k #LE# 60: X(t,c,s,k))> 22;
);
! the binary variables;

@FOR(links( t,c, s, k)  : @BIN( X( t,c, s, k));); 
@FOR(links( t,c, s, k)  : @BIN( Y( t,c, s, k));); 
@FOR(links( t,c, s, k)  : @BIN( Z(t, c, s, k));); 

!@FOR(links( t,c, s, k)  : @BIN( ds(t, c, s, k));!);

END
```

Appended Papers and Poster

(Paper 1)

On the Factors Afflicting Maintenance Planning in Mercantile Industry

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ABSTRACT

Ship maintenance contributes to a significant part of the ship operation costs. This paper reviews ship maintenance schemes, which include classification of maintenance schemes based on their types, locations and importance.
The review is followed by a discussion of different measures of the maintenance cost, which plays a major role in the operational costs. A case study of a Bulk Carrier is illustrated to demonstrate the maintenance costs and how these costs are linked with that of operation.
The paper identifies and evaluates the key factors which affect the maintenance planning and its costs; these factors are categorized as controlled and uncontrolled factors. The controlled factors are defined as that factors which the decision maker have an influence on; and the uncontrolled factors are those which are the decision maker can not control. The most significant factors are of those controlled factors and are recognized as: Selecting Maintenance Strategy, Planning Maintenance Scheduling and Crew Composition.

Keywords: ship maintenance, ship repair, maintenance planning, maintenance costs.

1. INTRODUCTION

Ships have been an important medium for trade and commerce for thousands of years. Ship owners are always looking for the best outcome from the ship and that usually happened when the ships are in a good working condition. In order to keep any ship in good condition maintenance has to be considered, therefore ship owners are constantly looking for improvements to maintenance programmers since ships that are out of service will have effect on the company revenue.

2. MARINE SHIPPING MAINTENANCE

Usually ship maintenance is considered in the early stages of the ship design. The designers and the owner review the plans for preventive maintenance with the classification society to confirm that the plans are accepted in accordance with the class society requirements for surveys after construction [1].

Ship availability can be improved by good maintenance planning and scheduling. The ship can be available if all the major components are available such as propulsion, power, cargo machines etc [2].

In the marine industry ship maintenance can be carried out in two different ways as shown in Figure 2-1: Types of ship maintenance. Ships are usually scheduled to go to ship yard every two and half years for intermediate classification survey and every five years for major classification survey.

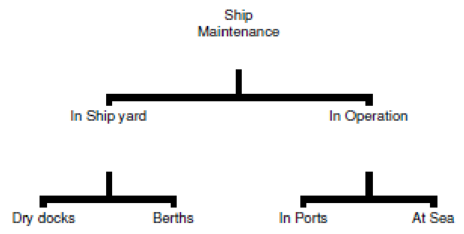

Figure 2-1: Types of ship maintenance

Ship maintenance varies from equipment to another based on the equipment location and the required maintenance procedure. Figure 2-2 shows an example of what parts in oil tanker in general needs maintenance.

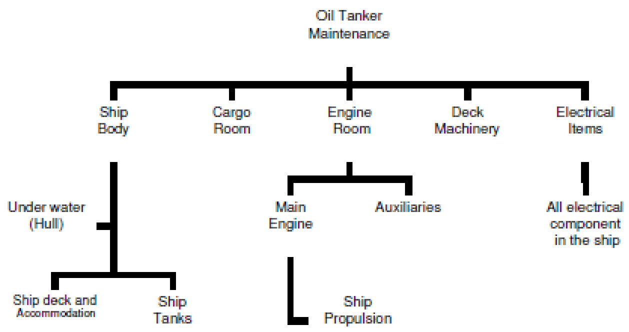

Figure 2-2: Parts of oil tanker maintenance

When a ship is in operation the maintenance is done by the people on board the ship, as B.S.F. Management Service Report suggests that some hours of the operators goes to maintenance, the hours spend in maintenance depends on their rank, but the figures may varies depending on the ship type and size. The table below shows the operator's maintenance hours [3].

Table 2-1: Crew maintenance time

Rank	Maintenance hours	Number of men
2nd Engineer	2hr Maintenance/day	(1)
3rd Engineer	4hr Maintenance/day	(1)
4th Engineer	4hr Maintenance/day	(1)
Junior Engineer	8hr (All day)	(0-2)
Electrician	8hr (All day)	(1)
Boatswain	4hr Maintenance/day	(1)
Mechanic	8hr (All day)	(1-2)
Seamen or Wiper (GP)	4hr Maintenance/day	(6-9)

The maintenance strategy for marine shipping vessels is a key factor that affects on the maintenance costs. As ships are very complicated systems, and there are many options for the maintenance strategy to obtain, it is recommended to choose more than one strategy for carrying maintenance for a ship in order to get the maximum output. Ship maintenance involves a system-wide program, including daily maintenance, examination and repair of all devices, the modification and update of programs and equipments [4].

Ship maintenance, like maintenance in other industries, typically employs two types of policies breakdown maintenance and preventive maintenance. Breakdown maintenance policy usually carried out with out any preventive maintenance except essential lubrication and making few re-adjustments. Preventive maintenance is to carry the maintenance in order to cut down the number times of breakdown.

The measurement of what maintenance is to be conducted would originally be based upon operating experience and manufacturer recommendations.

3. MAINTENANCE COSTS

In the marine shipping industry maintenance cost can be classified as one part of the ship operating costs. In general, ship operating costs vary depending on type, size, and age of vessel. Ship maintenance and operation costs include all the costs related to equipments and materials, personnel, and replacement inspection overhaul and repair.

Ship maintenance cost can be measured in different ways, it can be direct measurable maintenance costs and indirect measurable maintenance costs, some costs are controllable and some are not controllable.

4. CASE STUDY

The case study is giving to demonstrate the ship operation costs and show how the maintenance cost is linked to the operation costs. Data were collected from Ship Maintenance a Quantitative Approach book for operating costs of Bulk Carrier 75,000 tons six years of age. The operating cost was classified into five types of direct and indirect measurable costs personnel, storing, maintenance, insurance, and general.

