



Operation and Maintenance Management of Ship Machinery using System Dynamics

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Doctoral Dissertation

**Operation and Maintenance Management of Ship
Machinery using System Dynamics**

システムダイナミクスを活用した船舶機関システム
の運転・保守管理

July, 2014

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Abstract

The cost of operation must be considered when analyzing reliable support systems for ship main engines. While respecting the need for safety of ship from machinery risk of failure, the total cost of ship machinery operation (C_T) must also be kept at a minimum. This is an issue that frequently emerges in the operation of merchant ships as ship companies make an effort to gain better profits by reducing the expenses during operation. The determination of minimum C_T is not a simple matter because it includes some particular considerations such as running cost (C_r), maintenance cost (C_m) and downtime cost (C_d).

One is faced with the difficulty to decide the appropriate length of the maintenance interval (I_m) for machinery that yields the minimum C_T but still respects reliability. Along with the running time of machinery, the C_r increases according to the degradation of performance and reliability. Maintenance could reduce the C_r but this would cause a C_m increase. Since maintenance requires a C_m but also has the benefit of reducing the C_r , an optimization process which endeavors to balance the two to find the minimum C_T is needed. The optimization of marine machinery operation is a more complex discussion than for onshore machinery because of its maintenance inflexibility, which sometimes depends on access to shore based facilities or the availability of spare parts onboard.

This study presents an optimization process that minimizes the C_T by considering the minimum reliability requirement and the preference time and place of maintenance. The optimization problem compounds many factors that correlate with each other. The optimization process utilizes the simulation model, system dynamics (SD), which is capable of modeling the interrelationship between components of ship machinery operation e.g. cost component, reliability analysis, and ship voyage pattern. This study also presents a new development model of risk based maintenance (RBM) implemented for ship machinery to prevent high levels of risk during ship operation. Development of RBM resulted in an effective maintenance plan that compared well with the standard of maintenance published by the machinery's manufacturer.

In order to accommodate the matters explained above, this thesis is constructed as follows.

Chapter 1, introduction which contains background information, purposes, and scope of research, including proposed work to be done.

Chapter 2, briefly reviews ship machinery operation and the history of maintenance strategy, risk based maintenance (RBM) and explains the system dynamics (SD) simulation. The modeling process of machinery operation and maintenance in SD simulation is presented in this chapter.

Chapter 3. This chapter proposes new models in system dynamics (SD) simulations to determine the reliability index (RI) degradation of ship machinery which is installed in the main engine support systems of ships. The purpose of this study is to minimize the total operation cost (C_T) of machinery which is comprised of running cost (C_r), maintenance cost (C_m) and downtime cost (C_d). Reliability analysis is taken into account based on data from maintenance records. In this chapter, two kinds of optimization models utilizing SD are compared. Model 1, an optimization model without forecasting, utilizes a value of minimum RI as a decision to obtain the lowest C_T . The minimum RI is the level of reliability of machinery where maintenance actions need to be taken. Model 2, an optimization model with forecasting, constructs the maintenance judgment by forecasting the value of RI to avoid the minimum RI before a ship arrives at a destination port. Sea water and fresh water cooling pumps are analyzed as a case study. Model 1 resulted in minimum C_T , while model 2 reached a C_T lower than the outcome of model 1.

Chapter 4. In this chapter, an SD optimization model is proposed to minimize the C_T by considering the port availability constraint. In this constraint, it is assumed that the maintenance of the machinery is only possible at one particular available port. The purpose is to know how the constraint influences the composition of the cost compared with the results of the study in Chapter 3. In the case study, this chapter discusses the operation of pumps which are installed in the cooling system of a ship's main engine. System dynamics (SD) is used to build two kinds of proposed models of machinery operation, model 1 without forecasting, and model 2 with forecasting of minimum RI. The results were similar to the results in Chapter 3, model 1 results in minimum C_T , while model 2 reaches a C_T lower than that of model 1. Model 2 in this chapter, with

forecasting of minimum RI, resulted in the lowest C_T , much better than the other model. This shows that the forecasting model implemented in the problem with port availability constraint has the most significant impact on reducing the cost.

Chapter 5, considers the risk of machinery failure in the management of operation and maintenance of ship machinery. This chapter implements risk based maintenance (RBM) to minimize the frequency and consequences of ship machinery failure. As well as the common steps of RBM, such as identification of problem, risk assessment, risk evaluation, and maintenance planning are conducted, we also propose a new model called ship position estimation. First we look at preliminary identification i.e. identification of failure causes and symptoms as well as the history of failure over time. In the risk assessment, quantification of the consequences of failure (Cof) considers system performance loss, while the probability of failure (Pof) is obtained from the reliability analysis of the failure time history. Risk evaluation compares the result of the risk assessment with the risk acceptance criteria in order to determine the level of risk. The proposed model of ship position estimation recognizes the ship position on the voyage when the analyzed machinery is at a high level of risk. Maintenance planning is then carried out to keep the machinery under the risk acceptance level. This paper utilizes system dynamics simulation (SD) to create each step of the RBM. For our case study, the parts of the pumps in the main engine cooling system are analyzed. The output of the study is a proposed maintenance interval which is suitable when compared with the standard maintenance for the pumps. Additionally, the position, operation hours and distance covered of the ship are included when a pump reaches a high level of risk.

Chapter 6. Summarizes the studies of the previous chapters and discusses the result obtained. In this study, the optimum management of operation and maintenance for ship machinery is clearly presented. This is shown as the optimization of C_T by endeavoring to find the value of the minimum RI. The optimization utilizes SD simulation to build two models, model 1 without forecasting and model 2 with forecasting of the minimum RI. Model 2 shows the greatest impact on the reduction of C_T , much better than model 1, especially in the case study on the ship operated under the port availability constraint. Considering risk management, this study presents a new development in the RBM method. The beneficial outputs achieved are an improved maintenance plan and the addition of ship position estimation for ship machinery operation at a high level of risk. Further, this chapter draws conclusions and discusses other improvements that may be possible for future research.

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Nomenclature

| | |
|----------------|------------------------------------------------|
| A_i | : function of system performance loss |
| AI | : availability index |
| B_i | : function of financial loss of failure |
| C | : root cause of failure |
| CCFW | : central cooling fresh water pumps |
| C_d | : downtime cost |
| C_{di} | : downtime cost of i^{th} ship voyage |
| C_h | : specific heat of fuel oil |
| C_i | : function of human safety loss |
| C_m | : maintenance cost |
| C_{mi} | : cost of i^{th} maintenance |
| C_r | : running cost |
| C_{ri} | : running cost of pump at i^{th} ship voyage |
| C_T | : total operation cost |
| D_i | : function of environment loss |
| E_i | : extra cost of i^{th} maintenance |
| I_m | : interval between maintenance |
| I_m result | : proposed I_m using SD simulation |
| I_m standard | : standard of I_m published by manufacturer |
| JW | : jacket water pumps |
| m | : number of maintenance |
| m_p | : maintenance planning |

| | |
|----------------------|-----------------------------------------------------------|
| MTBF | : mean time between failure |
| OG dist. | : over ground dist. |
| O_p | : specific unit of fuel price |
| P_d | : distance between ports |
| PDF | : probability density function |
| P_{in} | : energy required to operate the electrical motor |
| PMS | : planned maintenance system |
| P_{of} | : probability of failure |
| $P_{of\text{limit}}$ | : P_{of} acceptance limit |
| P_{out} | : liquid horse power |
| RBM | : risk based maintenance |
| RI | : reliability index |
| R_{I_m} | : reliability at proposed I_m |
| RPM | : rotation per minutes |
| $R(t)$ | : reliability function |
| R_{t_r} | : reliability at t_r |
| S | : symptom of failure |
| SD | : system dynamics |
| S_t | : specific unit salary for engineer per unit of time |
| SW | : sea water cooling pumps |
| t_d | : downtime |
| t_{di} | : i^{th} downtime time |
| t_l | : loading unloading time |
| t_m | : time required for maintenance |
| t_{mi} | : time required for i^{th} maintenance |
| t_{op} | : total voyage time until arrived at port for maintenance |
| t_r | : running time |
| t_{ri} | : i^{th} running time |
| t_v | : voyage time |
| V_s | : service speed of ship |

β : shape parameter
 η : scale parameter
 γ : location parameter
 μ : location parameter
 σ : scale parameter
 ρ_v : density of fuel oil

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Chapter 1

Introduction

1.1 Background

Sustainable operation is the goal of all engineering departments in all shipping companies. Most efforts are aimed at reducing interruptions of ship service during voyages which can be caused by the problems of ship machinery. These problems cause downtime which presents unpredictable additional expense. The objective of ship companies is to minimize expenses and gain profit. With this in mind, an appropriate maintenance strategy for ship machinery is required to realize total operation cost reduction.

Machinery trouble is one of the main causes of ship accidents reported by IACS and INTERTANKO [1], [2]. It potentially increases the C_T of the ship because maintenance action caused by a breakdown must be carried out when machinery failure occurs. The C_T is comprised of a number of cost-incurring components including running cost (C_r), maintenance cost (C_m), and downtime cost (C_d). These cost components should be minimized when implementing a maintenance strategy for ship machinery in order to help management remain in budget.

The cost optimization of ship machinery operation should also consider safety when considering the risk of failure. Risk assessment is needed in order to estimate the level of risk. This is essential to establish an appropriate maintenance plan which is aimed to keep machinery

under the risk acceptance level since a severe failure during ship at sea may contribute to a catastrophic incident. From the above explanation, it is always necessary to consider an improvement of optimization of ship machinery operation to minimize cost and have a satisfactory development of maintenance plan to reduce the risk of failure of ship machinery during operation.

1.2 Research aim

Based on the background illustrated above, this research proposes some part of study, as generally constructed in Figure 1–1, which is aimed to:

1. Create a model for the management of ship machinery operation.

To meet this aim, modeling the operation of ship machinery is performed as part of this research (see publication at [3]). System dynamics (SD) is utilized to model the ship operation as well as the operation and maintenance of the ship machinery. This model deals not only with ship operation under maintenance inflexibility at sea (see publication at [4]), but also considers the constraints of port availability for machinery maintenance (see publication at [5]).

2. Determine the cost composition of machinery operation in order to seek the optimum operation cost (C_T) of ship machinery.

The modeling of the cost composition includes running cost (C_r), maintenance cost (C_m) and downtime cost (C_d). The optimization of total operation cost (C_T) of ship machinery is performed as shown in the publications at [4] and [5].

3. Propose a maintenance plan which considers the risk assessment of machinery failure.

This research purpose is done by presenting a new development in the risk based maintenance (RBM) implemented in the operation of marine machinery. This new model named “Ship Position Estimation” is proposed as one step in the RBM method which is usually comprised of only Preliminary identification, Risk assessment, Risk evaluation, and Maintenance planning. System dynamics (SD) simulation model of RBM is constructed to achieve this purpose.

