A SIMULATION MODEL OF THE MAINTENANCE CYCLE OF ROYAL MALAYSIAN NAVY SHIPS

by

MAHAMUD SAYUTI ABD. HALIM

Thesis submitted in fulfilment of the
requirements for the degree
of Master of Science

December 1993

ACKNOWLEDGEMENTS

I am very grateful and thankful to my supervisor Associate Professor Dr. Tan Kok Chye for his invaluable advice, suggestions, directions, guidance, assistance, patience, understanding and encouragement in completing this thesis. I would also like to thank my co-supervisor, Associate Professor Dr. Kuan Kee Sin for his help and concern.

I wish to thank the Ministry of Defense for its financial assistance. This research would not have been possible without the facilities provided by the University of Sciences of Malaysia, and the school of Mathematical and Computer Sciences, in particular.

Finally, I would like to dedicate this thesis to my beloved wife, Hawa, and children for their support. They have shown the encouragement that has lifted me through some of the discouraging moments that can occur in an activity such as thesis writing.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
ABSTRAK	vii
ABSTRACT	ix
CHAPTER ONE - INTRODUCTION	1
1.1 BACKGROUND	1
1.2 CATEGORIES OF SHIPS	2
1.3 MAINTENANCE CATEGORIES	2
1.4 MAINTENANCE ORGANIZATION	4
1.5 EXISTING PREVENTIVE MAINTENANCE POLICY CYCLE	7
1.5.1 Definition	7
1.5.2 Milestone	10
1.6 WORKSCOPE FOR SHIP UNDERGOING PREVENTIVE MAINTENANCE ROUTINES (SLIPPING/DED/REFIT AND LONG REFIT)	12

1.7 SHIPYARDS 13

1.8 SPARES REQUIRED FOR MAINTENANCE ROUTINE AT SHIPYARD 14

1.9 CONSTRAINT 14

1.10 THE STATEMENT OF THE PROBLEM 15

1.11 PURPOSE OF THE RESEARCH 15

1.12 SCOPE OF THE RESEARCH 16

CHAPTER TWO - MAINTENANCE 17

2.1 INTRODUCTION 17

2.2 DEFINITION OF MAINTENANCE 17

2.3 IMPORTANCE OF MAINTENANCE 18

2.4 OBJECTIVE OF MAINTENANCE 19

2.5 CLASSIFICATION OF MAINTENANCE 20

2.6 MAINTENANCE POLICIES 22

CHAPTER THREE - ACTUAL MAINTENANCE CYCLE 26

3.1 INTRODUCTION 26

3.2 PREVIOUS DATA OF CAPITAL SHIPS 27

3.3 PREVIOUS DATA OF FAC CLASS SHIPS 31

3.4 FACTORS AFFECTING MAINTENANCE TIME OF SHIPS UNDERGOING PREVENTIVE MAINTENANCE ROUTINE AT SHIPYARDS 38

3.5 DISCUSSION 47

CHAPTER FOUR - SELECTING INPUT PROBABILITY DISTRIBUTION 48

4.1 INTRODUCTION 48

4.2 KOLMOGOROV - SMIRNOV (K - S) TEST 50

4.3 IDENTIFICATION OF OUTLIERS 53

4.4 DETERMINATION OF DISTRIBUTION FITTINGS OF SHIPS VARIOUS ACTIVITIES 54

4.4.1 Capital Ship Various Activities 55

4.4.2 FAC CLASS Various Activities 60

4.5 DISCUSSION 68

CHAPTER FIVE - SIMULATION MODELING 69

5.1 INTRODUCTION 69

5.2 SIMULATION MODEL 70

5.2.1 Statement Of The Problem 70

5.2.2 Approach Taken In Building The Model 72

5.2.3 Extended Program Listing 74

5.2.4 Program Output 75

5.3 OUTPUT ANALYSIS 75

5.3.1 Analysis Of Capital Ship Model Output 79

5.3.2 Analysis Of FAC CLASS Model Output 88

5.4 DISCUSSION 91

CHAPTER SIX - GENERAL DISCUSSION 94

6.1 DISCUSSION 94

6.2 CONCLUSION 109

REFERENCES 111

APPENDICES

APPENDIX A : Delay of Ship in Shipyard due to Long Awaiting of Spare Parts and Technical

Problem. 114

APPENDIX B : Kolmogorov - Smirnov Test (Kreyszig, 1970) 118

APPENDIX C1 : Simulation Logic Diagram for Capital Ship 119

APPENDIX C2 : Extended Program Listing for Capital Ship 122

APPENDIX C3 : Simulation Output of Capital Ship 156

APPENDIX D1 : Extended Program Listing for FAC CLASS 160

APPENDIX D2 : Simulation Output of FAC CLASS 194

APPENDIX E1 : Sampling from the Normal Distribution for GPSS 199

APPENDIX E2 : Sampling from the Lognormal Distribution: Via Normal for GPSS 204

APPENDIX F : Individual Batch Means (Y_{rj}) for Capital Ship Cycle Simulation with Empty and Idle Initial State. 207

APPENDIX G : Summary of Data for Capital Ship Cycle Simulation: Batch Means and Cumulative Means, Averaged over 10 Replications 211

APPENDIX H : Data Summary for Capital Ship Cycle Simulation by Replication 216

APPENDIX I : Individual Batch Means (Y_{rj}) for FAC CLASS Cycle Simulation with Empty and Idle Initial State. 219