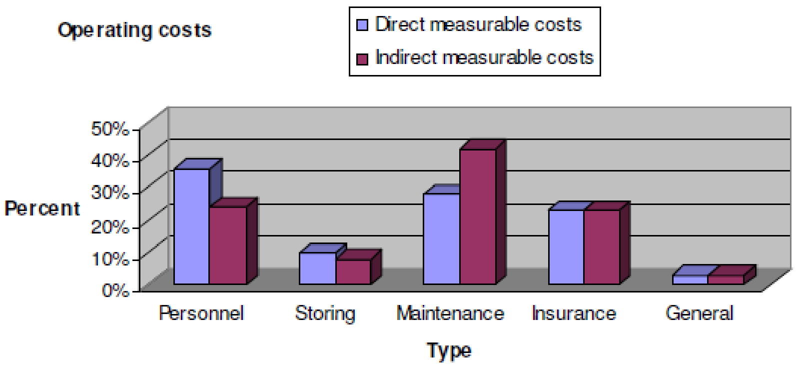

Figure 4-1: Comparison of typical ship operating costs

Result shows that maintenance costs are the largest item in the operating cost and the majority of this cost is controllable. Therefore attention should be made to the maintenance in order to reduce that cost which benefits the shipping company.

5. SHIP MAINTENANCE PLANNING FACTORS

Now a days overhauling in term of major survey is no longer supposed to be the only mean of maintenance but rather regular maintenance is required to be preventive in nature and allow for upgrading the equipment and condition of the ship. Thus, identifying factors which contribute to the maintenance effectiveness is very important.

The maintenance planning factors are divided into two main types, firstly some factors can be controlled and the cost can be reduced by applying an optimizing technique, and other factors are out of control, and the cost can only be optimized to some degree due to some limitation involves. The identified factors are listed in the table below.

Table 5-1: Ship maintenance planning factors

Controlled Factors	Uncontrolled Factors
Maintenance Scheduling	Ship Age
Selecting Maintenance Strategy	Ship Size
Ship Construction	Utilization
Number of Crew and Crew Composition	Ship Type
Shipyard Location	Classification Societies

6. CONCLUSION

- Maintenance costs are the largest item in the operating cost, and the majority of this cost is controllable.
- Attention should be made to the maintenance in order to reduce that cost which benefits the shipping company.
- Good maintenance specification can safe a lot of money to the shipping company.
- It is important to categories the controlled factor as these factors can be optimized in the maintenance.
- Finally consideration should be given to the maintenance planning as it is very crucial for maintaining the ship operation and minimizing the cost of its maintenance.

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(Paper 2)

Dry docked maintenance scheduling of commercial shipping vessels in Kuwait using an integer programming methodology

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Abstract

The scheduling of ship maintenance that requires the use of a dry dock is an important aspect of the management of a merchant shipping company's fleet. The decision to remove a vessel from operational service in order to facilitate dry-docked maintenance activities will naturally impact upon overall availability levels of the fleet (as well as flexibility and downtime), which in turn can have a bearing upon corporate revenue and cash-flow levels.

Operators therefore seek to manage the scheduling of these maintenance activities in an optimal way, using a combination of operational research based techniques and strategic management decision-making. Effective scheduling has an implied benefit to the dockyard operators in facilitating forward-planning of essential ship's maintenance tasks, which should ensure that the supply-chain is adequately prepared. This joined-up approach to scheduling will also provide useful data to plan and schedule the routing and docking of ships en-route to the dockyard.

The research described in this paper demonstrates the use of an integer linear programming model to facilitate the scheduling of dry-docked maintenance activities in an optimum way designed to maximize the availability of ships within the fleet. The optimization model is defined by three constraints; maintenance window, maintenance completion, and ship limit. The model used data from the Kuwait Oil Tanker Company's fleet which has 24 tankers of three different types. The results of this modelling approach demonstrate that the availability of the company's ships over a time horizon of 60 months is maximized and therefore potentially optimal in terms of impact upon corporate revenue (ceteris paribus). The limitations of this model are discussed and further work required to refine this approach in an operational setting is discussed.

Keywords: mercantile operations management, mercantile maintenance, operations scheduling, integer programming

1 Introduction

Efficient scheduling of ship maintenance requiring dry-docking is a vital component in the overall strategic management of a merchant shipping fleet; where this process is managed well, significant revenue and efficiency gains can be made since downtime is in theory minimized. Ordinarily ships are usually scheduled to undergo maintenance at a shipyard every two-and-a-half years for an intermediate classification survey and every five years for a major one (Elkhouly 2001). Shipping companies ordinarily attempt to carry out only the five-yearly major surveys with the classification societies; this is particularly the case with new vessels. This is possible due to the specification to which new ships have been built in recent years being to a much higher standard of construction than was previously the case. For example, the Kuwait Oil Tanker Company (KOTC) has proved to the classification society that ships built since the 2007's only need undergo five-yearly dry-docking (KOTC 2009).

In dry-docking, a ship is removed from the water to enable work to be performed on the exterior part of the vessel, which is ordinarily below the waterline. The owners usually plan and schedule their ships for dry-docking based on the dates of previous maintenance and on the latest date by which the classification society's inspection requirements must be met. The problem is that the scheduling is not planned to provide the optimum solution; therefore, optimum scheduling is needed to maximize the availability of ships. In this paper an optimum scheduling solution for the five-year major surveys is presented by a mathematical formulation which has been developed for the scheduling of the dry-docking maintenance of ships. The mathematical technique used is an integer model in order to formulate the relationship between the variables and solve the resultant scheduling problem. A branch and bound algorithm is used to solve the integer programming model.

An introduction to the dry-docking maintenance of ships has been presented in Section One. This is followed by a brief literature review of maintenance scheduling in Section Two. Section Three gives a description of the main problems associated with the scheduling of dry-docked maintenance. The mathematical model formulation is discussed in Section Four. The production of a recommended schedule for dry-docking maintenance for the Kuwait Oil Tanker Company fleet is presented in Section Five to illustrate an application of the model. The paper concludes with a summary and draws attention to the benefits of the proposed model.

2 Literature review

There has been little research carried out in ship maintenance scheduling; most of the studies focus on maintenance repair diagnosis (Graham et al. 1995). The most widely-used techniques in maintenance scheduling are knowledge-based systems, mathematical programming, and the branch and bound algorithm.