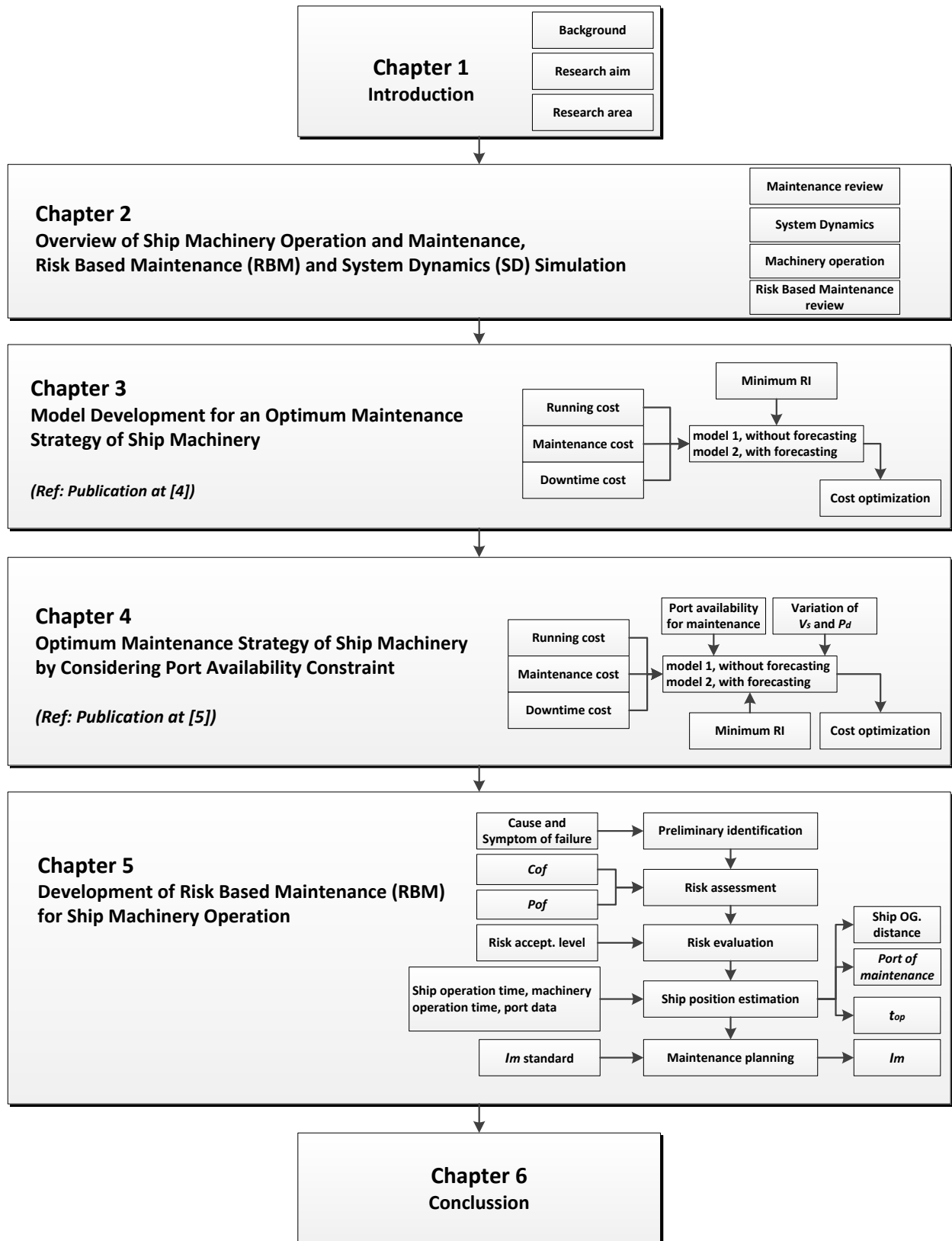


Figure 1-1 General construction of thesis

1.3 Research scope

The optimization of operation cost is done on the operation of the support system of the ship's main engine using system dynamics. The system that is chosen as the subject of this study is the cooling system of main engine, which includes both the high and low temperature cooling systems. The cooling system is one of the most important systems for the main engine since improper work, or a failure of the cooling system would prompt a variety of problems in its operation. These may result in an increase in the cost of operation as the well as cost for maintenance. Should the cooling system cause serious damage to the main engine, such as overheating causing permanent damage, the costs of repair or replacement would be exorbitant.

The subject of this optimization study focused on the cooling pumps. The cost optimization of pump operation is analyzed in order to know the appropriate operation and maintenance policy that would result in the most effective minimum operation cost. This is discussed in Chapter 3 and Chapter 4 both of which propose model 1, without forecasting, and model 2, with forecasting of reliability index of pump, as structured in Figure 1–1. Moreover, this research considers a risk assessment of machinery by proposing the development of risk based maintenance (RBM) which is developed through a case study on the parts of the cooling pump. The failure data of pump parts is collected from the operation of ship over 16 years, from 1997 until 2012. The analyzed parts include shaft, mechanical seal, O-ring and discharge valve. The proposed interval between maintenance (I_m), ship operation time (t_{op}), ship over ground distance (OG dist.), and recommended port location for maintenance are results of this study which are beneficial for a maintenance plan of the pumps parts of the cooling systems of the subject ship's main engine taken as case study discussed in Chapter 5, and as shown in Figure 1–1.

The cooling system (see Figure 1–2) is chosen as case study on in order to achieve the current research purpose i.e. to propose a new system dynamics model for cost optimization and development of RBM. The research area in the current research does not include other supporting systems of the main engine e.g. fuel oil system, lubricating oil system etc. These systems are not less important than the current focused system, and in future, they, as well as other machinery, including heat exchangers, valves, fuel oil pumps, lubricating oil pumps etc., should be subjects of study to see if the model proposed in this research holds true.

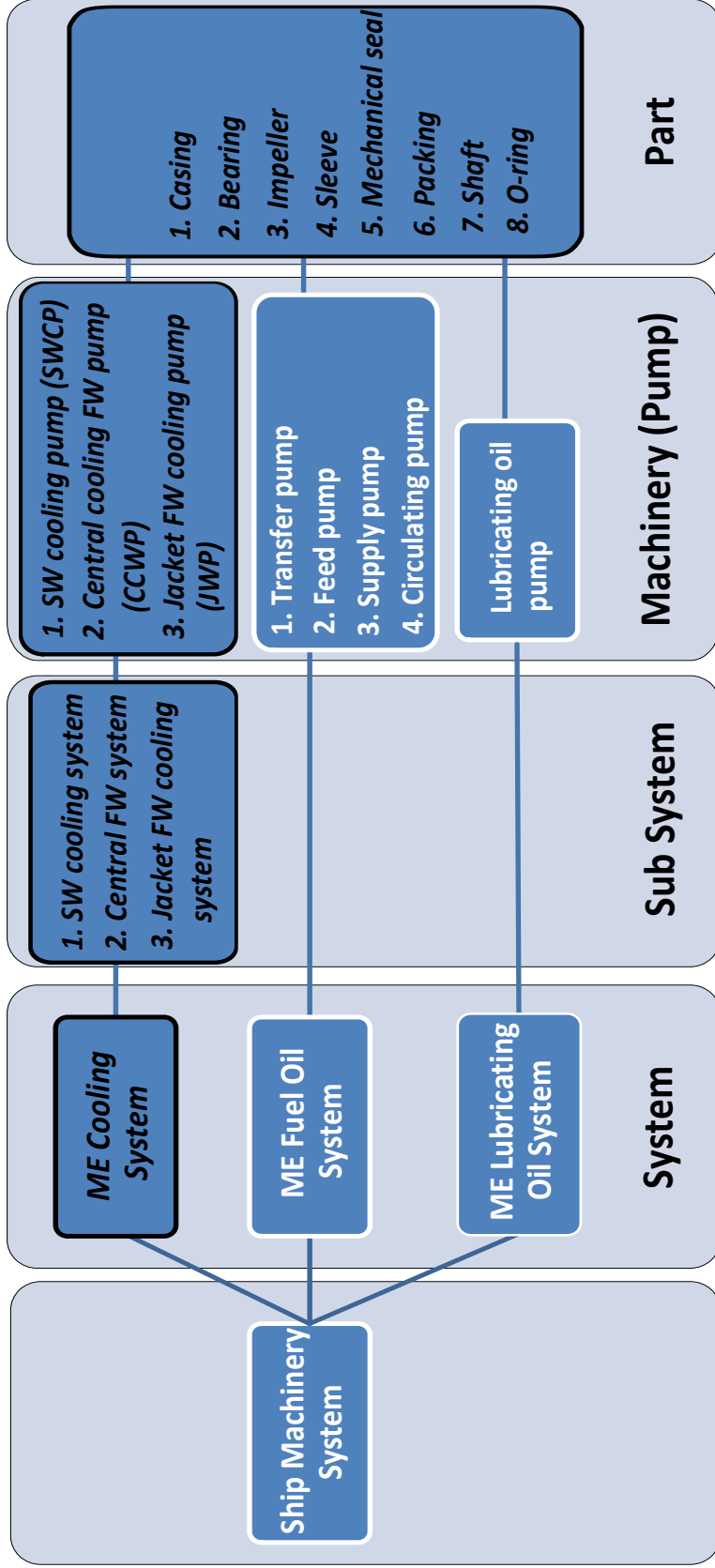


Figure 1–2 Machinery system in focus

Chapter 2

Overview of Ship Machinery Operation and Maintenance, Risk Based Maintenance (RBM) and System Dynamics (SD) Simulation

General description about the ship machinery operation and the evolution of maintenance strategy is discussed in this chapter, as well as risk based maintenance (RBM) and system dynamics (SD) simulation. At first, a review of the maintenance history is conducted. After that, the state of the art of SD along with its application for modeling the ship operation is introduced. Having the utilization of SD model for ship operation been introduced, this chapter shows the modelling of cost composition for the total cost optimization of machinery operation and maintenance.

In the end of this chapter, a general explanation on risk based maintenance (RBM) method is shown, following by the description of the proposed SD model for RBM. Overall, this chapter is intended to provide a brief and clear overview of maintenance evolution, to show the ability of the SD to be utilized in marine machinery operation and to give a preliminary view on the development of the RBM.

2.1 Literature review on maintenance history

Maintenance management has been through a long development process. In the beginning, corrective maintenance was conducted, after that periodic overhauls were introduced, and then planned preventive maintenance, condition monitoring, reliability centered maintenance, and expert system which finally led to the current research interest in the maintenance field, which considers risk such as study by Cooke, Arunraj and Khan [6], [7], [8]. Most of development process of maintenance management has been generally aimed at improving the availability and efficiency of equipment/ system, control the deterioration rate, environmental protection, and one of the most important objectives, to reduce the total cost of operation [8]. Regarding cost minimization, many researchers have discussed thoroughly to gain an improvement of the optimization model.

The issue of cost saving is necessary since cost balance is always needed in the consideration of operation and maintenance of machinery. The ability to minimize the expected average repair and replacement cost is a common consideration in optimal replacement problems. By considering the average repair and replacement cost, studies on optimal replacement problems have been conducted, i.e. Derman, Kolestari, Kao and Nakagawa [9], [10], [11], [12] deal with the equipment state expressed by method of Markov and Semi-markov process. Other studies by Drinkwater and Lambe [13], [14] discussed a cost optimization process based on the failure of equipment stated by poisson distribution, while the repair cost is expressed by exponential distribution. A well known rule called “repair cost limit rule” has been applied in years. This rule means that the repair of the equipment should be initiated when the cost of repair is less than an optimally determined limit of use, otherwise scrapping should be decided when the cost of repair reaches the determined limit. Further developing this rule, Ye [15] proposed to reduce the maintenance, operation cost, and purchasing budget, focussing the maintenance and operation cost more than just on the repair cost.

In the early stage, “as good as new” is assumed when the model for maintenance and replacement is proposed. This means that after repair, a system has the same condition, function and reliability level as when first operated. The reliability and performance of equipment can be assumed to be similar in condition as when the equipment was first installed. This also suggests

that the length of time to failure is always the same for all failures during life of the equipment. However, this perspective has been changed. Nakagawa [16] proposes a model that shows a decreasing value of interval between failures as a function of the number of maintenance. The length of interval between failures decreases with the increasing of the number of maintenance. Under real conditions, deterioration causes the performance and reliability of equipment after maintenance to be less than it was before maintenance. The model proposed by Nakagawa [16] which focuses on the decreasing length of interval between failures is referred to as imperfect repair of failure by Nguyen [17]. This model was also adopted by Jack [18] to determine the cost of repair in a finite time horizon. Moreover, Pascual [19] proposed a modelling process which not only set the overhaul times but also considered quality, service and replacement times. In that study, downtime cost and budget constraint were considered to analyze their effect on maintenance management. Other studies by Komonen [20], [21] concentrated on the maintenance decision making and presented two groups of cost, intervention cost and lost production cost based on failures and lost quality production due to equipment malfunction.

Imperfect maintenance has been studied by many researchers. Pham [22] has summarized and discussed various treatment methods for imperfect maintenance. One of the most important works is the classification of maintenance based on the ability to restore the condition of the equipment. Pham [22] classifies the treatment into 5 categories. First, *perfect repair*. As good as new is included in this maintenance category. Here, the failure distribution and failure rate function of the equipment are similar after the repair. It assumes that the repaired equipment behaves as newly installed equipment. Second category is *minimal repair/maintenance*. Sometimes known as bad as old. Maintenance is conducted on only part of a system. After maintenance has been conducted, the failure rate function of the system is similar to the one before maintenance. It can be assumed that the failure rate does not change after maintenance. Third, *imperfect maintenance*. The maintenance restores the condition, performance, and reliability of equipment but it is not the same as new equipment condition. It can be assumed that imperfect maintenance has a place between perfect maintenance and minimal maintenance. Fourth, *worse maintenance*. Maintenance action increases the failure rate of equipment. The performance decreases and the equipment life become shorter. One cause may be wrong maintenance decisions. Fifth, *worst maintenance*. Maintenance action does not bring the

equipment or system into a better level of performance/reliability, in contrary it has an affect to breakdown the equipment/ system. Overall [22] not only summarized and classified the maintenance actions but also pursued treatment methods, and optimal maintenance policies that are suitable for each of the maintenance categories.

Park [23] also focused on imperfect maintenance. Minimal repair is employed for a repairable system under a preventive maintenance plan. The cost optimization considering such a system was reached by obtaining the optimal interval between periodic preventive maintenance. A degradation ratio was introduced by Zhao [24] as a parameter for imperfect maintenance. This assumes that the analyzed system starts a new degradation mode following each preventive maintenance action. Another study by Pascual [25] considers three kinds of maintenance categories i.e. minimal repair (as good as before failure), imperfect overhaul (between as good as previous failure and as good as new) and perfect maintenance (as good as new). Their proposed model defines the optimal life cycle period, and the optimal periodic overhaul, as well as cost optimization, to obtain the optimum level of periodic maintenance. Study by Ahmadi [26] proposed a model called ‘intensity control’ which is used to obtain optimal inspection intensity and degree of repair of a system. The model is proposed to yield the optimum revenue for a deteriorating manufacturing system which considers the maintenance cost, the obtained profit as a function of performance of the system, and defect of the system. The output is the repair, inspection and replacement policies which respects on the state of the system. Another model development considering imperfect maintenance has been proposed by Kallen [27]. The proposed model is inspired by the reality, that it is difficult to model how imperfect maintenance influences the rate of deterioration and affects the performance/condition of the system/equipment. This effect has been modeled by using a superposition of renewal process.