APPENDIX J : Summary of Data for FAC CLASS Simulation: Batch Means and Cumulative Means, Averaged over 10 Replications 213

APPENDIX K : Data Summary for Capital Ship Cycle Simulation by Replication 230

MODEL SIMULASI KITARAN SENGGARAAN KAPAL-KAPAL

TENTERA LAUT DI RAJA MALAYSIA

ABSTRAK

Pada masa ini perancangan dan pengskedulan kapal-kapal Tentera Laut Di Raja Malaysia (TLDM) untuk rutin penyenggaraan cegahan, iaitu Slipping, DED dan Refit di limbungan, dilakukan dengan berpandukan kepada kitar polisi yang sedia ada yang mana mempunyai kekangan iaitu maksimum 1/3 daripada jumlah kapal boleh menjalani rutin senggaraan di limbumgan pada sesuatu ketika. Tetapi pada hakikat perlaksanaannya, iaitu masa sebenar yang diambil untuk menjalani satu kitar selalunya lebih daripada kitar polisi yang sedia ada oleh kerana pelbagai sebab. Oleh yang demikian, TLDM menghadapi masalah membuat perancangan dan pengskedulan kapal-kapal untuk rutin senggaraan berjadual dan juga keperluan operasi.

Oleh yang demikian adalah perlu untuk membuat kajian bagi mengatasi masalah ini. Di dalam penyelidikan ini, kami menentukan sama ada kitar polisi yang sedia ada boleh diikuti. Jika kitar polisi yang sedia ada tidak boleh diikuti oleh kerana faktor-faktor yang tidak dapat dielakkan, maka satu model simulasi akan dibina untuk mencadangkan kitar baru berdasarkan kepada kepada data-data yang sedia ada supaya perancangan dan pengskedulan kapal-kapal untuk rutin senggaraan dan juga

keperluan operasi dapat dilaksanakan dengan lebih cekap dan berkesan. Tambahan kepada itu, kami akan menentukan juga purata masa setiap kapal menunggu di dalam giliran untuk rutin senggaraan dan kesan penambahan jumlah bilangan kapal ke atas jumlah masa kitar.

95 % selang keyakinan untuk anggaran masa Refit, DED/Slipping, masa operasi, purata masa menunggu dan jumlah masa kitar juga dikaji dengan menggunakan kaedah simulasi.

ABSTRACT

Currently, the planning and scheduling of Royal Malaysian Navy (RMN) ships for preventive maintenance routine, i.e. Slipping, DED and Refit at shipyard, is done based on the existing policy cycle which has the constraint that a maximum of 1/3 of the total number of ships could undergo maintenance routine at shipyard at any one time. Unfortunately in actual practice, i.e. the actual time taken to go through the cycle is usually more than that of the existing policy cycle due to various reasons. As a result of this, RMN run into difficulties in the planning and scheduling of ships for preventive maintenance routine as well as operational requirement.

There is therefore a need to study ways to overcome this problem. In this research, we determine whether the existing policy cycle can be followed. If the existing policy cycle cannot be followed due to unavoidable factors, then a simulation model is to be developed to propose a new cycle based on the previous available data so that planning and scheduling of ships for maintenance routines as well as operational requirement could be carried out more efficiently and effectively. In addition, we will also determine the average time each ship spent waiting in the queue for maintenance routine, and the effect of increasing the total number of ships on the total cycle time.

The 95 % confidence interval for mean time estimate of the Refit, DED/Slipping, Operational time, average waiting time and total cycle time are also studied using simulation approach.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The Royal Malaysian Navy (RMN) has expanded rapidly to keep abreast with current developments in the region with respect to security. Many new and modern sophisticated ships and equipment are acquired to arm the RMN in order to transform it into a deterrent force for stability, both politically and economically. These ships and equipment are mostly built and supplied by foreign countries and inevitably have made the RMN to be very dependent on foreign technologies and materials. In order to maximize the utilization of the resources available, a very effective and efficient maintenance management system has to be developed. This system may have to be reviewed at a later date when required.

Although the RMN has both locally and overseas trained personnel in various fields of specialization, the operational readiness of ships and equipment is still not satisfactory. This is because many other factors such as maintenance standards, logistics support and disruption of maintenance routine due to operational requirements have contributed to such discrepancies.

1.2 CATEGORIES OF SHIPS

The RMN ships are divided into two main categories namely Capital Ships and Small Ships. The various types of Capital Ships and Small Ships are shown in Table 1.1 and 1.2 respectively.

1.3 MAINTENANCE CATEGORIES

There are three types of maintenance categories carried out by the RMN ships.

Preventive Maintenance (Time and Occasion). Preventive Maintenance (PM) is applicable to equipment which, for operational or safety reasons, must have a low risk of failures or for which maintenance must match a specific occasion such as docking. It is based on calendar time or 'hours run'. PM is carried out based on Planned Maintenance Schedule (PMS). The PMS specifies what preventive maintenance operations are needed, its frequency and who should carry out the operations.