Deris et. al. (1999) model ship maintenance scheduling as a constraint satisfaction problem (CSP) to maximize the availability of either a ship, a squadron or a fleet for operations which have satisfied maintenance requirements, dockyard availability and operational requirements. The variables used in the model are based on the start times and their domain values are the start and horizon of the schedule. An application of this model was used by the Royal Malaysian Navy. Constraint-based reasoning (CBR) was adopted, which requires start times for the first activities of maintenance cycles. Genetic algorithm (GA) is then adopted to establish the start times of the first activity.

Artana and Ishida (2002) address a method for determining the optimum maintenance schedule for components in the wear-out phase. A case study and sensitivity analysis on a liquid ring primer in a ship's bilge system were used. The interval between maintenance for the components was optimized by minimizing the total cost. A premium solver platform, a spreadsheet-modelling tool, was utilized to model the optimization problem. The optimization process investigates n-equally spaced maintenance at an interval of Tr.

Baliwangi et. al. (2006) developed a methodology based on the integration of ship maintenance scheduling management with risk evaluation in a Life Cycle Cost (LCC) approach. The methodology was designed to establish the optimal maintenance scheduling in several steps, which include determining component function, generating the predicted timings and possible component combinations, analysing the associated alternatives and uncertainties, and lastly selecting the best alternative using a criterion LCC.

Oke (2006) have redefined the expression that defines the period-dependent cost function for preventive maintenance scheduling activity. The approach involves transforming the preventive maintenance cost function that is expressed in terms of several variables into a more precise framework. A case study from the shipping industry is also presented.

In other industries, Kralj and Petrovic (1995) have studied the maintenance scheduling in power generation. Clark et al. (1992) studied the maintenance scheduling of buildings and Smits and Pracht (1991) have studied the maintenance scheduling of an airline.

3 Description of the problem

In any merchant shipping company dry-docking maintenance is very important for ensuring that ships are seaworthy and ready to carry out the operations required. This can only be guaranteed if effective planning and management of maintenance is achieved.

In the current situation, dry-docking maintenance is carried out based on two factors; previous dry-docked maintenance and the due date for the classification society survey. However, it is clear that other factors must also be considered in order to optimize the dry-docking maintenance of ships; this will include factors such as the demands on a ship's operations as well as dockyard availability.

As emphasized previously, the availability of vessels is paramount to commercial shipping companies; the corporate risk management strategy is based on this availability and therefore, unanticipated or long duration maintenance operations are likely to have a significant impact upon profitability and revenue. Therefore, dry-docking maintenance should be scheduled in an optimum way; this could be achieved by applying a mathematical approach to identifying the best possible solution to scheduling. This paper therefore adopts a numerical solution to the problem using a zero-one integer linear programming model.

4 Mathematical model formulation

The mathematical model of ship maintenance scheduling is presented in this section, using the zero-one integer-programming.

The first step after identifying the problem in model formulation or construction is to establish the decision variables, which are the controllable parameters whose values can be controlled by the decision maker and which affect the functioning of the system, in this case zero-one values. An objective function is then identified which should satisfy all constraints on the decision variables. The objective function for this model is to maximize the availability of the ships. The constraints to which the model is subjected have limited values.

A shipping fleet typically contains various different types of vessels, with each type comprised of several classes of ships of that type, and the fleet maintenance planning horizon is usually around 5 years or 60 months. The aim is to schedule the dry-docking maintenance tasks for different types of vessels (t=1,…..,T) each type consisting of different classes (c=1,…..,m) and ships (s=1,……..,n) in order to maximize each ship's availability over the planning period (k) subject to ship maintenance constraints. Figure 1 shows the indices used in this model.

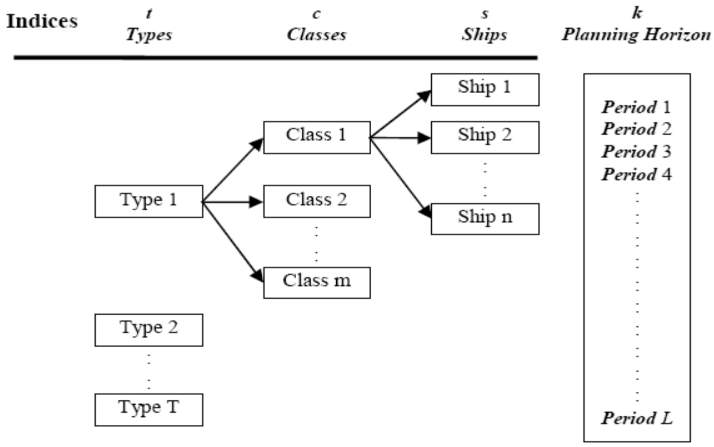

Figure 1: Model indices

4.1 Decision variables

The first step in constructing the mathematical model is to identify the decision variables which may be controlled and serve to determine the outcome of the maximization or minimization decisions. The development of such values will provide the optimal solution. For dry-docking ship maintenance scheduling problems the decision variables are designed as follows:

$$x_{tcsk} = \begin{cases} 1 \\ 0 \end{cases}$$

Where 1 is the ship s of the class c in type t during the period k in operational status, otherwise, 0

Also, define

$$y_{tcsk} = \begin{cases} 1 \\ 0 \end{cases}$$

Where 1 if ship s of the class c in type t is not in maintenance during period k, otherwise 0 where:

t represents the type $t = 1,2,3,\ldots\ldots,T$

c represents the class $c = 1,2,3,\ldots\ldots,m$

s represents the ship $s = 1,2,3,\ldots\ldots,n$

k represents the number of the planning horizon period k=1,2,3,…….,L

The decision variable x_{tcsk} is set to 0 for two reasons:

1. When the ship s in class c of type t is undergoing maintenance work during period k, ($y_{tcsk} = 0$).

2. When it is idle, ($y_{tcsk} = 1$).

Thus, when the ship is not under maintenance ($y_{tcsk} = 1$), this does not necessarily imply that it is in operation ($x_{tcsk} = 1$), as it could simply be idle. Therefore, the following constraints are needed to link variables x_{tcsk} with variables y_{tcsk}.

$x_{tcsk} \le y_{tcsk}$ for all *t,c,s,* and *k*.