In a further development, maintenance study considers risk management. One method is risk based maintenance (RBM). RBM focuses on the management of the risk of failure. Risk quantification is obtained by combining the results of consequence of failure (*Cof*) and probability of failure (*Pof*) analysis. RBM was initially proposed by Khan [8] as a structured comprehensive method comprised of a step of modules. Since that time, RBM has been implemented in many fields. It was successfully employed by Khan [28] to analyze the risk in

ethylene oxide production facilities and brought down the original high risk of the equipment. In another study, Krishnasami [29] developed RBM in a power generating plant. The outcome showed that critical risky equipment could be identified, and the reliability of the equipment could be increased. Additionally, it reduced the cost of maintenance including cost of failure. In an oil refinery, a development of RBM has also been satisfactorily implemented by Bertolini [30].

The literature of RBM mainly discusses problems in the fields of industrial applications and transportation systems [7]. In the industrial field, this method specifically appears in mechanical, chemical and electrical fields such as shown by Khan, Dey, Fujiyama, and Masataka [8], [28], [31], [32], [33]. Its application on transportation systems is conducted by Dey and Dey [31], [34]. In the marine field, there is little research considering risk analysis in the maintenance strategy for ship machinery. Some previous studies by Handani and Artana [4], [5], [35], [36] show a maintenance strategy which minimizes the total operation cost. The optimization process is carried out by adjusting the appropriate maintenance interval in order to obtain the minimum total cost of machinery operation. There is a necessity to consider risk analysis in the maintenance strategy of ship machinery because not only total operation cost needs to be minimized, but the cost-incurring of loss caused by failure, as well. In this study, the RBM method is adapted for use in the maritime field, especially for risk management of ship machinery operation.

2.2 Literature review on system dynamics

A study of a complex system containing many variables needs a method capable of explaining the behavior of the system. The information, as well as the pattern of behavior that is quantitatively analyzed in this kind of system, should be clearly understandable. One who wishes to gain this kind of interpretation when analyzing a complex system should consider a modeling method called *system dynamics*. Bouloiz [37] expresses that the changing of behavior overtime of a complex system is a major consideration of system dynamics. The system dynamics was first developed by Forrester [38]. It was utilized to model dynamic and complex problems mainly in the social sciences. System dynamics is capable of modeling complex processes as well as showing its behavior over time by enabling the cause and effect relationship between the

components which interact in the system. The system dynamics is defined as “*the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organizational form and guiding policy*”, which was originally established by Forrester in his work [39].

Bouloiz [37] defines that in system dynamics, there are four steps that need to be completed in order to model a process. In the first, one should interpret the problem to be solved, including the purpose, and related components that may possibly influence the system. In the second step is building the cause and effect diagram. This diagram draws the relationships between entities in the system by connecting positive or negative relationships. Positive relationship means a reinforcing of relationships between entities, on the contrary, negative relationship means counteraction between the relationships. These relationships enable the changing of variables in the system as reported by Sterman [40]. The third step, constitutes the usage of stock and flow diagrams. Stock represents a level or state variable of the analyzed system, while flow means the rate of change in a state. The stock and flow diagram is a quantitative way of interpreting the cause and effect diagram which was constructed in the previous step. The stock and flow diagram consists of stock/level element, flow element, auxiliary and constant element, and information link [41], [42]. Figure 2–1 shows an example of a stock and flow diagram. The fourth step, is to insert the equation and formula into the flow that allows the model to calculate the initial data inserted into the model. Flow auxiliary, changes the level of the stock over a defined time.

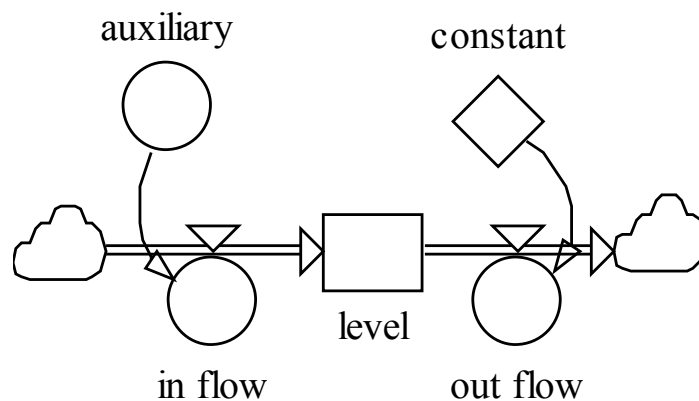


Figure 2–1 Stock and flow diagram

In this step, the behavior of the stocks and the flows during the defined time as well as the behavior of the whole system is analyzed. The system dynamics model may be comprised of many sub models gathered together to construct a main system dynamics model. In consideration of this ability, many researchers have recently developed system dynamics for a wide variety of problems.

Proposed in early 1960's, system dynamics has been developed and implemented in a wide scope of study as well as in industry application. Utilization of system dynamics can be found in the following literature. In project management, Rodrigues [43] has shown a comparison study between work by traditional approaches and by using system dynamics. The study shows that system dynamics can give solutions explaining in more detail about the interrelationship between projects components compared to traditional approaches. In supply chain management, system dynamics appears in the work by Ashayeri and Choi [44], [45]. Ashayeri [44] analyzes a development of a demand plant in a project which emphasizes the interrelationship between sub components such as logistics, marketing, sales and executive management. The simulation using system dynamics results in a satisfying calculation of the financial consequences on improved demand under various scenarios of simulation conditions. Choi [45] shows the utilization of system dynamics in a postponement strategy for the automobile industry. System dynamics helps to find the optimal shipping point and the right postponement level for problems under consideration.

System dynamics is being used in a variety of studies and projects, including in aviation transport management. Study on airport terminal performance was conducted by Manataki [46]. The research takes a case study of the Athens airport terminal. The performance of the airport terminal is analyzed with many variables including capacity, waiting time, level of service, capacity, heavy traffic of passengers etc. System dynamics has been utilized as a user-friendly tool in this study. Knowledge management in an airlines company was conducted by Zaim [47]. They used system dynamics to analyze knowledge management, which consists of generation, retrieval, transfer and utilization, and have positive relationships between each other. In maintenance management, some researchers have used system dynamics modeling. A study by Fan [48] analyzes a military weapon maintenance supply system. The study constructs a model

to analyze the occurrence of a bullwhip effect on the management of maintenance supply system. The output of the simulation is a suggestion to improve the army repair and logistic systems that will have an impact on reducing the bullwhip effect. Management of operation and maintenance of ship machinery appears in the work by Baliwangi [49]. System dynamics is utilized to model the system behavior of the cooling system of a ship. This study gives a clear description of the operation and maintenance plans. Other research by Handani [3] presents a preliminary step on constructing a model to reduce the total operation cost of ship machinery using system dynamics. Following by Handani [4] which proposes an optimization model using system dynamics to find the most economics operation plan of ship machinery. The study focuses on the operation of the cooling pump of a ship's main engine. The model deals with the reliability analysis, cost analysis and ship operation analysis including voyage time, loading and unloading time. The outcome of the study shows an optimum total operation cost which considers running cost, maintenance cost and downtime cost of cooling pumps. Application of system dynamics in ship operation also appears in a study by Handani [5]. This study is the extension of the study by Handani [4]. A constraint is set to specify an optimization problem to be solved. Port availability constraint is considered in the model which means that the maintenance action can only be done in a particular port. The system dynamics model presents an interrelationship of the components of the optimization model as well as results the minimum total operation cost of cooling pump under the port availability constraint.

In the scope of safety and risk management study, application of system dynamics can be found in the study by Bouloiz [37]. This study analyzes safety factors of the storage unit of a chemical product. The safety factor emphasized in the study includes technical, organization and human term. System dynamics is constructed to dynamically relate the safety factors in the system of storage unit. The simulation results the way to improve the safety of the system through management of organization, technical and human factors.

2.3 Modeling the ship machinery operation and maintenance

2.3.1 General description of the operation of ship machinery

Ships need working main engines. Support systems of ship main engine i.e. cooling, fuel oil and

lubricating systems, could be categorized as complex systems that are constructed of many machineries installed both in series and parallel. In this chapter, the modelling of ship machinery is not provided for all of the support systems of the main engine. One particular system is taken for consideration as focused study. A cooling system of ship main engine is illustrated in the following description to ease understanding of the problem regarding the system discussed.

The cooling system is very important to support the main engine in that it keeps the temperature low enough to prevent damage caused by overheating. The cooling system of the main engine is constructed of several pieces of machinery. The pump is one of the most important pieces since it transfers the fluids throughout the cooling system. There are sea water (SW) cooling pumps, central cooling fresh water (CCFW) pumps and jacket cooling fresh water (JW) pumps. The SW pumps work to supply sea water from a sea chest to the central cooler which allows heat to transfer from the fresh water in the central cooling loop, to the sea water. This happens while the CCFW pump distributes low temperature fresh water in the central cooling system into the lubricating oil cooler of the main engine, generator set and scavenge air cooler. The JW pumps circulate high temperature fresh water into the main engine jacket and also the jacket water cooler. All pumps are installed as parallel systems to provide redundancy in the unlikely event of a pump failure during the ship voyage.

2.3.2 Pump operation during voyage

Cooling systems of a ship's main engines could be categorized as complex systems that are constructed of many individual machinery pieces installed. The pumps which are taken for the case study in this paper are categorized as parallel installations which provide for the main pump and standby pump in the system. The main pump is operated during the ship voyage, while the standby pump is operated when failure of the main pump occurs. An overview of the ship operation as well as the pump operation during a voyage is shown in Figure 2–2 and Figure 2–3 respectively.

The route of the ship voyage is from Port A – Port B – Port C and back again. Figure 2–2 shows the order of the voyage clearly, while the t_v and t_l respectively indicate the time required for the ship to travel from one port to another and the time elapsed for loading and unloading in

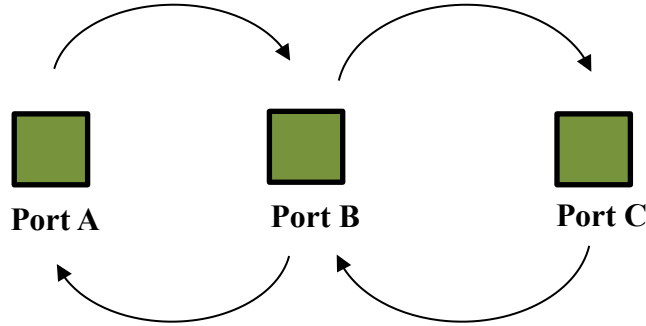


Figure 2–2 Illustration of the voyage pattern

the port. During the ship voyage, the cooling pumps are operated. Reliability of machinery is gradually degraded as running time (t_r) increases. The pump reliability degradation occurs until the reliability of the pump reaches the minimum reliability index (RI) at point F as shown in Figure 2–3. At this point, the main pump needs to be replaced by the standby pump in order to keep the cooling system of main engine working. The maintenance of the main pump can be done in the port nearby.

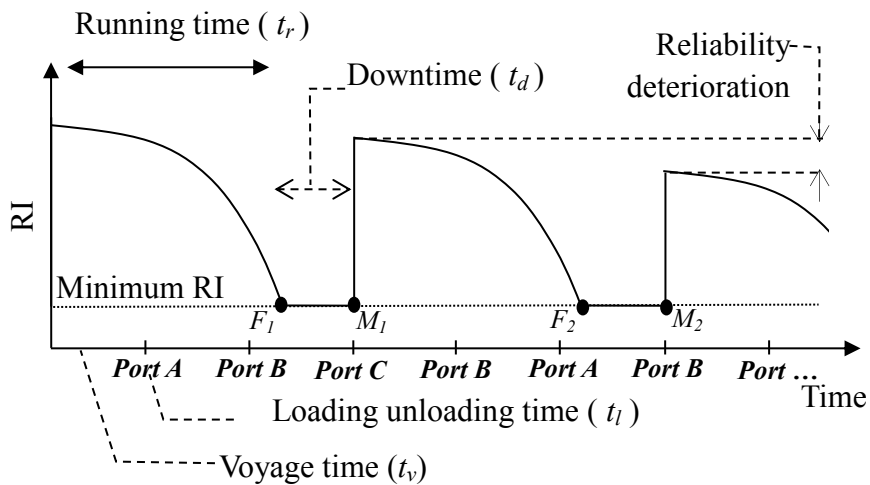
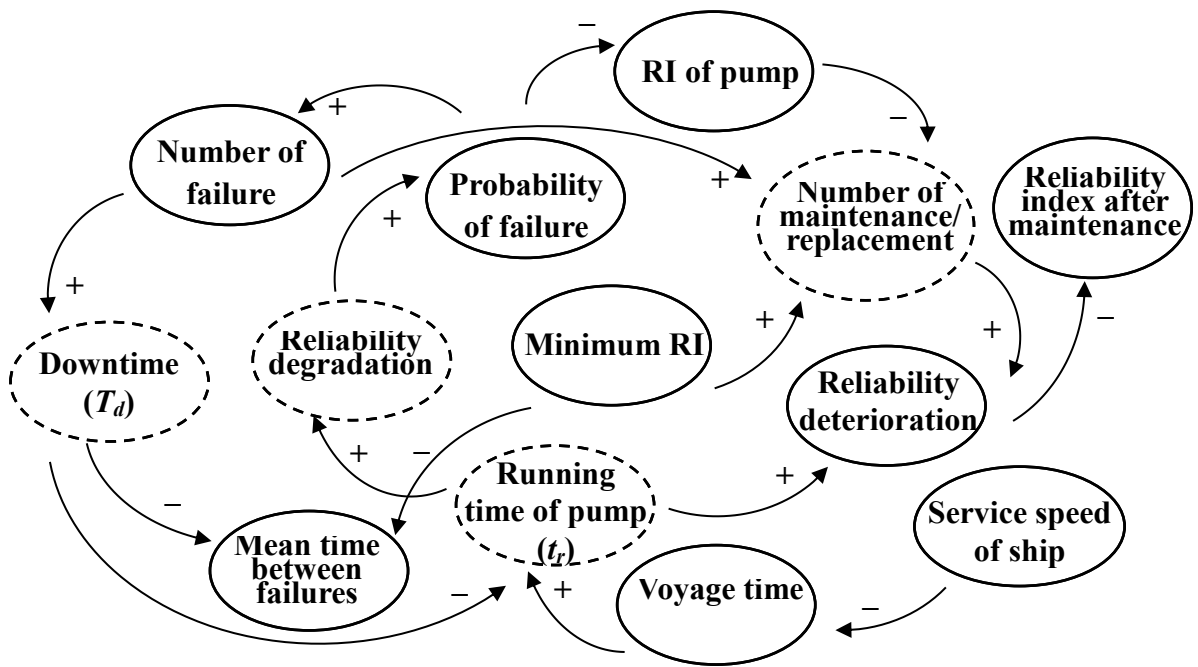