Corrective Maintenance (Monitored Wear-Out). Corrective maintenance is applicable to equipment which can conveniently be repaired or replaced outside the dockyard programme upkeep period, and for which a marginally increased risk of breakdown, is acceptable because redundancy has been built in, or the system that it serves does not significantly affect the operational status. Corrective maintenance is based upon needs, as judged by the ship's engineering officers with the aid of

Table 1.1: Types and Names of Capital Ships

TYPE	NAME
CORVETTE	KD KASTURI KD LEKIR
MPSS (MULTI PURPOSE SUPPLY SHIP)	KD SRI INDERA SAKTI KD MAHAWANGSA
LST (LANDING SHIP TANK)	KD RAJA JAROM KD SRI BANGGI
OPV (OFFSHORE PETROL VESSEL)	KD MARIKH KD MUSYTARI
SURVEY SHIP	KD MUTIARA

Table 1.2: Types and Names of Small Ships

TYPE	NAME
FAC G (FAST ATTACK CRAFT (GUN))	KD PAUS KD YU KD JERONG KD TODAK KD PARI KD JERONG
FAC 1M (FAST ATTACK CRAFT 1 (MISSILE)	KD PERDANA KD SERANG KD GANAS KD GANYANG
FAC 2M (FAST ATTACK CRAFT 2 (MISSILE)	KD HANDALAN KD PENDEKAR KD PERKASA KD GEMPITA
PC (PATROL CRAFT)	
OTHER SMALL SHIPS	

appropriate condition monitoring and assessment techniques available.

Breakdown Maintenance (Natural Wear-Out). Breakdown maintenance is applicable to equipment whose breakdown will not affect the fighting efficiency and the safety of the ship.

1.4 MAINTENANCE ORGANIZATION

The main maintenance organization of RMN is shown in Figure 1.1. Fleet Material Command (FMC) is a division within the Royal Malaysian Navy (RMN), primarily responsible for recording, updating, retrieval and maintenance of at least the following information:

(i) RMN's ship and equipment repairs information.

(ii) RMN's ship and equipment maintenance information.

(iii) RMN's ship and equipment testing information.

There are eight main divisions under the auspices of Fleet Material Command, namely:

1. *Administrative Authority (ADMIN).* This department undertakes the administrative tasks of the Fleet Material Command.

2. *Fleet Trial Authority (FTA).* This department performs tests on ships and equipment.

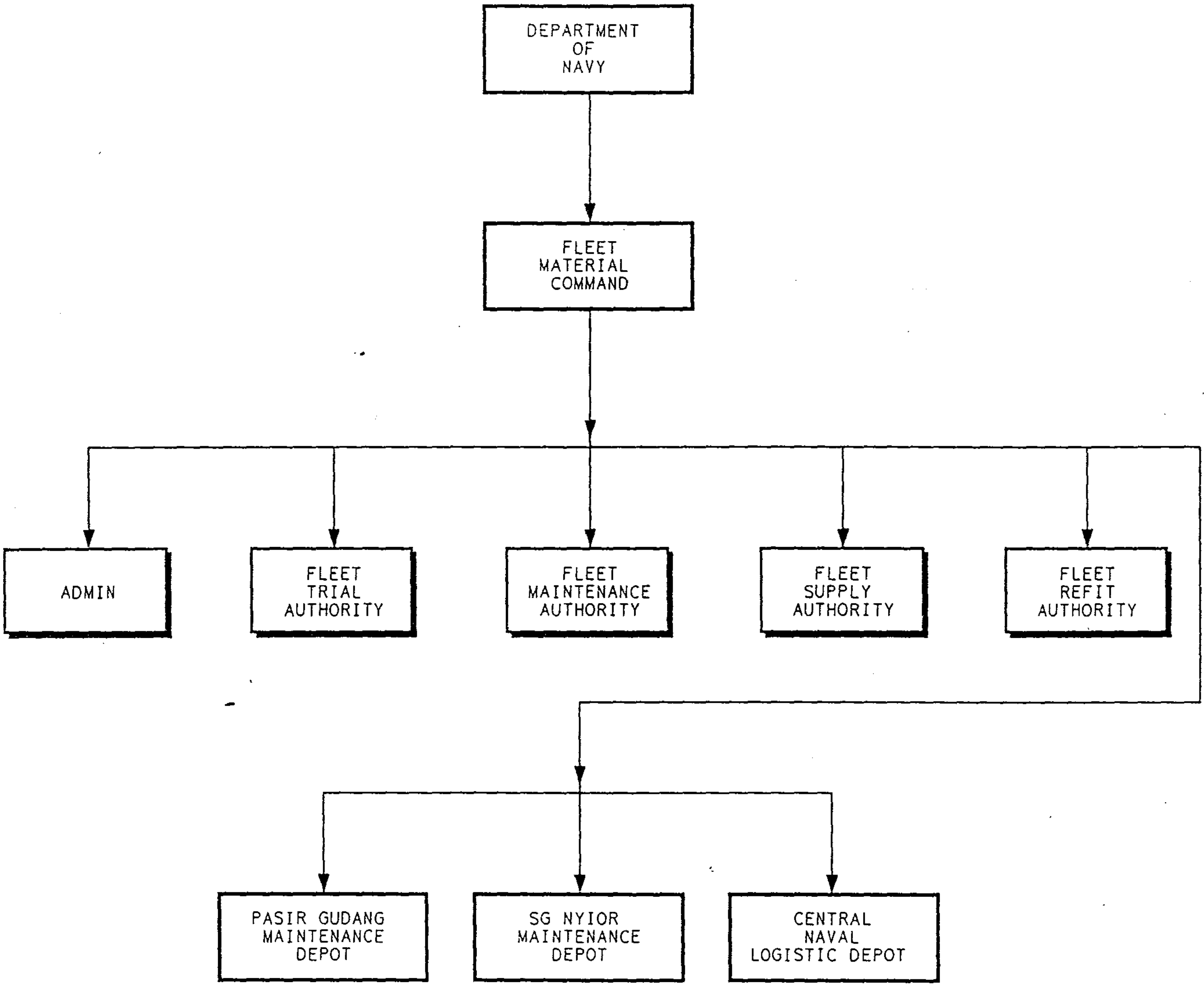

Figure 1.1 : RMN Main Maintenance Organization

3. *Fleet Maintenance Authority (FMA).* This department prepares, records and manages the following: information regarding ships or units, ship's system, equipment history, main defects, equipment, Planned Maintenance Schedule (PMS), standard materials, equipment specification, maintenance documents, document circulation and running hours of main equipment.