4.2 The set of constraints

The ship maintenance scheduling problem is one of constraints optimization. The objective function has to be maximized or minimized according to certain constraints. In this model the following constraints will be considered:

1. Maintenance window
2. Maintenance completion
3. Ship limit constraints

4.2.1 Maintenance window

According to the requirements of the classification society, a ship must go into dry dock for maintenance regularly (every five years for a major survey and key maintenance) in order to keep the ship's efficiency at a standard level. This can be achieved by specifying the latest time that the ship can be operating without maintenance and the earliest time it can be placed under maintenance. Mathematically the maintenance window can be expressed as follows:

$$y_{tcsk} = \begin{cases} 1 & \text{if } k < E_{tcsk} \text{ or } k > B_{tcs} \\ 0 & \text{if } E_{tcs} \leq k \leq B_{tcs} \end{cases}$$

Where:

E_{tcs} = Earliest time that ship s of the class c of type t can be taken for maintenance

B_{tcs} = Latest time that ship s of the class c of type t can be taken for maintenance

Thus y_{tcsk} is fixed at 1 before the earliest and after the latest times to allow for the starting period for maintenance of ship s in class c of type t and can be 0 or 1 between those times.

4.2.2 Maintenance completion

The purpose of this constraint is to ensure that the maintenance time (dry-docking period) for each ship occupies the required duration without interruption. This means that once the ship is in dry dock for maintenance, the work must be carried out without stopping until the maintenance is finished and the ship returns to operation.

To model this constraint, a zero-one decision variable should be introduced which will represent the start of a ship's maintenance period.

Therefore, let

$$S_{tcsk} = \begin{cases} 0 \\ 1 \end{cases}$$

Where 0 if ships of the class c in type t starts it's maintenance on period k, otherwise 1

Therefore, the maintenance completion constraint will take the following form:

$$y_{tcsk} = 1 - k + \sum_{q=1}^{k} S_{tcsq} \qquad \textbf{(1)}$$

for $E_{tcs} \le k \le E_{tcs} + D_{tcs} - 1$

$$y_{tcsk} = 1 - D_{tcs} + \sum_{q=k+1-D_{tcs}}^{k} S_{csq} \qquad \textbf{(2)}$$

for $E_{tcs} + D_{tcs} \le k \le B_{tcs}$

$$\sum_{k=1}^{B_{tcs}-D_{tcs}+1} S_{tcsk} = B_{tcs} - D_{tcs} \qquad \textbf{(3)}$$

$$\sum_{k=1}^{B_{tcs}} S_{tcsk} = B_{tcs} - E_{tcs} \qquad \textbf{(4)}$$

Where $D_{tcs} =$ duration of maintenance for ship s in class c of type t.

The first equation ensures that a job will be completed once work begins on any ship s in period k. The other two equations ensure that in period ($B_{tcs} - D_{tcs}$) and onwards, no new maintenance job will be started but that in these periods the maintenance jobs which have been started can be completed.

10

4.2.3 Ship limit constraints

There are always a maximum number of ships which can go for maintenance during certain periods without the shipping company experiencing an unacceptable loss of fleet carrying capacity or revenue earning potential. A limited number of ships of one type in each class can, therefore, be sent for maintenance work and the remaining ships must stay in operation. Therefore, this constraint is used to limit the number of ships of one type in one class which can be sent for maintenance at any one time. The mathematical representation of such a constraint can be presented as follows:

$$\sum_{c=1}^{n} x_{tcsk} \geq n - r \quad \textbf{(5)}$$

Where k runs across all time intervals: $k = 1,2,3,\ldots..,L$ and r is input data which indicate the maximum number of ships that are allowed to be maintained in period k.

4.2.4 Objective function

The objective function of the model can be presented as follows:

$$\text{Max.} \sum_{t=1}^{T} \sum_{c=1}^{m} \sum_{s=1}^{n} \sum_{k=1}^{L} x_{tcsk} \quad (6)$$

Where x_{tcsk} represents the number of ships s available in class c of type t throughout the maintenance planning period k.

Subject to:

$$x_{tcsk} \leq y_{tcsk} \quad (7)$$

And equations (1) – (5)

5 Implementation and results

In order to validate the methodology, a scheduling of dry-docking maintenance for Kuwait Oil Tanker Company (KOTC) ships has been produced. Using data obtained from the KOTC fleet, which contains 24 vessels and is comprised of three different types of tanker (*t*=1 for crude oil tankers, *t*=2 for product oil tankers, and *t*=3 for gas tankers), each type having two different classes and a planning horizon of 60 months.

The maintenance constraints are the maintenance window, maintenance completion, and ship limits. For the maintenance window, the earliest and latest maintenance limits can be determined from the previous experience of ships' engineers (this information is based on expert judgement rather than a mathematical approach); the maintenance period usually starts at the earliest chosen time, which is month one $E_{tcs} = 1$, and the end of latest chosen time, which is month 60, $L_{tcs} = 60$. The maintenance period on average takes from two to three months; in this example the maintenance period chosen is set to three months. The completion constraint is chosen to ensure that if a ship is in dry dock it has to complete the docking time without any interruption to the work. The ship limit constraint ensures that the minimum number of ships is in the dockyard for maintenance during the same period. In the example, the maximum number of ships in the fleet allowed to be in dry dock is two. An integer programming approach has been used to solve the model by using the LINGO modelling and optimization package (Schrage 1999). The results are demonstrated in the table and figure shown below, which identifies the dry-docking period for every ship in the KOTC fleet.