Figure 2–3 Reliability degradation of the operation of a single pump

Reliability degradation which is shown in Figure 2–3 causes decreasing performance of machinery while also increasing the operation cost (C_T). To optimize the minimum value of C_T one should thoroughly consider its composition, such as running cost (C_r), maintenance cost (C_m) and downtime cost (C_d). In Figure 2–3, it is clear that these three compositions of cost rely on the minimum RI. The value of C_r will increase if the minimum RI is set at a low value because the lower the value of the minimum RI, the longer the interval between maintenance (I_m). Longer I_m causes higher C_r . On the other hand, the C_m is lower because of longer I_m , i.e. the amount of maintenance decreases. The C_d tends to increase with a higher value of minimum RI or shorter I_m . The cost optimization will be clearly discussed in the following chapter.



* (+) : positive relationship, (-) : negative relationship

* Dashed line means the same object in Figure 2-3 and Figure 2-4

Figure 2–4 Overview of ship machinery operation

2.3.3 Cause and effect relationship diagram of ship machinery operation and maintenance

A dynamics event exists in the complex system which is influenced by related environmental effects. A causal loop diagram is useful for constructing such a system. The pump operation has a particularly complex environment as drawn in the following Figure 2–4. The causal and effect relationship of the environmental component in this figure shows that many systemic impacts take a significant role in the pump operation, such as reliability degradation, operation time of pump, maintenance, downtime, reliability deterioration etc. in the following chapter, the causal loop diagram will be transferred into an SD simulation to allow each of the aspects to contribute each other. This dynamics contribution will clearly show what information has emerged and what alternatives should be proposed for future research purposes, in this case a minimum C_T of pump operation by the optimization of minimum RI.

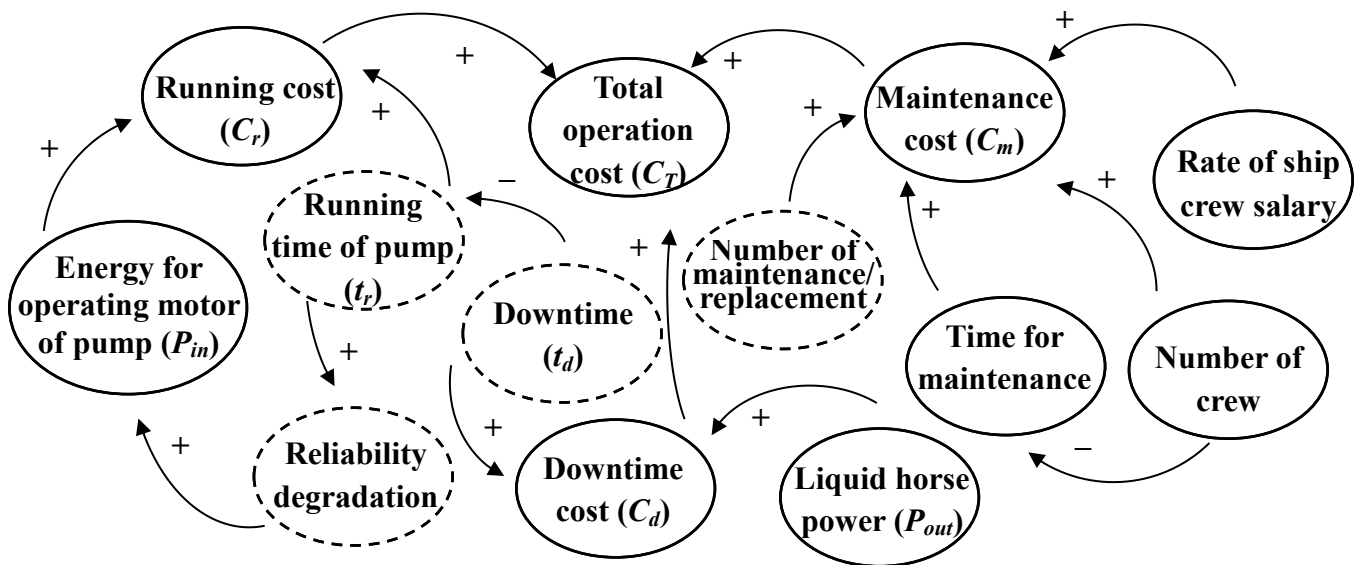
In the causal loop diagram, the feedback loop provides relationships between environment aspects. A positive feedback loop means that there is a positive relation between the connected aspects. Inversely, the negative feedback loop has a negative relation to them. As shown in Figure 2–4, when the pump is operated, the operation time will increase. At the same time, the RI will decrease. The longer the operation time, the reliability degradation will take a bigger impact on the degradation of RI. In the practice, the reliability degradation may noticed by the decreasing of pump performance. Since pump operation is necessary during ship voyages, the reliability degradation could not be avoided. In addition, the more reliability degradation occurs, the pump failure will be more likely to happen because there is a positive relationship between reliability degradation and probability of failure.

As time goes by, the failure probability of the pump increases in the same time followed by the degradation of RI. The maintenance is then required for bringing the RI back to the initial level. The maintenance is decided after the RI has achieved the minimum RI. The higher the set minimum RI, the more frequent the maintenance will be done and the shorter the I_m . This study assumes the maintenance restores value of RI less than the initial value because of 0.05% reliability deterioration. RI after maintenance appears as a new restored value of RI following maintenance. The more frequently maintenance is taken, the more the RI of the pump deteriorated.

The causal loop diagram in Figure 2–4 clearly shows that minimum RI governs the number of maintenance. Eventually, minimum RI influences the operation cost of the pump including the influences on C_r , C_m , and C_d . The other changeable variable that may influence the cost is the service speed of ship (V_s). The V_s has a negative relation with voyage time. The faster the V_s , the shorter the time needed for voyage. It means that the operation time will decrease. Accordingly, the most profitable cost minimization of ship operation can be obtained by optimizing the value of minimum RI as well as V_s .

2.3.4 Cause and effect relationship diagram of operation cost

The environment arrangement of the causal loop diagram of operation cost appears in Figure 2–5. The component which has a dashed line means that it also takes a role in the Figure 2–4. C_T has strong relationship with C_r , C_m and C_d , it is a positive relation.



* (+) : positive relationship, (-) : negative relationship

* Dashed line means the same object in Figure 2-4 and Figure 2-5

Figure 2–5 Cost composition of ship machinery operation

The bigger value of C_r , C_m and C_d , the bigger the value of C_T . C_r depends on the length of the running time and the power of the electric motor of pump. Each of them is connected as a positive loop with C_r . The longer the running time and the bigger the power of the motor, much C_r will be expended in the running period of pump.

The value of P_{in} has positive relationship with reliability degradation. It is because when reliability degradation occurs, the pump needs more energy to work as initial condition. While C_m is influenced by the time needed for conducting maintenance, rate of ship crew salary and the number of crew needed for maintaining the pump. Since the relation is positive, the longer, the more expensive and the more numerous of them, the more C_m spent. Lastly, the longer the downtime, the more expensive the value of C_d will be.

2.4 Modelling the RBM

This chapter also discusses a preliminary step on the modeling of the development for risk based maintenance. The overall modeling process of RBM and its development will be discussed completely in Chapter 5. In current discussion, the cause and effect diagram is constructed for used in the next step in building the SD model of RBM. Figure 2–6 shows the basic thinking of the RBM development which is interpreted into the cause and effect relationship diagram. By using this diagram, relation between one unit and others can be clearly understandable and allowing each unit to counteract each other.

In Figure 2–6, it can be seen that the risk is depend on the probability of failure (Pof), consequence of failure (Cof), additionally, it also depends on the number of maintenance/replacement. Both Cof and Pof have positive relationship with risk while the relationship of the number of maintenance is negative. This relationship gives clarification that the value of risk with Cof and Pof will reinforce each other while the number of maintenance/replacement will counteracts with the value of risk. In the further breakdown of the diagrams in Figure 2–6, Cof has a positive relationship with performance function which also positively related to the magnitude of the failure symptom. This relationship explains that the more catastrophic the magnitude of the failure, the performance function will be higher. This contributes to reinforce the value of Cof as well as the risk becomes higher. The operation condition such as ship service

The risk acceptance level has an important role in the maintenance decision making. By using this, the level of risk can be defined whether in the high, medium or low risk category. The risk acceptance level takes role in determining when the maintenance needs to be carried out. By considering on it, the risk acceptance level is connected to the number of maintenance using negative relationship. The number of maintenance will be higher when the level of risk acceptance level is lower. Contrary, the higher the level of risk acceptance level, less number of maintenance becomes. Further, the number of maintenance contributes to govern the value of risk. In cause and effect diagram, they are counteracts each other. Additionally, the number of maintenance also determines the length of interval between maintenance. More frequent the maintenance takes place, the shorter interval between maintenance will be. The less frequent the maintenance, the interval between maintenance become longer. In Figure 2–6, it can be seen that the interval between maintenance is connected positively with ship over ground distance and ship operation time. Both of them are related with the proposed model “ship position estimation”. The ship over ground distance and ship operation time interpret both of their value when the model of ship position estimation reaches the recommended place/ port to carry out maintenance.

After the cause and effect diagram has been constructed, the next step is constructing the model in system dynamics. This chapter does not discuss the SD model construction because this will be appeared clearly in the Chapter 5. Step by step of the RBM process will be constructed in Chapter 5, as can be interpreted in Figure 5–1. The SD model of RBM is drawn in Figure 5–2. In this figure, all the step of RBM including Preliminary identification, Risk Analysis, Risk Evaluation, Maintenance Planning as well as the proposed model i.e. Ship Position Estimation are simulated using SD.

Chapter 3

Model Development for an Optimum Maintenance Strategy of Ship Machinery

3.1 Introduction

The purpose of this chapter is to show how to manage the operation and maintenance of ship machinery in order to minimize the C_T . Some previous studies have analyzed how to optimize the cost for the operation of machinery or systems. Satisfactory work has been done by Nguyen [50] with the optimization of preventive maintenance by altering the frequency of repair. In the case of ship machinery operation, Artana and Handani [35], [36], [51] gave a description on the optimization for the replacement and scheduling process for machinery entering the wear out phase period by giving a minimum RI and availability index (AI). Another study by Baliwangi [49] analyzes the management of operation of machinery in the useful life period that has a constant failure rate. Further, Handani [3], [52] endeavored to find the value of minimum RI as a work limitation of machinery which results in the minimum C_T for ship machinery during its useful life period. The minimization of C_T highly correlated with the frequency and length of time between maintenance. The reliability degradation results in the increasing of the C_r of component. The lower the reliability, the more costly C_r becomes. The maintenance of machinery, which needs C_m , has benefit to reduce the C_r . Based on the balance point of C_r and

C_m , the optimization model discussed in this chapter is developed.

3.2 Problem description

One of accomplishing a better profit gained on ship operation is to do an optimization of C_T of ship machinery which considers the C_r , C_m and C_d of machinery operation. Each of those cost compositions has their unit cost that needs a rigorous concern on it in order to gain a better result of optimization. The unit cost included in the cost composition of pump operation can be derived from the operational ship data. The operational illustration of the pump is interpreted in Figure 2–3, Figure 3–1 and Figure 3–2.