4. *Fleet Supply Authority (FSA).* This department keeps track of inventory and supply on behalf of the Fleet Material Command.

5. *Fleet Refit Authority (FRA).* This department prepares Standard Defect List (SDL), Material Preparation (MATPREP) List; schedule time for refitting, DED or slipping and it keeps track of repair status, etc.

6. *Sg.Nyior Maintenance Depot.* This depot is responsible for overseeing the small ships undergoing maintenance routine at shipyards in the northern region.

7. *Pasir Gudang Maintenance Depot.* This depot is responsible for overseeing the small ships undergoing maintenance routine at shipyards in the southern region.

8. *Central Naval Logistic Depot (CNLD).* This department reviews additional parts requisition from the Principal Naval Overseer (PNO), performs stock check and sends available parts to the PNO. PNO monitors works carried out at shipyard.

1.5 EXISTING PREVENTIVE MAINTENANCE POLICY CYCLE

The existing preventive maintenance policy cycle for capital ships and FAC class are shown in Figure 1.2 and Figure 1.3 respectively.

1.5.1 DEFINITION

DED (Docking and Essential Defects). DED is a repair routine for the hull of the ship below water level and for urgent defects including Alterations and Additions performed on capital ships only. Its duration requires a time frame of 10 weeks (2 weeks Pre DED, 6 weeks DED and 2 weeks Post DED).

Slipping. Slipping is a repair routine for the hull of the ship below water level and for urgent defects including Alterations and Additions performed on small ships only. Its duration requires a time frame of 6 weeks (1 week Pre Slipping, 4 weeks Slipping and 1 week Post slipping).

Refit. Refit is a repair routine for the following activities:

a. Repairs of ship's body and equipment based on the Planned Maintenance Schedule (PMS)
b. Repair defects that are beyond ship staffs (crew) or base staff (support from the base) capability to repair.
c. Alterations and Additions.

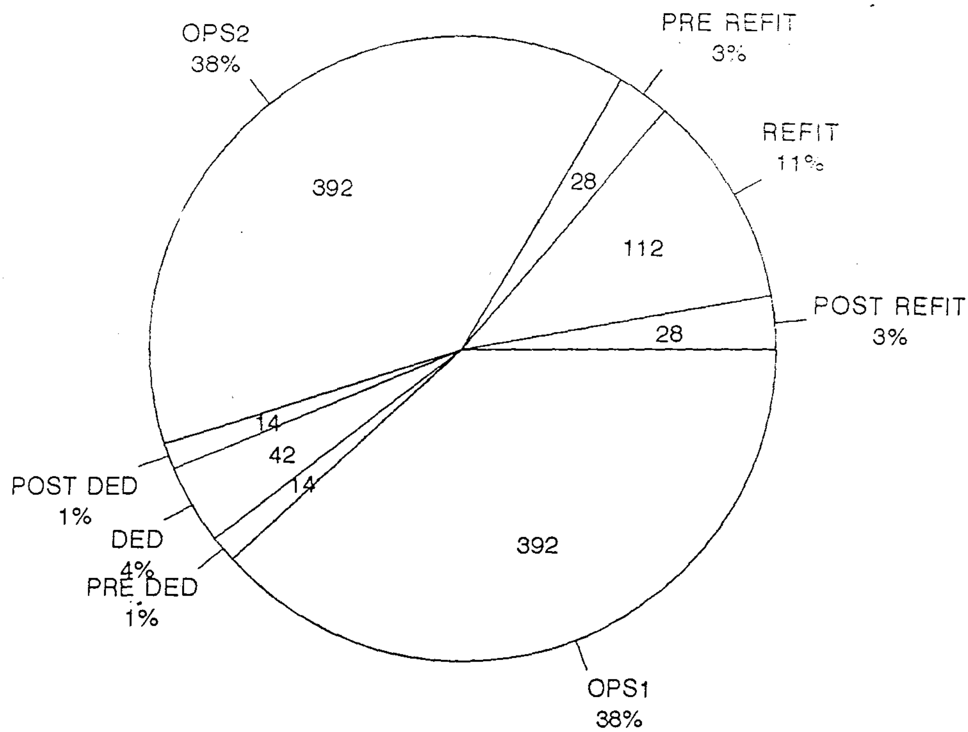

Figure 1.2: Capital Ship Existing Policy Cycle (Total Cycle Time is 1022 Days)