Type	Class	Ship	Period
T1	C1	S1	5-7
T1	C1	S2	36-38
T1	C1	S3	50-52
T1	C1	S4	44-46
T1	C2	S1	20-22
T1	C2	S2	53-55
T1	C2	S3	39-41
T1	C2	S4	12-14
T2	C1	S1	55-57
T2	C1	S2	42-44
T2	C1	S3	29-31
T2	C1	S4	24-26
T2	C2	S1	58-60
T2	C2	S2	9-11
T2	C2	S3	39-41
T2	C2	S4	17-19
T3	C1	S1	4-6
T3	C1	S2	1-3
T3	C1	S3	12-14
T3	C1	S4	31-33
T3	C2	S1	8-10
T3	C2	S2	27-29
T3	C2	S3	57-59
T3	C2	S4	18-20

Table 1: KOTC fleet dry-docking maintenance scheduling

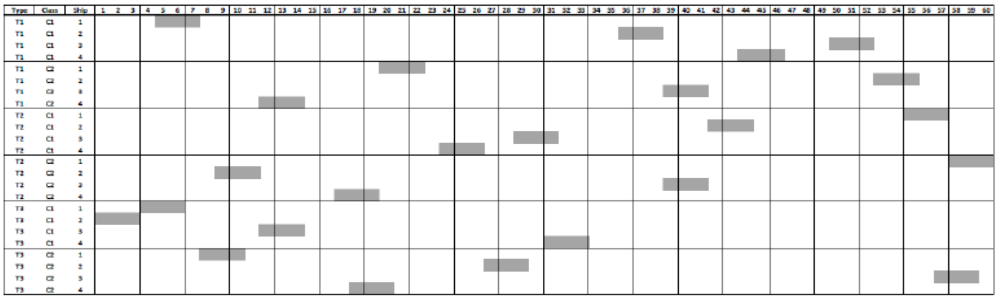

Figure 2: KOTC fleet dry-docking maintenance scheduling

The results from the example show that dry-docking maintenance is scheduled between months 1 and 60. The example also shows that once the dry-docking maintenance task starts, it will continue until it completes its duration, which in this case is three months. The example shows that the maximum number of ships scheduled for the shipyard to carry out dry-docking maintenance is two. Therefore, the model used in the example offers successful results, as shown in Figure 3.

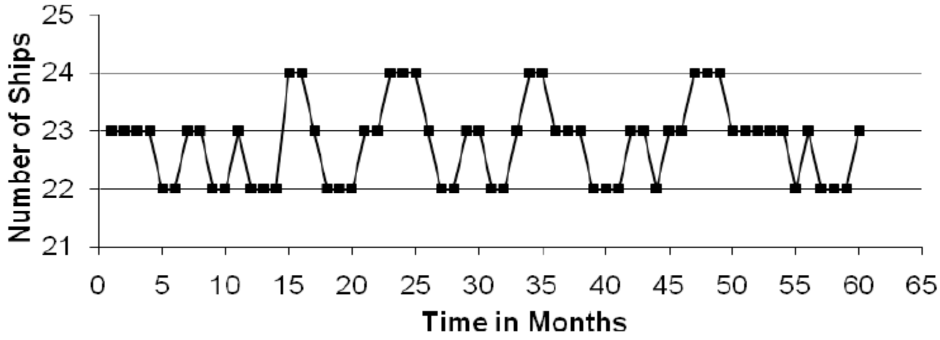

Figure 3: Ships' availability

From Figure 3 it can be seen that the model has maximized the ships' availability: 16.67% of the window period shows all 100% of the ships are available; 46.67% of the window period shows that only one ship is out of service for maintenance, which represents 96% of the ships as being in service; and 36.67% of the window period shows that two ships have been removed for maintenance, which represents 92% of the ships as being in service.

6 Conclusion

In this paper a maintenance scheduling methodology is proposed to optimize the scheduling of dry-docking for maintenance of the vessels in the KOTC fleet. The basic constructs of the model illustrate a zero-one integer programming problem; mixed integer programming techniques have been shown to be a useful approach to scheduling maintenance tasks. The implementation of the model proves the applicability of the method to the scheduling of a merchant shipping company's dry-docked maintenance activities.

The objective function of the model was to maximize ships' availability. The objective function can be extended to include the cost of the dry-docking maintenance activities. In further research, it is anticipated that multiple constraints could be added to the model to accommodate the budget for the dry-docking and the demand for the ships in different seasons. Fuzzy parameters could also be applied to cover any variation in the input data. A stochastic approach may also yield greater power in detecting the variability in certain constraints.

The intention of the model is to help decision makers in planning and scheduling maintenance work; it could also aid operation researchers in understanding the relationships between the different processes.

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(Paper 3)

PERFORMANCE MEASUREMENT OF MARINE VESSEL MAINTENANCE OPERATIONS: A CASE STUDY OF KUWAITI SHIPPING COMPANIES

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ABSTRACT

Organisations that operate complex, high cost assets must develop effective and robust maintenance strategies in order to ensure that their commercial operations realize optimum revenue streams. Maintenance costs usually account for a significant proportion of the total operational costs; it is for this reason that performance measurement metrics are important in contributing to the strategic direction of the organisation. Consequently, maintenance performance can be used as an indicator for potential organizational growth.

In the marine industry in particular, maintenance performance measurement (MPM) requires the consideration of a large number of variables and factors, which can often be difficult to define and assess. In order to accommodate the complex set of criteria that needs to be encapsulated within the measurement process, this paper sets out a methodology to capture the necessary data as part of a wider asset management strategy.

In this paper an interpretive approach is adopted to identify the ship maintenance performance measurement (SMPM) indicators. A case study is carried out on three Kuwaiti marine shipping companies which cover different trade interests ranging from small transport ships to large oil tankers. Semi-structured interviews are conducted with six senior staff experts from the three organisations. The sample includes strategic, corporate and tactical managerial levels. Thus, this paper elucidates on the relevant measuring indicators and concludes that ten thematic criteria should be adopted to provide an evaluative framework for performance measurement. Underpinning these themes, a range of specific factors which should be considered are described. Future work will examine how these criteria may be encapsulated within a framework that integrates project level maintenance performance with strategic corporate objectives. The need for weighting individual elements within the framework will also be addressed in future research.

Keywords: Maintenance performance indicators, Maintenance Performance measures, Performance measures.

1. INTRODUCTION

Within the engineering sectors, maintenance is often considered an important aspect of the operational activities in which and organisation is involved with. The consequences of inappropriate maintenance planning and scheduling can be significant. Maintenance expenditure in the UK manufacturing industry (as an example) ranges from 12 to 23 per cent (Cross 1988). Dekker (1996), reported that in refineries, maintenance spending is about 30% of the total staffing costs. The mining industry spends between 40 to 50 % of the operating costs on maintenance (Campbell 1995). Alhouli, et al. (2009) showed, in a case study of data presented on Bulk Carrier 75,000 tons vessel six years of age, that maintenance costs account for the largest proportion of operation costs (40%) based on the sample surveyed.