In this chapter, the focus ship is operated with 14.5 knots service speed from Port A – Port B – Port C which has a distance between Ports of 2600 and 3500 miles respectively. The voyage is completed regularly by traveling back to Port A in same way via Port B. The cooling pumps are assumed to be operated continuously only during the voyage time and stopped when the ship has arrived in port. Reliability degradation occurs with the running time goes by and it does not occur when the operation is stopped. Because the t_l is represented as gridlines on the horizontal axis as shown in Figure 2–3, Figure 3–1 and Figure 3–2, the reliability curve appears as a smooth shape as if there is no impact of pump stopping. The reliability degradation appears until point F is reached. This point means that the RI of the pump reaches the minimum RI which acts as an indicator of the requirement for preventive maintenance.

By altering the value of minimum RI, this study conducts the minimization of the C_T . Minimum RI is closely related to the interval between maintenance (I_m). The value of I_m will be longer due to the reduction of the value of minimum RI. Besides that, the change of I_m impacts on the value of cost composition. The longer the I_m more C_r consumed for running the pump and likely reduces the C_m . In contrast, the higher the value of minimum RI or the shorter the I_m , less C_r consumed and higher the number of preventive maintenance occurs, which means the C_m is costlier. While the C_d will be the value of variation based on where the point F_l occurred, measured from the nearest port. This variation occurs caused by the length of downtime which is influenced by the remaining voyage time to accomplish one trip counted after the pump reaches minimum RI.

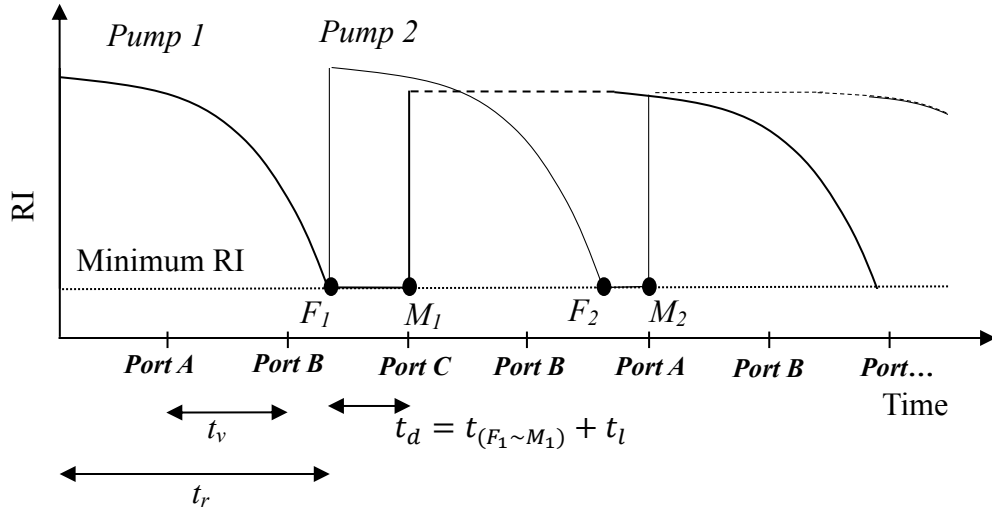


Figure 3-1 Model of parallel pump operation without forecasting of RI

3.3 Breakdown of operation cost

Operation cost of cooling pump of ship main engine is comprised of cost compositions i.e. running cost (C_r), maintenance cost (C_m), and downtime cost (C_d). The modeling of these three cost compositions are expressed as follows.

3.3.1 Running cost (C_r)

Equation (3-1) expresses running cost (C_r) of cooling pump. Electric motors consume energy to drive pumps. C_r appears by converting this energy into a cost. In Equation (3-1), $P_{in}(t)$ is the energy required to operate the electrical motor of pump, O_p is the specific unit of fuel oil price, C_h is the specific heat of fuel oil and ρ_v is the density of fuel oil. The number of maintenance is symbolized by m , while $(m + 1)$ represents the number of I_m or the number of running terms of the certain pumps.

$$C_r = C_{r_1} + C_{r_2} + \dots + C_{r_{(m-1)}} + C_{r_m}$$

$$\begin{aligned}
&= \int_0^{t_{r_1}} \left(\frac{P_{in}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt + \int_0^{t_{r_2}} \left(\frac{P_{in}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt + \dots + \int_0^{t_{r_{(m-1)}}} \left(\frac{P_{in}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt \\
&\quad + \int_0^{t_{r_m}} \left(\frac{P_{in}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt \\
&= \sum_{i=1}^{i=(m+1)} \int_0^{t_{r_i}} \left(\frac{P_{in}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt \tag{3-1}
\end{aligned}$$

where :

- C_{r_i} : running cost of pump at i^{th} ship voyage
- t_{r_i} : i^{th} running time
- ρ_v : density of fuel oil
- C_h : specific heat of fuel oil
- P_{in} : energy consumed
- O_p : unit oil price
- m : number of maintenance

Equation (3-1) interprets the total energy cost which can be obtained from the number of kilowatts consumed in a given time period ($P_{in}(t)$) multiplied by the cost per kilowatt. In the ship, this energy is obtained by combusting some amount of fuel oil in the electrical generator set.

3.3.2 Maintenance cost (C_m)

The C_m comes out as the result of maintenance of pump. The determination of C_m is relied on the specific unit salary for engineer per unit of time (S_t), the length of time elapsed for maintenance (t_m) and extra cost (E) such as replacement of component of pump. The value of m depends on minimum RI and I_m .

$$C_m = C_{m_1} + C_{m_2} + \dots + C_{m_{(m-1)}} + C_{m_m}$$

$$\begin{aligned}
&= \left(\int_0^{t_{m_1}} S_t(t) dt + E_1 \right) + \left(\int_0^{t_{m_2}} S_t(t) dt + E_2 \right) + \dots + \left(\int_0^{t_{m_{(m-1)}}} S_t(t) dt + E_{m-1} \right) \\
&\quad + \left(\int_0^{t_{m_m}} S_t(t) dt + E_m \right) \\
&= \sum_{i=1}^{i=m} \left(\int_0^{t_{m_i}} S_t(t) dt + E_i \right) \tag{3-2}
\end{aligned}$$

where:

- C_{m_i} : cost of i^{th} maintenance
- S_t : engineer unit salary
- E_1 : extra cost of i^{th} maintenance e.g. replacement of spare part
- t_{m_i} : i^{th} maintenance time
- m : number of maintenance

3.3.3 Downtime cost (C_d)

The C_d appears as result of failure of equipment or overhaul. In this period, the cost that the company pays is classified in two categories, intervention cost and C_d which is comprised of cost of lost production and other consequential costs such as reconfiguring alternative production lines, using less efficient methods, reduced product quality, lost raw material, etc. as explained by Pascual [19]. In this study, the pump system is connected in parallel for redundant purpose. The downtime problem caused by pump overhaul or failure problem can be quickly solved by switching to the stand-by pump. It is assumed that the stand-by pump is always successful in covering the failure problem of the main pump. There is no failure on replacing the function of the main pump with the stand-by pump. This reason causes the above intervention cost to not appear. Intervention cost is not calculated the in this study. Only C_d is emerged during downtime periods with the value as expressed in Equation (3-3).

$$C_d = C_{d_1} + C_{d_2} + \dots + C_{d_{(m-1)}} + C_{d_m}$$

$$\begin{aligned}
&= \int_0^{t_{d_1}} \left(\frac{P_{out}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt + \int_0^{t_{d_2}} \left(\frac{P_{out}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt + \dots + \int_0^{t_{d_{(m-1)}}} \left(\frac{P_{out}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt \\
&\quad + \int_0^{t_{d_m}} \left(\frac{P_{out}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt \\
&= \sum_{i=0}^{i=m} \int_0^{t_{d_i}} \left(\frac{P_{out}(t) \cdot O_p}{\eta_c \cdot C_h \cdot \rho_v} \right) dt \tag{3-3}
\end{aligned}$$

where :

- C_{d_i} : downtime cost of i^{th} ship voyage
- t_{d_i} : i^{th} downtime time
- ρ_v : density of fuel oil
- C_h : specific heat of fuel oil
- P_{out} : liquid horse power
- O_p : unit oil price
- m : number of maintenance

The C_d is comprised by cost of loss production. In this case, production in the pump operation stands for pumping the fluids through the cooling system by producing the liquid horse power (P_{out}). Pump failure means disability for transferring the cooling fluids in a certain working capacity and pressure, because the liquid horse power is not generated. Equation 3-3 interprets the production loss by converting the liquid horse power (P_{out}) and multiplying with the cost per kilowatt.

The C_T of the pump is the summation of all the cost composition. The formula represents the cost calculation of C_T using its composition including C_r , C_m , and C_d is shown in the following construction:

$$C_T = C_r + C_m + C_d \tag{3-4}$$

3.4 Modeling approach: system dynamics simulation

3.4.1 Interpreting the problem into the model

SD is utilized to simulate the operation condition of the ship machinery including the running period in the voyage time, loading and unloading time, maintenance time, downtime etc. The C_T which is comprised of C_r , C_m and C_d is calculated by using the SD simulation during the operation of the ship. This paper endeavors an optimization of minimum RI for acquiring the minimum C_T of the cooling pumps. Figure 2–3 has illustrated the general operation of single pump in ship voyages. In term of a parallel system, Figure 3–1 depicts the optimization for the parallel operation system of two pumps. Pump 1 is operated until the RI curve intersects the minimum RI at point F_1 which is the minimum allowable value of RI.

Pump 2 is switched from standby state to the operation state to substitute the pump 1 which is going to be maintained in the next port. In contrast, this rule is also applied when the operation of pump 2 reaches the point F_2 . This chapter introduces a simulation model which conducts optimization for minimizing operation cost of machinery by finding the value of minimum RI. Further, the optimization model which represents the optimization of pump operation in Figure 3–1 is named by model 1, optimization without forecasting.

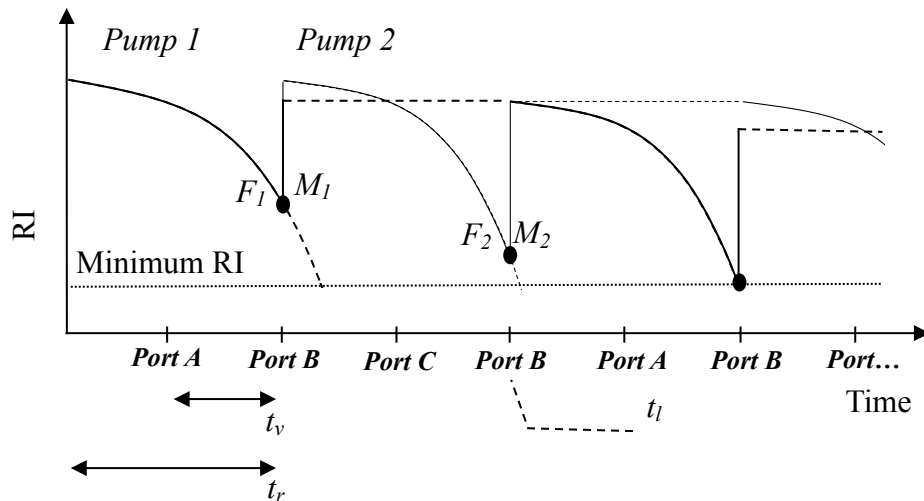


Figure 3–2 Model of parallel pump operation with forecasting of RI

This study also proposes a new model for minimizing C_T . The basic thinking of this model is a forecasting method that makes an effort to predict the value of RI of the operating pump during the voyage time. This model forecasts the value of RI in the next subsequent voyage. If the RI is lower than minimum RI, the maintenance needs to be performed when the ship has arrived in the next subsequent port after voyage. This model provides a prediction when the maintenance is proposed to be done in order to avoid C_d . The C_T , as the result of the optimization model, could be reduced further by using the forecasting model illustrated in Figure 3–2. This model will be called model 2, optimization using forecasting. In model 2, Equation (3-4) contains only C_r and C_m since C_d does not appear as the result of forecasting. It is shown in the following equation.

$$C_T = C_r + C_m \quad (3 - 5)$$

3.4.2 SD simulation

The causal loop diagram in Figure 2–4 and Figure 2–5 hereafter has been developed into an SD model as shown in Figure 3–3, SD model of pump operation and Figure 3–4, SD model of total operation cost of pump operation. This is a generic SD model which demonstrates the interactions existing between various effects in the environment of pump operation as well as its calculation of operation cost. The optimization for model 1 (without forecasting) and model 2 (with forecasting) is represented based on the scenario described in the Figure 3–1 and Figure 3–2 respectively.

Since there is a standby pump for each type of pump, the substitution of which pump is being operated is determined by an element called “Pump operation switch”. This element includes in SD model which appear in Figure 3–3. The detail of the element “Pump operation switch” is determined by the expression in the Equations (3-6) and (3-7). They represent how the alteration between pump 1 and pump 2 acts as the main pump or standby pump in model 1 and 2 respectively. The minimum RI becomes a variable in the optimization process. It acts as the level tracer of RI for operating the pump. In model 1, the pump 1 has to be switched to the standby pump when RI is less than the minimum RI. Soon after the ship arrives in port, pump 1 will be maintained.