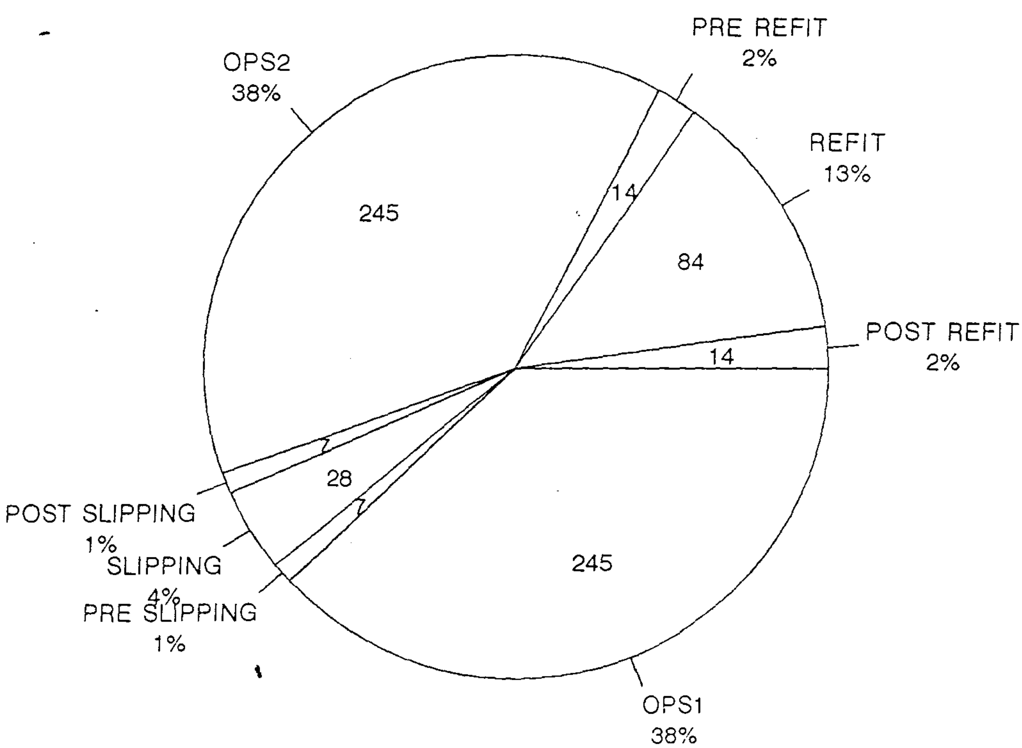

Figure 1.3: FAC CLASS Existing Policy Cycle (Total Cycle Time is 644 Days)

The refit routine covers the following activities:-

	Capital Ships (24 weeks)	Small Ships (16 weeks)
a. Pre Refit	4 weeks	2 weeks
b. Refit	16 weeks	12 weeks
c. Post Refit	4 weeks	2 weeks

Long Refit. Long Refit is a repair routine for the ship's body and equipment based on the PMS and other defects including Alterations and Additions. A thorough examination is performed to determine if enhancements are required. The time frame required is similar to that of the refit process. This routine is carried out after the refit process is performed twice.

Ship operational time (OPS). OPS is applicable to both capital ships and small ships. OPS1 is the operational time immediately after refit and before DED/slipping. OPS2 is the operational time immediately after DED/slipping and before refit.

Pre slipping/DED/Refit. The activities carried out during this period are as follows:

a. To conduct Harbour Acceptance Trial (HAT) and Sea Acceptance Trial (SAT) to determine the status of the equipment on board the ship and to determine any new defects so that they could be included in the First Supplementary Defect List (1st Supp).

b. To finalize the workscope before the ship enter the shipyard.

c. To destore fuel, ammunition and spares kept on board which are not required for the maintenance routine.

d. To remove guns and electronic equipment if necessary.

e. To collect available spares required for the maintenance routine at CNLD.

f. To make final preparation before sailing to the shipyard.

Post slipping/DED/Refit. The activities for this duration are as follows:

a. To restore fuel, ammunition and spares which have been destored before the maintenance routine.

b. To conduct post slipping/DED/refit meeting to determine the status of the ship and any problem that may arise.

c. To carry out fumigation of the ship if necessary.

d. To carry out Gun Functional Trial in order to determine the status of the weapon system.

e. To carry out degaussing, compass swing, measured miles and full load trial.

1.5.2 MILESTONE

Figure 1.4 shows the major milestone leading up to Start Date of Refit or DED/Slipping.