In addition to the high cost of maintenance, the breakdowns and downtime have an impact not only on meeting the goals and objectives of the organization, but also on health, safety and the environment. Therefore, measurement of maintenance performance has become a crucial element in strategic asset management.

Measurement provides the basis for an organization to assess how well it is progressing towards its predetermined objectives. It helps to identify areas of strengths and weaknesses, and to decide on future initiatives, with the goal of improving organizational performance (Amaratunga and Baldry, 2002).

In any marine shipping organization, measuring maintenance performance is important since it provides signposts to problem areas and assists in the prioritisation of tasks. It can assess the marine organization achieve it's objectives whilst improving the organization performance.

An introduction to maintenance and measurement in general is presented in section one of this paper. This is followed by an overview of maintenance performance measurement in section two. Section three presents a case study of three Kuwaiti marine shipping companies. The various criteria that are present in ship maintenance performance indicators are identified in section four. In the final section the paper, conclusions are drawn with the importance of measuring the maintenance performance for the marine organisations evaluated.

2. AN OVERVIEW OF MAINTENANCE PERFORMANCE MEASURMENT

Due to the complexities in the maintenance process and the difficulties of arranging the resources, professionals lack a thorough understanding of the maintenance process to construct a correct decision making (Pintelon et al. 1995). Therefore, maintenance measurements become central in controlling and monitoring a maintenance process which will guide appropriate and corrective action.

To measure the maintenance performance, it is important to develop metrics, which can be used to evaluate the effectiveness of the maintenance carried out (Wireman 1998). Furthermore, an appreciation of the corporate and cultural issues associated with implementation need also to be evaluated.

Maintenance performance indicators can reflect the process or system status, and it can show the reduction of downtime, cost and waste, productivity level, quality, and health and safety for the system. These techniques may also be used to inform financial reports, monitoring the performance of employees, customer satisfaction, environmental rating, and overall equipment effectiveness. Standard indicators such as maintenance budget, plant availability targets, planning and scheduling, mean time between failures (MTBF), and mean time to repair (MTTR), maintenance reliability, work process productivity, are all commonly used techniques.

To facilitate and support the management and control of performance measurement and its alignment with the organizational objectives, a strategy to implement these approaches within a broader framework of management is required. Such a framework should provide a solution for performance measurements by linking them to the organisational strategy and consider criteria consisting of financial and non-financial indicators (Parida and Kumar 2006).

The characteristics of performance measures includes relevance, interpretability, timeliness, reliability and validity (Al-Turki and Duffuaa 2003). Balanced performance measurement frameworks have been developed by many researches to measure financial and non-financial perspectives. Kaplan and Norton (1992) developed a balanced scorecard which works on four perspectives, financial, customers, internal process, and innovation and learning. It covers both financial and non-financial aspects of the business process.

Other researchers have developed frameworks considering non-financial measures to achieve competitive advantages (Kaplan and Norton 2001). A nine-point performance framework was devised by Kutucuoglu et al. (2001) they recognise three performance needs, goals, design, and management. They combined performance and strategy into a matrix.

Sinclair and Zairi (1995) involved the employees in the development of performance measurement system. Another framework was developed by Riis, Luxhøj et al.(1997) the framework shows cross levels and functional integration of maintenance management, which attempt to relate maintenance to manufacturing strategy.

The balanced scorecard was adapted by Tsang (1998) to bring a strategic approach to MPM, the approach consists of a mix of outcome measures and performance drivers, indicating the outcome of past decisions and predicting the future outcomes.

Two new approaches were provided by Dwight (1999), system audit approach and the event analysis approach. The system audit approach concentrates on the degree of alignment between the maintenance systems and the goals of the organization it is serving. And the event analysis approach focuses on understanding the impact on the value of the organizations of the specific actions undertaken during the period.

Strategic maintenance management (SMM) approach was presented by Murthy, Atrens et al. (2002) the approach has two elements maintenance management and effective maintenance management. The maintenance management is a critical core business activity crucial for business survival and success and as such it must be managed strategically; effective maintenance management needs to be based on quantitative business models that integrate maintenance with other decisions such as production etc.

Parida and Chattopadhyay (2007) presented a proposed MPM framework, which is balanced, holistic and integrated, and focuses on both internal and external effectiveness, considering the maintenance performance indicators from multi-criteria hierarchical level of the organization.

The need of maintenance performance measurement in different industry is important to measure and evaluate, control and improve the maintenance activities for ensuring achievement of organisational goals and objectives. Industries are improving the performance measurement of their organizations, as some organisations are working to develop specific maintenance performance measurements frameworks and identify the best indicators that outfit their organisation. The maintenance performance indicators are measures of efficiency, effectiveness, quality, timeliness, safety, and productivity amongst others things. An example of industries used the maintenance performance measurement frameworks are nuclear industry, oil and gas industries, railway industry, process industry, and energy sector.

The marine shipping industry has little work on the maintenance performance measurements. In the marine industry the measures are concentrated on the ship safety and pollution prevention. One example of measurement in the marine industry is Tanker Management and Safety Assessment (TMSA). The TMSA is a guideline to measure and assess tanker operations' management system developed by Oil Companies International Marine Forum (OCIMF). The TMSA guidelines defined 12 elements of management practices. The elements provide a checklist approach for ship operators who are aiming to achieve safety and environmental excellence. Element four is the element of reliability and maintenance standards, the main objectives of this element is to establish maintenance standard so that all ships in the fleet capable of operating safely without the risk of an incident or detention (Turker and Deha Er 2008).

3. CASE STUDY OF KUWAITI SHIPPING COMPANIES

Interpretive approach is adopted in this case study in order to analyse and identify the present status of the maintenance organization of three Kuwait shipping companies, Kuwait Oil Tanker Company (KOTC), Livestock Transport and trading Company (KLTT), and Gulf Rocks Company (GRC). The interviews carried out with selected and key responsible personal of the three companies. The interviews covers different trade interest with view of gaining an in-depth understanding of the organizations stakeholders needs, maintenance process, and existing maintenance performance measurement systems. The interviews undertaken with six experts in those companies; these interviews gave valuable information which could be used to evaluate maintenance need and maintenance performance in the maritime industry.