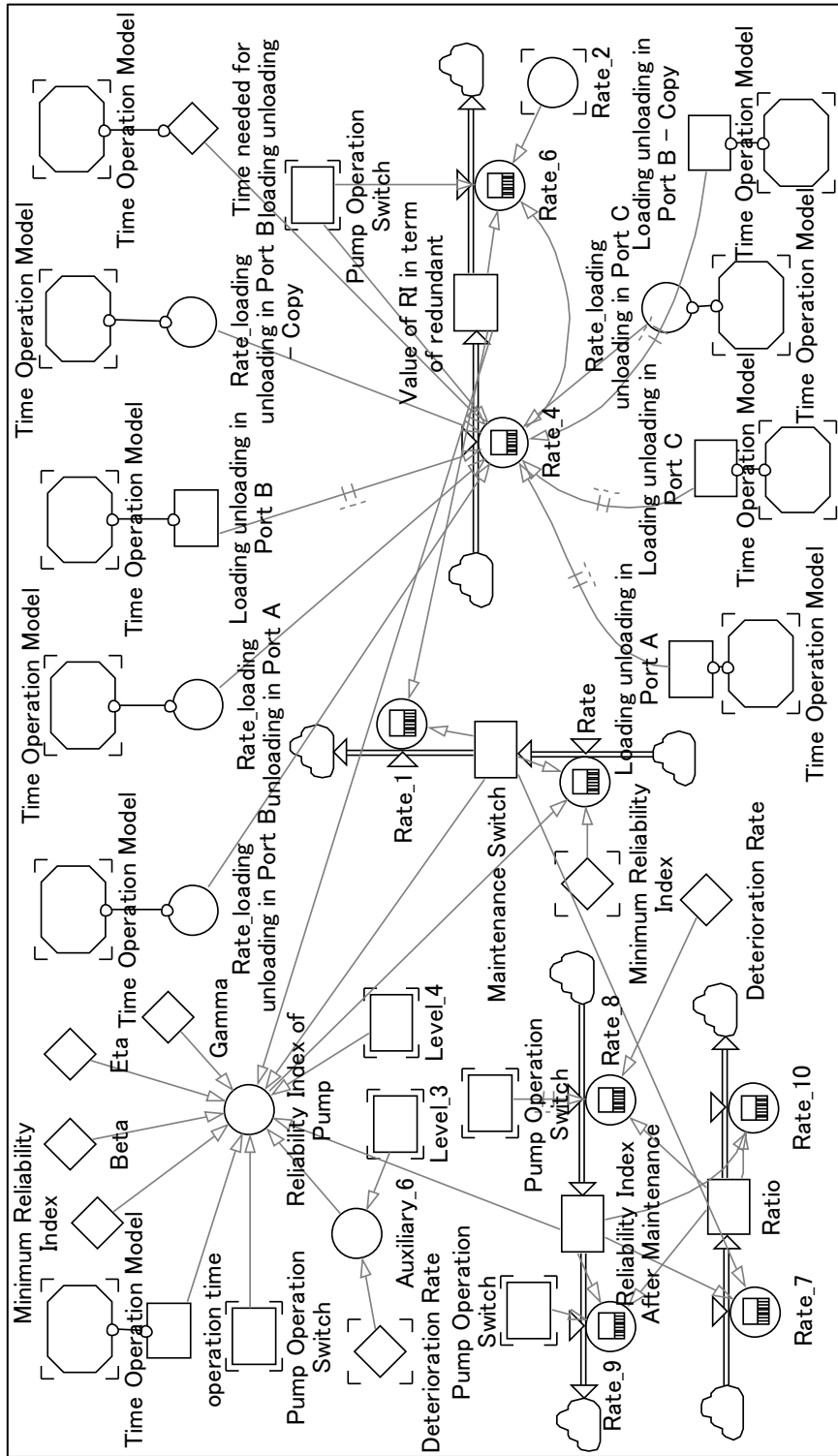


Figure 3-3 Diagram of generic SD simulation of pump operation

Whenever the reliability index is higher than the minimum RI, the pump 1 continue to operate. While in model 2, pump 1 will be substituted in the present port by the standby pump if the forecasting result of RI states that the RI of pump 1 in the next subsequent port is less than the minimum RI. In contrary, if the result of the forecasting states that the reliability is higher than the minimum RI, the operation of pump will be continued and the maintenance do not carried out in the next port until the forecasting shows the decreasing reliability under the minimum RI. The alteration of the main pump and the standby pump varies the length of running time, downtime and the port where the maintenance is done.

Model 1

$$\text{Pump operation} = \begin{cases} \text{switched, if } RI < \text{min RI} \\ \text{(pump 1 is maintained after arrived in port)} \\ \\ \text{not switched, if } RI \geq \text{min RI} \\ \text{(operation of pump 1 is continued)} \end{cases} \quad (3 - 6)$$

Model 2

$$\text{Pump operation} = \begin{cases} \text{switched, if forecast of RI in next port } < \text{min RI} \\ \text{(pump 1 is maintained in present port)} \\ \\ \text{not switched, if forecast of RI in next port } \geq \text{min RI} \\ \text{(operation of pump 1 is continued)} \end{cases} \quad (3 - 7)$$

Figure 3–4 shows the SD model of C_T . This model calculates the C_r , C_m , and C_d using the Equations (3-1), (3-2) and (3-3) respectively. These equations are inserted into SD model elements named “Running cost calculation”, “Maintenance cost calculation” and “Downtime cost calculation”, while the C_T is calculated in “Total operation cost calculation”. Both model 1 and model 2 contain the cost model in Figure 3–4 and respectively rely on Equations (3-6) and (3-7) which constitute a decision making whether the pump need to be placed on the maintenance action or continue its operation.

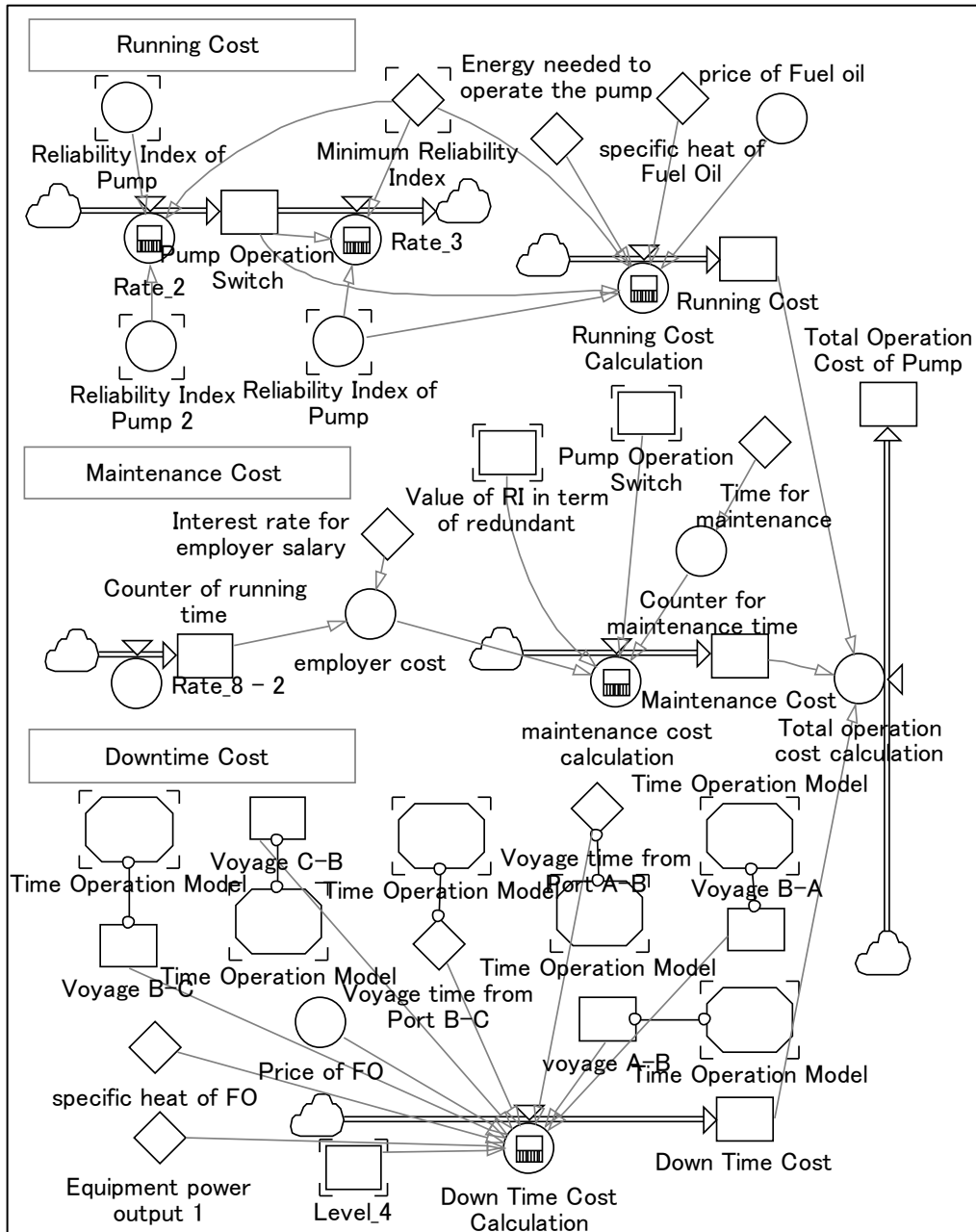


Figure 3-4 Total operation cost model

Input parameters into simulation in this chapter are shown in Table 3-1. The data is referred from the reference on the previous study by Artana [35]. This data is inserted into the simulation model which shown in Figure 3–3 and Figure 3–4.

Table 3-1 Input data of simulation

| Parameters | Value |
|---------------------------------------------|------------|
| Ship service speed | 14.5 knots |
| Port distance | |
| Port A – Port B | 2600 miles |
| Port B – Port C | 3500 miles |
| Power of pump motor | |
| No 1 and 2 SW pump | 20 kW |
| No 3 SW pump | 15 kW |
| No 1 and 2 CCFW pump | 20 kW |
| No 3 CCFW pump | 15 kW |
| No 1 and 2 JW pump | 14 kW |
| Simulation time (interval between docking) | 2.5 years |
| Rate of reliability deterioration | 0.05 % |
| Time duration at port | 3 hours |

The failure modeling of the main engine cooling pumps uses Weibull distribution. Weibull distribution is the distribution that best fits time to failure (TTF) obtained from the maintenance records. This distribution contains three parameters namely β (shape parameter), η (scale parameter) and γ (location parameter). The Weibull distribution has the probability density function and the reliability function as in the Equations (3-8) and (3-9) respectively. While the probability density curve and reliability curve of Weibull distribution are shown in Figure 3–5.

$$f(T) = \frac{\beta}{\eta} \left(\frac{T - \gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta} \right)^\beta} \quad (3 - 8)$$

$$R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^\beta} \quad (3-9)$$

where:

- β : shape parameter
- η : scale parameter
- γ : location parameter

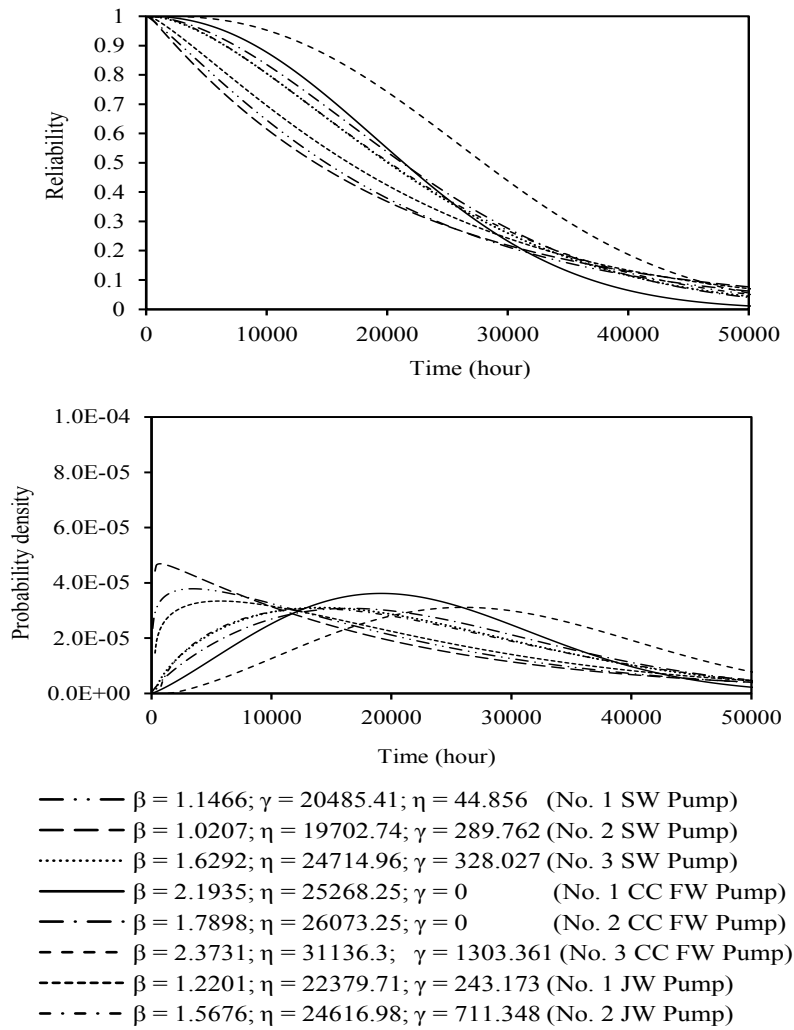


Figure 3-5 Reliability curve and probability density curve

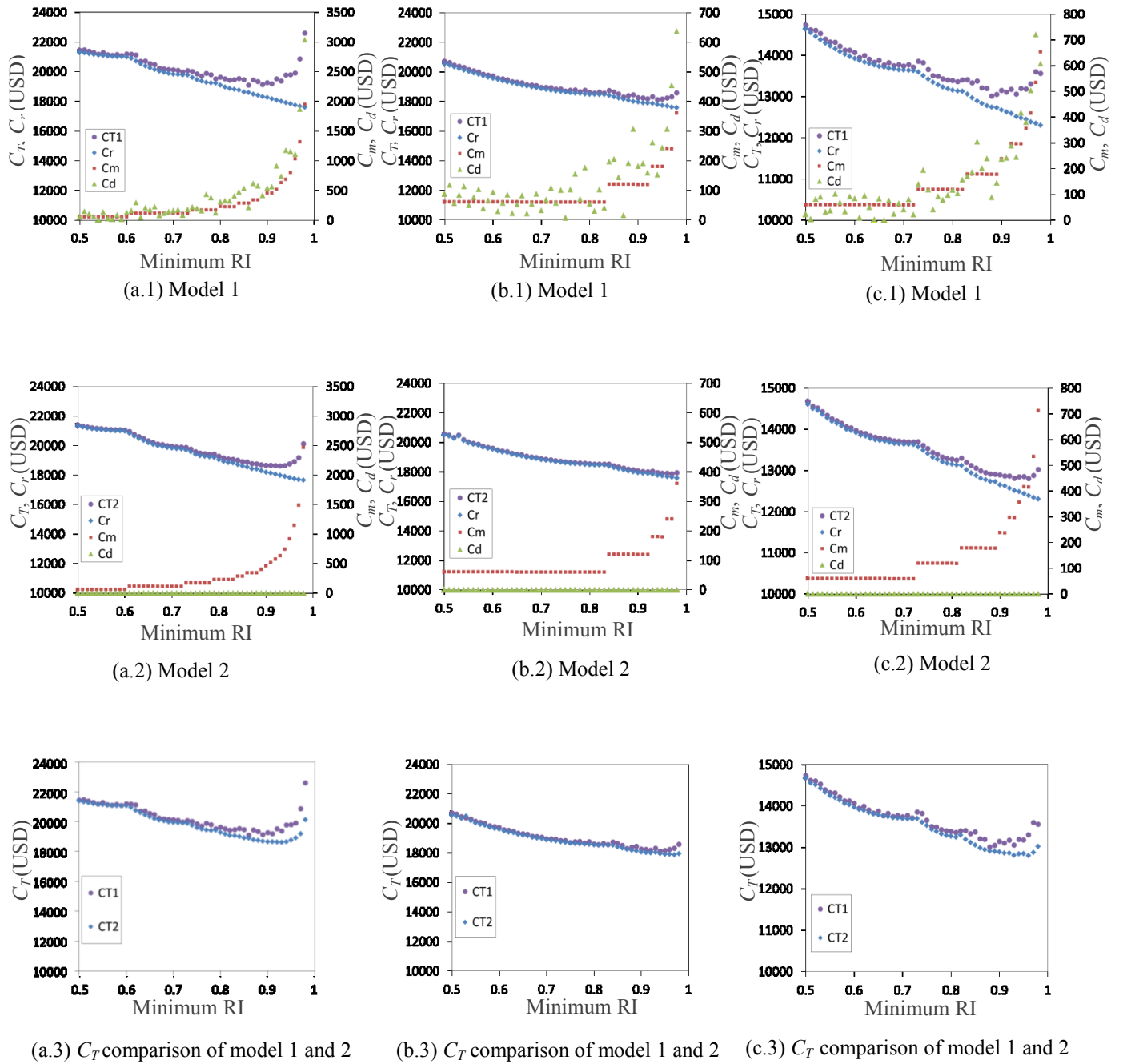


Figure 3–6 Simulation results. (a) No 1 and 2 SW Pump, (b) No 1 and 2 CCFW Pump, (c) No 1 and 2 JW Pump

The 3 parameters Weibull distribution suits for all of the pumps except for CCFW Pumps which suit the best on the 2 parameters Weibull distribution. The 2 parameters Weibull distribution has β and η parameters while the value of γ is zero. SD model in Figure 3–3 contains the element named “Reliability Index of Pump” for calculating the RI of the pump. The Equation (3-9) is included in this element. By inserting the equation into this element, reliability is calculated.

3.5 Results and Analysis

The operation of the cooling pump of the main engine has been simulated using SD in model 1 and model 2 which represent models without forecasting and with forecasting as clearly described before in the Figure 3–1 and Figure 3–2 respectively. The result of the SD simulation will be compared with the real data taken from the original ship operation and the previous research work. As mentioned before, the simulation condition and data is referred from the previous research work by Artana [35]. In this chapter, the result of the cost optimization using SD simulation will be discussed.

Figure 3–6 shows the result of the simulation on the three kinds of analyzed pumps. It illustrates the cost and its evolution according to the changes of minimum RI. Basically in model 1 and model 2, the C_T of each pump initially decreases because the C_r seems to have a decreasing trend according to the increasing of minimum RI. The increasing of the minimum RI affects the reducing of running time (t_r). The reduction of t_r reduces the C_r . In contrary, the longer the t_r , the C_r will increase because of there is performance deterioration.

The C_T decreases until reaching the minimum point and increases aftermath caused by the increasing of the C_m and C_d following the increasing of minimum RI. The decreasing C_r curve does not seem like a very much smooth curve. All of C_r curves not only in model 1 but also in model 2 show a wavy shape while decreasing. This phenomenon is caused by the difference of the location of point F (see Figure 3–1 and Figure 3–2) which indicate the length of t_r . During the degradation of the C_r curve, there are some different wave shapes that represents the difference in m . For example in Figure 3–6. a.1, the range of minimum RI between 0.75-0.82 and 0.83-0.93 have the different value of m .

However the value of C_m tends to be costlier along with the increasing of the minimum RI. The I_m is shorter when minimum RI increases. If the I_m shorter, the m will happen more frequently. Finally the C_m increases according to the increasing of minimum RI. In the other hand, it is clear that the value of C_d fluctuates. It is because the failure time of the pump variates depend on the minimum RI. It also causes the fluctuation of the length of downtime and the value of C_d . When the minimum RI increases, the amount of downtime will also increase and the C_d will be costlier. A different case happened in model 2 where the C_d does not appear because the forecasting model prevents downtime from occurring.

From Figure 3–6, it is revealed that the minimum RI where the minimum C_T could be obtained vary according to each type of pump. The optimization on the No 1 and 2 SW pump operation is shown in Figure 3–6. The optimization in model 1 reaches the minimum C_T in the amount of \$19,100 USD when the minimum RI is set at 0.86. While the model 2 is \$18,600 USD with the minimum RI at 0.93. In the optimization of the No. 1 and 2 CCFW pump, the optimum C_T for model 1 and model 2 are \$18,100 USD and \$17,900 USD at the minimum RI of 0.94 and 0.97 respectively. While for No. 1 and 2 JW pump, the value of optimum C_T are \$13,000 USD and \$12,800 USD with the minimum RI is 0.88 and 0.96 in model 1 and model 2 respectively. It is clear that model 2, using forecasting, has a benefit in making more reduction on the C_T as the result of preventing downtime from happening as one of the causes of C_d . The No. 3 SW pump and No. 3 CCFW pump have the operation schedule in the port service only when spending 3 hours during the port activity. Their C_T are \$173 USD. During the 2.5 years simulation, their operation without any maintenace due to the RI of these pumps does not reach the minimum RI during the operation time.

Table 3-2 Result and comparison

| | Real data | Optimization [35] | Model 1 | Model 2 |
|------------|-----------|-------------------|---------|---------|
| C_T (\$) | 70,740 | 50,763 | 50,226 | 49,642 |
| Reduction | | 28.24% | 29.00% | 29.82% |

Table 3-2 compares the result of optimization [35], model 1 and model 2 with the real data of planned maintenance system(PMS) which the value is \$70,740 USD. The model 1 results of the optimization of C_T are nearly identical with the results of optimization in [35]. It convinces us that the model is reasonable for representing the optimization in this particular type of ship machinery operation. Model 1 endeavors for the optimum value of C_T with the result of reduction, which is 29 % and nearly close to the result of the optimization in [35]. The proposed model 2, which uses a forecasting model, results 29.82 % reduction of the C_T . Model 2 improves the reduction of C_T . The reduction of C_T in model 2 seems insignificant compared to model 1 and optimization [35]. It may be because of the difficulty of recognizing the concrete value of C_d . In this study, the determination of C_d is only considered on the characteristics of the pump itself. C_d is calculated based on the liquid horse power which is unable to be generated if the pump needs repair/ maintenance. There are many other factors included in the C_d which are not able to be recognized and converted into the cost. The additional work load of the ship crew, loss of time etc. are example of these factors.

In this study, the determination of C_m can be improved when more detail of t_m as well as E for each of failure components of pumps could be known. In this research, t_m is considered to be the average time required for maintaining the pump. While carefull analysis should be taken when considering about S_t especially when different type of ship, company or flet. The value of S_t may varies because of the difference of them. The C_r represents the cost of energy used by pump. Since it is relied on the P_{in} and variable conversion i.e. O_p , C_h , ρ_v , and η_c , the conversion of the cost could possibly changes depend on the crude oil price. In this step of study, it is assumed to be unchanged. For completion in future research, it can be considered as well as the improvement of determination for the performance degradation which also influences the C_r . Concerning on the deterioration of RI after maintenance is also important. The existence of the deterioration is the consequence of the imperfect maintenance which is employed in this research. It is important to know the exact value of it, which represents the effect of the maintenance on the reliability of pump. Current research applied a constant value to assume the reliability degradation.

After knowing that the model 2 has the benefit of reducing the C_T , furthermore the

substantial matter is how to deal with the management operation and maintenance of the ship machinery to realize the most economical strategy. More consideration of the optimization in the SD simulation that has been done, is important to be conducted by paying more attention on the minimum RI, I_m , ship voyage trajectory, the pump's performance and the ship service speed. These components have significant influence on the output of the ship machinery operation. This research does not discuss the voyage conditions of the ship such as weather condition, wind, sea currents, etc. These factors may affect the ship service speed and voyage time. Therefore such matters could be additional parameters for future models.

3.6 Summary and conclusion

This chapter analyzes a quantitative simulation model of cost optimization on ship machinery operation. The simulation on the machinery in the cooling system of a ship's main engine which involves the SW pump, CCFW pump and JW pump has been conducted using SD simulation models 1 and 2, as discussed in previous chapter. Following the results of the SD simulation, the optimization using model 1 obtained minimum C_T which was nearly the same as the previous research. Model 2 had optimization results better than model 1. Applying model 2 into the pump's operation needs a good strategy for determining when and where the maintenance needs to be carried out. This decision of course relied on the I_m which could be derived from the minimum RI of the optimization result. Therefore model 2 gives the important information about appropriate minimum RI and I_m in order to acquire the lowest C_T as the most economical operation of pump.

Simulation results of optimization in proposed model 2 obviously shows the different value of the minimum RI for each analyzed pumps even though they have the same types and same properties. From this difference it can be identified that the I_m of each pump also exhibits a different value. This could be a recommendation for the ship crews which sometimes apply annual maintenance using the same interval period for the same type of pumps. Furthermore, The environmental condition of the ship voyage pattern may need more attention. Weather condition, wind direction, wave current etc. potentially influence the voyage condition like the ship service speed. In this research, it was not included in this simulation mechanism. Pump's optimization model can be improved by taking this matter under consideration for future work. Moreover,

there is a tendency of the same type of pumps to be costlier or more economic when they are operated. Since in the cooling system uses a standby mechanism, there is a model improvement opportunity for managing which pump is preferable to be the main operating pump. This model improvement may possibly further reduce the current optimum value of C_T .

Chapter 4

Optimum Maintenance Strategy of Ship Machinery by Considering Port Availability Constraint

Preventive maintenance has been adopted as one of the strategies to overcome machinery failure which can cause downtime of machinery systems [50]. This maintenance strategy is mostly applied to onshore machinery operations where the maintenance action is relatively easy to carry out without constraints of time and place. This chapter proposes models for a maintenance strategy of ship machinery operated offshore which is assumed to have maintenance inflexibility e.g. maintenance action can not be carried out during voyages and sometimes port constraint does not support for maintenance. The aim of this model is to manage the operation time and maintenance period of machinery in order to attain the minimum C_T under such kind of constraint.