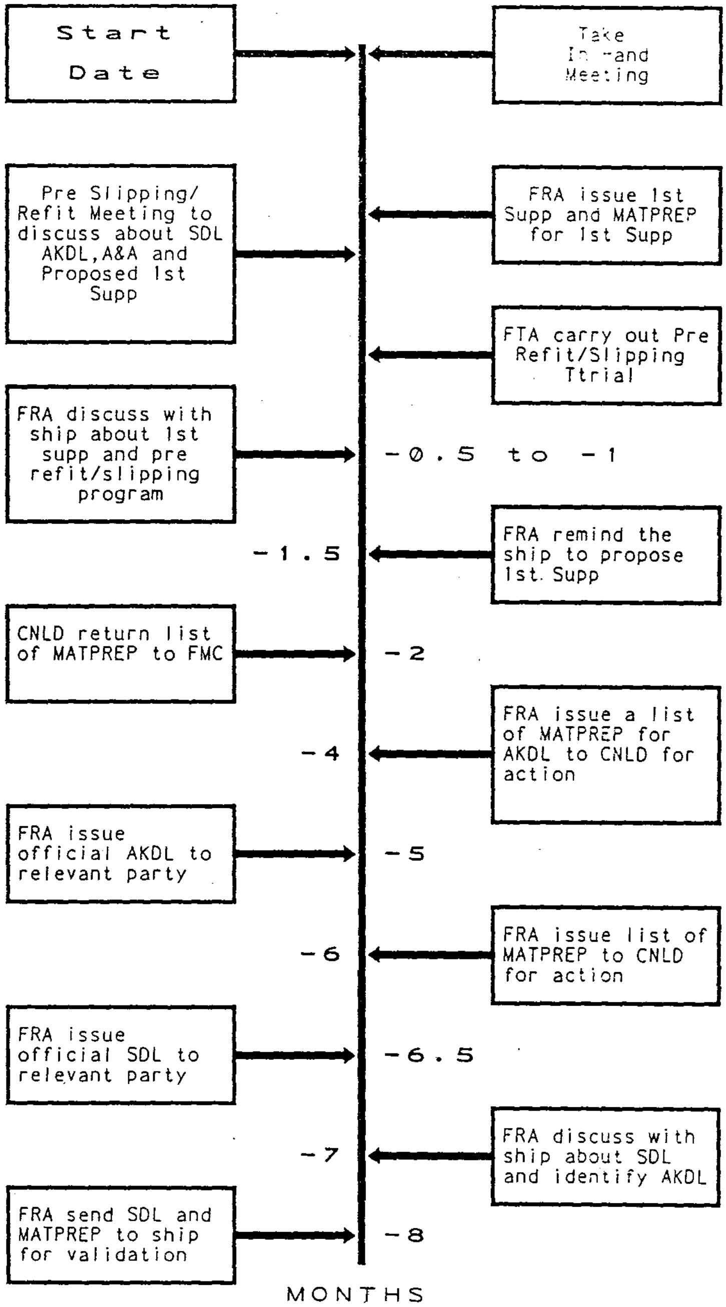

Figure 1.4: Major Milestones to Start Date for Maintenance Routine

1.6 WORKSCOPE FOR SHIP UNDERGOING PREVENTIVE MAINTENANCE ROUTINES (SLIPPING/DED, REFIT AND LONG REFIT)

The workscope for ships undergoing maintenance routine in shipyards comprise of the followings:

1. *Standard Defect List (SDL).* It contains the workscope based on Planned Maintenance Schedule (PMS). This list is produced 6 1/2 months before the *start date* of the maintenance routine. Based on this SDL, the Fleet Refit Authority (FRA) will produce the SDL-Material Preparation (MATPREP) List.

2. *Additional Known Defect List (AKDL).* A list of defects of main equipment. An additional document known as AKDL-MATPREP is produced after the final AKDL. Final AKDL is prepared 5 months before the *start date* of maintenance routine.

3. *First Supplementary Defect List (1st Supp).* This list contains additional defects which occur after the AKDL has been prepared and could not be rectified before the ship goes to the yard for maintenance routine. From this, the 1st Supp Matprep is also produced.

4. *Alterations and Additions .* Alterations and Additions make a change of equipment fitted in a ship or change to the structure of the ship to improve, for example, operational efficiency or habitability. Alterations and Additions normally require a change to 'as fitted' drawing.

5. *Supplementary Work Order.* In the execution of the above works, a number of ship's fittings and equipment are subjected to surveys and examinations. Resulting from these surveys and examinations, further defects may be discovered and the extend of rectification is to be carried out and ascertained. Such rectification works are carried out under supplementary work order.

1.7 SHIPYARDS

The various yards capable of undertaking RMN ships for maintenance routines are shown in Table 1.3. All these shipyards are commercial shipyards. Capital ships could only go to class A shipyards, whereas FAC class ships could go to either class A or class B shipyards for their preventive maintenance routine. There are also other shipyards lower than class B which are meant for other small ships and are therefore not listed here. The shipyards listed in Table 1.3 can also be categorized both as shiprepairers and also shipbuilders.

Table 1.3: Various Yards Capable of Undertaking Capital Ships and FAC Class for Maintenance Routine

YARD	CLASS	SHIPS
NAVAL DOCKYARD,LUMUT,PERAK	A	CAPITAL SHIP & FAC CLASS
MALAYSIAN SHIPYARD ENGINEERING, JOHOR	A	CAPITAL SHIP & FAC CLASS
SABAH SHIPYARD,LABUAN	A	CAPITAL SHIP & FAC CLASS
HONG LEONG LURSEN SHIPYARD, BUTTERWORTH	B	FAC CLASS
PENANG SHIPBUILDING CORPORATION, PENANG	B	FAC CLASS

1.8 SPARES REQUIRED FOR PREVENTIVE MAINTENANCE ROUTINE AT SHIPYARD

All spare parts required for the maintenance routine i.e. slipping, DED, refit and long refit are supplied by the Central Naval Logistic Depot (CNLD) except for standard engineering material such as plating, screws, nuts, grease, certain type of hoses, basic electrical components such as resistors, capacitors, inductors, bulbs, etc. are to be supplied by the shipyard. Occasionally, at the discretion of the RMN, a Non Availability Certificate, an authority for shipyard to purchase certain spares for the maintenance routine being carried out is issued to the yard if the yard could supply them earlier than the RMN sources.