An introduction to those companies will be provided next:

3.1. Kuwait Oil Tanker Company

The Kuwait Oil Tanker Company (KOTC) is one company in the Kuwait Petroleum Company KPC group, it is mainly involved in the ownership and management of tanker ships engaged in the transport of crude oil, refined petroleum, and liquefied petroleum gases (LPG). KPC is an integrated oil company that enjoys international recognition in the petroleum industry. It is the top company amongst the Kuwait government's operations in the petroleum sector.

The Kuwait Oil Tanker Company now owns fleet of 24 tankers which can transport a total capacity of 3.2 million Metric Tons. This fleet comprises crude/product carriers, crude carriers, product carriers, and Gas carriers (KOTC 2009).

KOTC have adopted the Task Assistant software platform, which was originally launched in 1998 as part of a joint development venture between Ulysses Systems Ltd and Lyras Shipping. The main feature of Task Assistant is to be able to incorporate company information with matching documentation and procedures relating to the implementation of the International Safety Management (ISM) Code. The Task Assistant also includes modules for purchasing, planned maintenance, fleet management, crew management, quality and safety.

3.2. Livestock Transport and Trading Company

Livestock Transport and Trading Company (KLTT) is a Kuwaiti public shareholding company established in 1973; it is one of the major pioneering international companies in live sheep transport. The company owns a fleet of four highly technical modern sheep carrier vessels to transport live sheep from Australia to the Arabian Gulf area (KLTT 2009).
The company have marine fleet department which comes under the Assistant Manager Director (AMD). The marine department have a fleet manager and a deputy fleet manager, then two superintendents technical and operational. The ships' maintenance comes under the technical superintendent, who arranges the maintenance manually, based on defect reports and also arranges the dry-dock times based on the ships' due dates.

3.3. Gulf Rocks Company

The Gulf Rocks Company (GRC), incorporated in the state of Kuwait in 1997, it is a publicly traded shareholding company listed on the Kuwait stock market from the beginning of March 2004. GRC have three Bulk Carriers (Handymax). GRC is considered one of the largest producer & trader of aggregates in the region, which is used for building and road constructions.

Technical Managers of Gulf Maritime Ship Management Company (GMSM) coordinates and schedules dry-docks and daily operation for the GRC fleet. GMSM is a Kuwaiti Company handling the technicality, fleet personnel and operation of shipping companies. The GRC have special Engineering and Operation Departments equipped with experienced Engineers and Officers.

3.4. Interviews

The interviews and discussion were conducted at the strategic/corporate and tactical/managerial level of the three companies using five main issues, which covers the importance of maintenance, budget and maintenance costs, crew and staff, maintenance measures, and maintenance planning.

The first issue is the importance of maintenance, the importance of maintenance has produced an increasing interest in the development and implementation of optimal maintenance strategies for improving system reliability, preventing the occurrence of system failures, and reducing maintenance costs of deteriorating systems. In the marine industry maintenance is very important as loss of a major mechanical system can but the whole ship at risk.

All the interviewees agreed that maintenance is a very important issue in the marine industry. The primary importance is to carry out maintenance in order to ensure that the ship is operating in a safe environment; additionally, good planned maintenance will maximize the ships' availability, which maximizes the ships' revenue.

The second issue is the maintenance costs and budget, the maintenance costs and budgets has always been an important measure in the marine shipping industry. It is usually comes under ship operation costs which vary depending on different factors such as age, size, and type. Shipping companies always have some budget for the fleet and for individual ships within the fleet and the budget also can vary depends on the same factors.

Companies usually have an operation budget and the maintenance is only one part of that budget, also the maintenance budget cannot be fixed because there are many factors such as type and status of the vessel which influence on the maintenance expenditure.

In order to reduce the cost for maintenance the experts remarked on that they had two different opinions of how to reduce maintenance costs; good maintenance scheduling and planning can reduce the maintenance budget and you should have good people on board. Therefore it is important to focus on those issues in order to achieve an optimum maintenance costs.

The third issue is crew and staff, as B.S.F. Management Service Report suggests that some of the operating hours of the operators goes to maintenance, and the hours spent in maintenance depends on their rank, therefore some of the ship's maintenance is done by the people on board the ship, which in count the costs of maintenance (Shields et al. 1996). And that is true according to the companies experts as they reported that the staff usually carry out some maintenance which they can manage; however, in certain areas of maintenance it has been identified that the most effective maintenance is to be done by a specialist, as the specialist carry the maintenance in more professional way as they have the experience on the machine or equipment they maintained.

Added that crew can prevent maintenance from being successful as substandard crew can cause big problems. Therefore the quality of the crew is very important factor in measuring the maintenance performance as they can provide good or bad maintenance depending on their skills and knowledge.

The fourth issue is dealt with how the shipping companies measuring the maintenance performance in their organizations, in the small companies KTTL and Gulf rocks, the experts insisted that the most important measure is the maintenance budget as budget can give good indication on how good the maintenance has been done for the fleet they own. Whereas in KOTC have a different measure they are applying the TMSA.

The expert agreed on the key performance indicators from literature given in the interview which measures the maintenance in the marine shipping industry. The indicators are reliability, maintainability, availability, failure, downtime, maintenance budget, and safety and environments.

The experts added that other indicators are important to consider, such as satisfaction of classification requirement, the scheduling of maintenance, the human factor, the availability and quality of spares, ship operation, and volume of communication.

The fifth issue discussed in this interview was the maintenance planning factors; maintenance planning can be done in optimum way to reduce the maintenance costs and to maximize the ship availability which will eventually maximize the shipping company revenue. Identifying the factors which influence on the planning is very important.

The maintenance planning factors are divided into two main types, firstly some factors can be controlled and the cost can be reduced by applying an optimising technique, and other factors are out of control, and the cost can only be optimized to some degree due to some limitation involves.

Examples of uncontrolled factors are ship age, ship size, ship type, utilization of the ship, and the influence on the classification society.

The controlled factors are ship maintenance scheduling, selecting maintenance strategy, quality of maintenance carried out, considering the maintenance from ship construction, number of crew and crew composition, selecting ship repair yard and its location, the life cycle of the equipment's, the recommendation from the manufacturing company, the average time for operating the machine, and maintenance costs and budget.

The expert's comments that all factors are important factors but the maintenance scheduling and the quality of work are more important among all the factors. Therefore good maintenance scheduling for the ships or for equipments within the ship can give good optimization results. In addition the quality of the work or maintenance carried out is very important, therefore improving in the quality of maintenance can save money and time.

4. SHIP MAINTENANCE PERFORMANCE MEASUREMENT INDICATORS

In this section, ship maintenance performance measurement indicators are identified and then categorized in to criteria. Different hierarchical levels of the organization are used to measure these indicators.

The criteria used are identified based on abduction research methodology which combines the literature survey and interviews conducted with the three Kuwaiti marine shipping companies.

From both literature survey and interviews ten criteria which can be used in ship maintenance performance measure were devised. Those criteria can provide clear vision for the decision maker. The ship maintenance measuring performance criteria and their indicators are listed in Table 1.

Table 1: Criteria with the ship maintenance measuring performance indicators

Criteria	Source	Maintenance Performance Indicators
Maintenance strategy.	Interviews.	• Maintenance strategy costs. • Planned maintenance. • Unplanned maintenance. • Emergency maintenance.
Dry docking scheduling.	Interviews.	• Dry docking costs. • Dry docking time. • Selection of ship yard. • Ships availability.
Budget and cost.	Literature review (Kaplan and Norton 2001) and Interviews.	• Maintenance budget/operation budget. • Maintenance budget. • Maintenance cost.
Ships equipments.	Literature review (Kutucuoglu et al. 2001).	• Downtime. • Availability. • Breakdowns. • Spare parts.
Customer satisfaction.	Literature review (Kaplan and Norton 2001) and Interviews.	• Customer complaints. • Customer penalties. • Customer satisfaction. • New customer addition.
Staff (Employee).	Literature review (Sinclair and Zairi 1995) and Interviews.	• Staff retention. • Staff complaints.
Health safety and environment (HSE).	Literature review (Parida and Kumar 2006).	• Number of accidents and incidents. • Number of legal cases. • Compensation paid. • HSE complaints.

Learning and growth.	Literature review (Kaplan and Norton 2001)	• New ideas generation. • Skill improvement training.
Classification requirements.	Interviews.	• Classification satisfaction. • Expired certificates. • Certificates dates.
Ships operation and demand.	Interviews.	• Shipment delays. • Port authority penalties. • Ships readiness.

5. CONCLUSIONS

This paper presents an examination of the issues associated with the performance measurement of maintenance operations in mercantile companies. The initial findings, which, were based on a literature survey and interviews held with managers at the strategic, corporate and tactical level reveal a wide range of potentially influential factors.

An interpretive approach was used to identify the ship maintenance performance measurement indicators. The selection of criteria was biased to satisfy the requirement of this research paper. In all, ten specific criteria (and their associated indicators) were established; this provides an informative insight into the factors that maintenance planning decision-makers should be considering in developing effective schedules.

Whilst the findings may possibly be generalised to other similar organisations, it should be noted that the case study findings exert a significant influence upon the conclusions drawn here.

Further research, development of ship maintenance performance measurement framework (SMPM) can be more appropriate as it can explore the ship maintenance performance indicators in more details and enable the decision maker to weight and measure the maintenance performance in their organization in an effective way.

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SHIP MAINTENANACE COST OPTIMIZATION

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Introduction

The maintenance function has been the servant of the engineering profession. It enables the machinery in the industry to operate with reliable and safe performance at specific maintenance cost. Depending on the nature of the system, maintenance action can be planned, the following Figure 1 shows the maintenance types and how they are linked to each other:

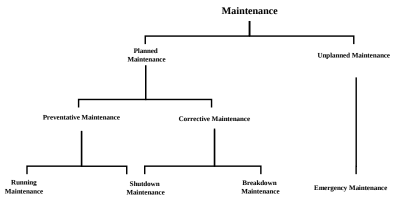

Figure 1: Types of maintenance (White, 1979)

Optimization:

The increase demand of maintenance results in a grow of the maintenance cost which have to be considered. So balancing between maintenance and cost of maintenance is an important issue, so an optimizing method is needed to overcome this type of problem. Figure 2 the basic age repair/replace model.

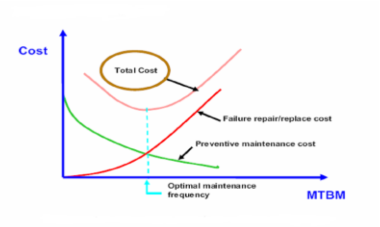

Figure 2: the basic age repair/replace model (McCall, 1964)

Ship Maintenance:

Ship maintenance and ship repair can be done in two different ways see Figure 3.

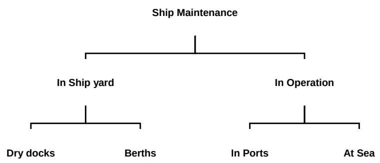

Figure 3: Ship Maintenance

Element Of Ship Maintenance:

Maintenance of a ship varies, the following figure shows what parts of Oil Tanker in general needs maintenance Figure 4.

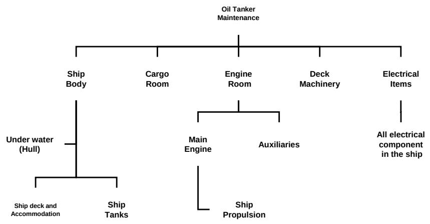

Figure 4: Oil Tanker Maintenance

Ship Maintenance Costs:

Ship maintenance costs are identified within the operation costs. The operation costs are classified in to controllable and uncontrollable costs and the maintenance costs are classified as direct measurable and indirect measurable costs. An example was given and result showed that 42% of the operation costs are a maintenance costs and 72% of the maintenance costs are controllable.

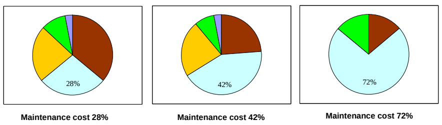

Figure 5: Maintenance cost comparison for Bulk Carrier 75,000 tons (Shields et al., 1996)

Conclusions:

- **Maintenance costs are the largest item in the operating cost.**
- **The majority of this cost is controllable.**
- **Attention should be made to the maintenance in order to reduce that cost which benefits the shipping company.**
- **Good maintenance specification can safe a lot of money to the shipping company.**
- **Finally consideration should be given to the maintenance planning as it is very crucial for maintaining the ship operation and minimizing the cost of its maintenance.**

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