1.9 CONSTRAINT

The Fleet Operational Command has imposed a condition that at least 2/3 of the total number of ships must be operational at any one time. This implies that only a maximum of 1/3 of the total number of ships are allowed to be in shipyards undergoing preventive maintenance routine, i.e. Slipping/DED, Refit or Long Refit. Since there are 9 capital ships and 14 FAC CLASS ships, this means that only a maximum of 3 capital ships and 4 FAC CLASS ships are allowed to undergo preventive maintenance routine at shipyard at any one time.

1.10 THE STATEMENT OF THE PROBLEM

At present the planning and scheduling of ship for preventive maintenance routine, i.e. slipping, DED, refit and long refit at shipyard, is done based on the existing policy cycle for capital ships and FAC CLASS are shown in Figures 1.2 and 1.3 respectively. Unfortunately, the actual time taken by the ship going through the cycle is not following the existing policy cycle due to various reasons which will be discussed in chapter 3. This makes the planning and scheduling of ships for preventive maintenance routine as well as operational requirements very difficult, inefficient and ineffective.

1.11 PURPOSE OF THE RESEARCH

The main aim of the research is to determine whether the existing policy cycle of the ship as shown in Figures 1.2 and 1.3 for capital ships and FAC CLASS ships respectively can be followed. If the existing policy cycle cannot be followed due to unavoidable factors, then a simulation model is to be developed to propose new cycles for both the capital ships and FAC CLASS based on the previous available data so that the planning and scheduling of the ships for preventive maintenance routine i.e. slipping, DED, refit and long refit as well as operational requirement could be carried out more efficiently and effectively.

In addition, this research will assist the RMN in determining the following information accurately:

1. The average time that each ship spends waiting in the queue for maintenance routine at shipyard if she has to wait due to the constraint mentioned in Section 1.9 so that she could be deployed for operational requirement.

2. The effect of increasing the total number of ships on the total cycle time.

1.12 SCOPE OF THE RESEARCH

Royal Malaysian Navy ships are divided into various categories as described in section 1.2. In planning and scheduling of ships for preventive maintenance routine subject to operational requirement, each of these categories has to be carried out separately. Due to the large amount of data and time that may be required in order to study and to model the whole system, this research will focus on the capital ships and the FAC CLASS only. The same method can be used for other categories of ships.

CHAPTER TWO

MAINTENANCE

2.1 INTRODUCTION

We started thinking more seriously about maintenance after the last war but it was not until 1957 that there was a British technical journal to deal with it, nor until 1961 there was a national conference about it (Parkes, 1968). In this chapter we will find out useful information about maintenance and study various analysis of maintenance by previous researchers.

2.2 DEFINITION OF MAINTENANCE

Maintenance is defined by British Standard (1964) *Glossary of Terms used in Maintenance Organization* as work undertaken in order to keep or restore every facility, i.e. every part to an acceptable standard. Bovaird (1961) defines maintenance as an act of prevention and repair. Monks (1987) defined *maintenance* as any activity designed to keep resources in working condition or restore them to operating status. This does not necessarily mean that everything should be in the absolute best operating condition with all new parts so that breakdown never occur, that is infeasible from a practical standpoint. It does, however, mean that maintenance activities should be evaluated in light of the goals (and costs) of the total system of facilities, equipment and people. In many cases the system goals are best satisfied by minimizing long-run maintenance costs. At other times safety considerations, reliability, or short-term economic conditions may be overriding criteria.

2.3 IMPORTANCE OF MAINTENANCE

Today the question, 'is maintenance necessary?' is increasingly being asked. It has been estimated that somewhere in the region of 12,000 million pounds per annum is spent on maintenance of equipment in British industry. This may appear to be a large figure and to offer scope for considerable savings. Even a 1 per cent saving would amount to 20 million pounds. Unfortunately the problem is not as easy as this for two reasons: (i) we do not know the magnitude of the true benefits obtained from any level of investment in maintenance services; a 1 percent saving is only useful if the benefits are not reduced by an amount exceeding this; (ii) we do not know the magnitude of the work involved in specific areas of maintenance, let alone in the area as a whole, in studies aimed at improving performance, either in terms of improved benefits, for the same cost, or reduced cost, for the same benefits, or in terms of cost/benefit mixtures (White, 1968).

Jardine (1973) gave an example that, replacement of a piston ring in a car engine before failure of the ring may only involve the piston ring charge plus a labour charge, whereas after failure its replacement cost may also include the cost of a cylinder rebore.

2.4: OBJECTIVE OF MAINTENANCE

The objectives of maintenance engineering given by United Nations Industrial Development Organization (UNIDO) (1971) are as follows:

1. To extend the useful life of equipment. This is particularly important for developing countries in view of their lack of capital.
2. To ensure the optimum availability of installed equipment for production. Developing countries should aim at getting the maximum possible return from investment.
3. To ensure instant operational readiness of all equipment for emergency use. For example standby units, rescue units etc.
4. To ensure safety of personnel.

The first two objectives must obviously be carried out economically, i.e. maintenance should result in a reduction of the overall operational cost. The prevailing thinking in many developing countries, and perhaps also in some developed countries, is that maintenance problems demand solutions that are primarily engineering or technical. The exclusive pursuit of a policy based on such thinking may bring with it the danger that the economic as well as the managerial and organizational aspects of maintenance will be carried out.

Of the various approaches and techniques employed to attain adequate maintenance, the first and most important is maintenance prevention. Efficiency does not mean doing unnecessary tasks ten times better. Maintenance prevention starts at the design and purchase stages. Study of repeated failures with a view to reducing their occurrence through change of design or material or both, improved working conditions, and training of maintenance and operational personnel are important steps towards attaining maintenance prevention after the equipment has been put into operation.

Maintenance work that is not eliminated by maintenance prevention must be planned. Several approaches and techniques can be used: preventive maintenance, corrective maintenance, etc.

2.5 CLASSIFICATION OF MAINTENANCE

Maintenance can be classified into three different types:

Preventive maintenance (PM). PM represents those inspections and work that is planned in order to prevent a sudden failure of equipment. A successful preventive maintenance program will result in a reduction in equipment failures. It will also result in longer service life of production equipment and more total hours of use prior to retirement from service (Niebel, 1985). Monks (1987) defines PM as the routine inspection and service activities designed to detect potential failure conditions and make minor adjustments or repairs that will help prevent major operating problems. An effective preventive maintenance program for equipment requires proper trained personnel, regular inspections and service and an accurate records system.

The principal objectives of preventive maintenance include (Niebel, 1985):

1. To minimize the number of breakdowns on critical equipment.
2. To reduce the loss of production that occurs when equipment failures take place.
3. To increase the productive life of of all capital equipment.
4. To acquire meaningful data relative to the history of all capital equipment so that sound decisions as to repair, overhaul, or replacement can be made so as to maximize the return on capital investment.
5. To permit better planning and scheduling of required maintenance work.
6. To promote better safety and health of the work force.

Corrective maintenance (CM). CM has been defined as that which is carried out when equipment fails, or falls below an acceptable condition, while in operation (Kelly and Harris, 1978).

Breakdown maintenance (BM). BM is the repair, often of an emergency nature and at a cost premium, of facilities and equipment that have been used until they fail to operate (Monks, 1987).

2.6 MAINTENANCE POLICIES

Various maintenance policies have been proposed to reduce the occurrence of system failure. The policies of age replacement, block replacement and periodic replacement with minimal repair at failure have been particularly important. Age replacement policy is in force if a unit is always replaced at the time of failure or T hours after its installation, whichever occur first; T is a constant unless otherwise specified. If T is a random variable, we shall refer to the policy as a *random age replacement* policy. Under a policy of *block replacement* the unit is replaced at times kT (k = 1,2,...), and at failure. This replacement policy derives its name from the commonly employed practice of replacing a block or group of units in a system at prescribed times kT (k = 1,2,...) independent of the failure history of the system (Barlow and Proschan, 1965). Barlow and Hunter (1960c) introduce the notion of periodic replacement or overhaul with minimal repair for any intervening failures. In this model it is assumed that the system failure rate remains undisturbed by any repair of failures between the periodic replacements. Barlow and Hunter show how to calculate the optimum period between replacements or overhauls for an infinite time span. In addition, they compare results obtained under this policy with those for the optimum age replacement policy, thus providing the decision maker with the information needed to choose between them.

One problem involving these policies has been the search for optimum policies. For the case where the system operates for an infinite amount of time (called the infinite horizon or infinite time span case), the expression for the expected long run cost per unit time must be determined and then minimized. Often the minimization is the more straight forward part of the problem, while in order to obtain the expected cost per unit time some probabilistic arguments are required. Recent research concerning maintenance policies with time dependent costs and probabilities is surveyed by Block, et al. (1986).

Handlarski (1980) proposed a new approach for the maximization of profit by optimal scheduling of machinery. Only one objective function (profit) is used instead of two (availability and cost). The latter approach inevitably resulted in suboptimization. In addition, the "single objective" approach naturally lends itself to comparisons of efficiency between any preventive maintenance policies. Optimal solutions were found in order to compare the efficiency of the commonly used policies of age and block replacement. Numerical results show that age replacement can be more profitable. Optimal solution for these two maintenance policies were also found in the specific case where a maintenance repair is superior in quality to a breakdown repair.

The optimal maintenance policy for a fleet of vehicle (also applicable to planes, earth-moving equipment, etc.), where failure of a component such as dynamo, carburetor, etc. results in immobilization of the vehicle, is a well-established problem. The case of a single component is discussed by Campbell (1941), that of two components by Sasieni (1956), the periodic inspection approach by Drenick (1960a) and specific military application in Weiss (1956a).

A summary of a case study that was conducted over a period of three years on a fleet of vehicles which was geographically widespread and was assumed to be homogeneously used, and failures of components were time function rather than usage (mileage) function is discussed by Brosh, et al. (1975). One task of the research team engaged in the study consisted of listing feasible policies, formulating their behavior and recommending selection techniques on the strength of the available data. Five policies appeared to be feasible:

1. Replacement of component upon failure.
2. Planned replacement of components, irrespective of their age (on which no information is available), at predetermined regular time intervals.
3. Planned replacement as above, on the basis of information, of those components whose age limit has been exceeded at the time the vehicle is called for maintenance.
4. Unplanned replacement of predetermined subsets of components irrespective of age, whenever a failure occurs.
5. Unplanned replacement as above, subject to age limitation.

For some equipment, maintenance cost increases with age. This is likely to be true with machinery composed of an assembly of working parts. An easily recognizable example would be that of a motor car. In such instances, it is not possible to assess what the maintenance costs will average over a long period unless it is also known how long it is proposed to keep the equipment before scraping it. It also means that maintenance costs obtained when studying a comparatively new piece of equipment cannot be taken as the expected long term costs.