4.1 Introduction

In the previous chapter in this book, as well as in the study by Handani [3], [4], [51], [52] maintenance could be conducted in all destination ports. This chapter considers the one port as a constraint (see Figure 4–1), which means that the maintenance can be done only in one particular port, the main port, because maintenance service is only available there. This constraint seems to

increase the C_T and

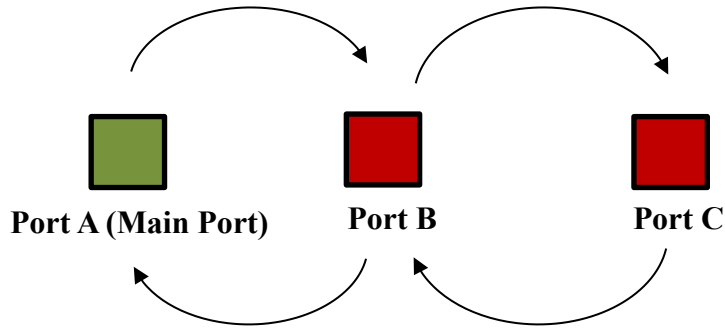


Figure 4-1 Ship voyage under constraint

affect configuration of C_r , C_m , and C_d . In the operation of ship machinery, the C_r increases according to the degradation of reliability and performance. Maintenance is required to maintain the performance and reliability level of machinery to a satisfying state. Maintenance could reduce the C_r but it induces C_m . While C_d appears since failure exists until the machinery is repaired. Based on this circumstances and constraint, a particular maintenance strategy is proposed to minimize the C_T .

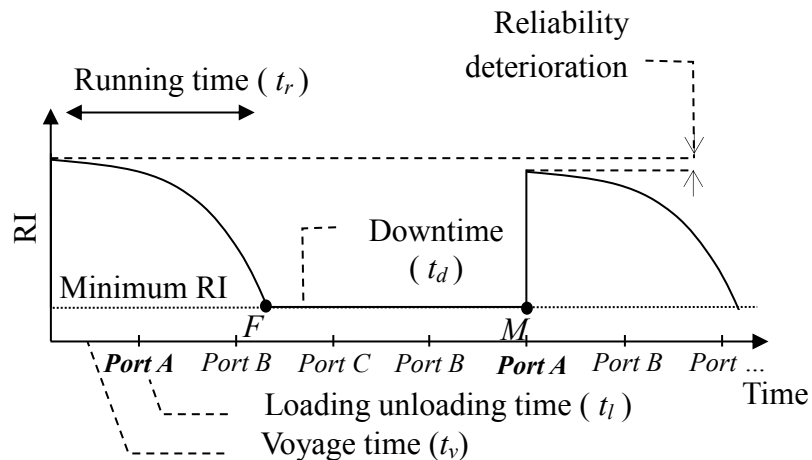


Figure 4-2 Reliability degradation of pump operated under port availability constraint

Figure 4–1 shows the ship voyage pattern by considering port availability constraint. Based on this voyage pattern, the reliability degradation of the cooling pump focused in this chapter can be drawn in Figure 4–2. This figure shows that maintenance of pump is done in the port A after the RI of pump reach minimum RI. Maintenance can not be done in Port B or in Port C. This condition causes the downtime is longer than the downtime illustrated in Figure 2–3 which has been discussed in Chapter 2. Furthermore, the optimization of the cooling pump operation and maintenance shown in Figure 2–3 has been done in the Chapter 3. This chapter will discuss the effect of the port availability constraint on the configuration of cost composition as well as the optimization of C_T .

4.2 Modeling the problem

SD is utilized to simulate the operation of a cooling pump of the ship's main engine which considers port constraint in this chapter. The simulation process includes a reliability analysis of pump, and a cost analysis. The construction of an SD simulation is best preceded by a knowledge of the system behavior through the utilization of a causal effect relationship diagram. This diagram shows the components which have a role inside the system. Previously, causal and effect relationship diagram has been discussed in Chapter 2 to express the operation and cost composition of pump as shown in Figure 2–4 and Figure 2–5. The causal effect relationship diagram and SD simulation model of the pump operation, which a port constraint is considered, are going to be discussed in in this section.

4.2.1 Cause and effect relationship of pump operation

Cause and effect relationship diagram is constructed to clearly see how the system operates. Figure 4–3 depicts the work of system components in the operation of a pump. In the diagram, running time (t_r) of pump has a positive relationship with the voyage time (t_v) because t_r of pump will be longer when the t_v is longer. By increasing t_r , reliability degradation of the pump occurs causing an increase in the probability of failure. The higher the probability of failure, RI of pump becomes lower because a negative relationship connects them. If the RI is low, the pump needs maintenance. Low RI increases the number of maintenance events. Maintenance activity causes reliability deterioration overtime. It is assumed that the reliability of a pump can not be restored

to its initial value. Reliability index after maintenance is assumed to be 0.05 % degraded.

Figure 4–3 is a cause and effect relationship diagram of the operational cost of a pump. In this figure can be seen that C_T has a positive relationship with C_r , C_m and C_d . The higher the value of these cost compositions, the higher the C_T will be. C_r is connected positively with t_r and P_{in} . By increasing t_r , reliability degradation occurs, P_{in} increases and finally C_r also increases. C_m depends on t_m and the number of maintenance events, while C_d has a positive relationship with P_{out} and t_d . The length of t_m and number of maintenance reinforces with the value of C_m . P_{out} and t_d have a reinforce action as well with C_d .

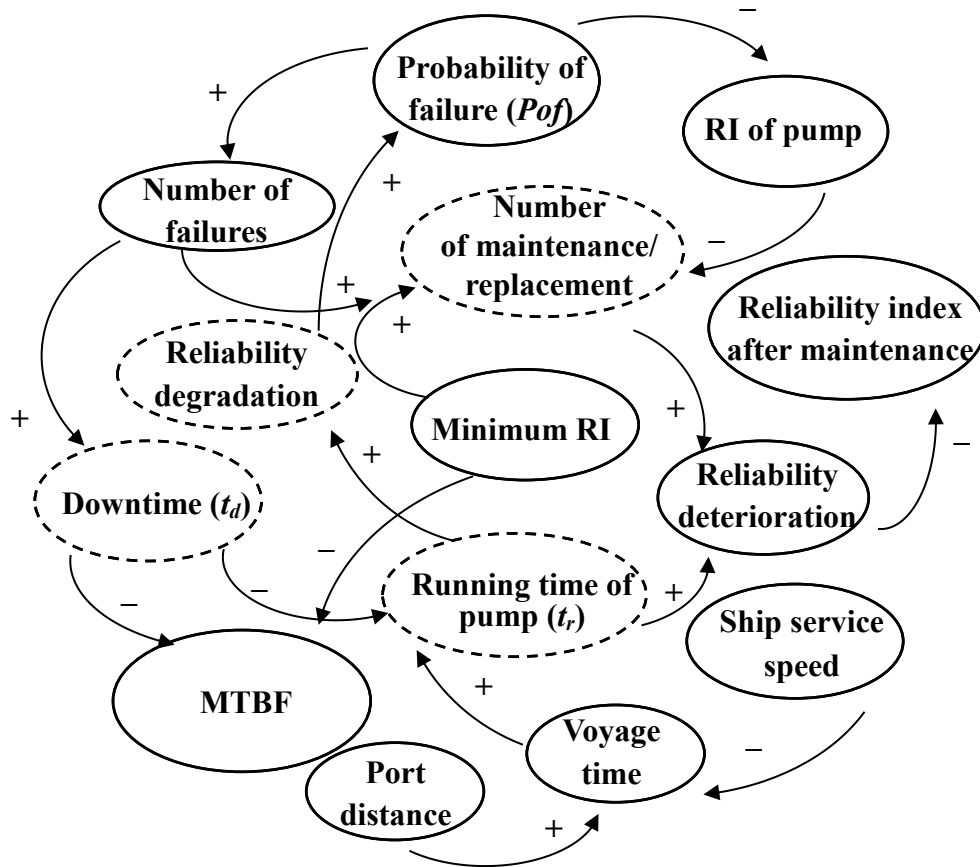


Figure 4–3 Cause and effect relationship diagram of machinery operation

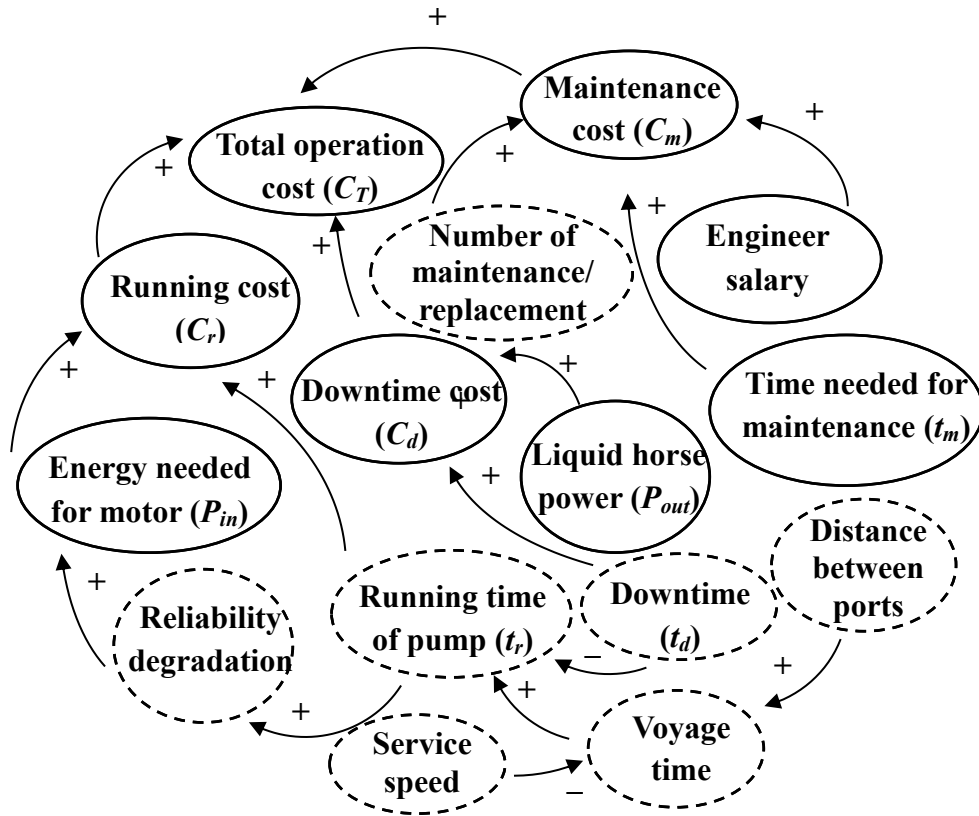


Figure 4-4 Cause and effect diagram of cost composition

4.2.2 System dynamics simulation model

Similar with Chapter 3, this chapter proposes model 1 and model 2 based on SD. Model 1 is an optimization model without forecasting which utilizes the minimum value of RI as the decision point to obtain the lowest C_T . While model 2 is an optimization model with forecasting that constructs its maintenance judgment by forecasting the value of RI which will avoid the machinery reaching minimum RI before the ship arrives at the main port again. Model 2 emphasizes an action to decide maintenance before the reliability of machinery decreases under the minimum RI. The maintenance is always taken account in the main port just before the minimum RI is reached. The following expressions describe the main concept of model 1 and model 2 proposed in this chapter. Equation (4-1) and Equation (4-2) represent how the model 1 and model 2 alter the working pump. The alteration deals with the changes of the operation of the main pump and the redundant pump.

Model 1 :

$$\text{Pump 1} = \begin{cases} - \text{switched to standby pump, if RI} < \text{minimum RI} \\ \text{(pump 1 is maintained after arrival in port A)} \\ \\ - \text{not switched, if RI} \geq \text{minimum RI} \\ \text{(operation of pump 1 is continued)} \end{cases} \quad (4 - 1)$$

Model 2 :

$$\text{Pump 1} = \begin{cases} - \text{switched to standby pump,} \\ \text{if forecast of RI in next port A} < \text{minimum RI} \\ \text{(pump 1 is maintained in port A)} \\ \\ - \text{not switched to standby pump,} \\ \text{if forecast of RI in next port A} \geq \text{minimum RI} \\ \text{(operation of pump 1 is continued)} \end{cases} \quad (4 - 2)$$

The causal effect relationship shown in Figure 4–3 and Figure 4–4 are developed into the model in SD. Equation (4-1) and (4-2) are also applied in order to build model 1 and 2, and each of them contain models of reliability analysis and cost analysis. The model of reliability analysis in Figure 4–5 includes a calculation of reliability analysis, ship voyage conditions, pump operation decisions etc. The data inserted into this model are pump distribution parameters, pump operation time, port distance etc. The cost analysis model in Figure 4–5 contains calculations of C_r , C_m , and C_d . The data inserted into this model are O_p , P_o , C_h , ρ_v , S_t , and E . Summation of C_r , C_m , and C_d obtains C_T as its final result which is calculated in the part of the model named “Total Operation Cost of Pump”.

4.3 Results and Analysis

The results of the simulations are shown in Figure 4–7. This figure shows the simulation results of the three focused cooling pumps of a main engine using model 1 and model 2. The result of the SD simulation will be compared with real pump operation data taken from real time ship operation and previous research work. As mentioned before, the simulation conditions and data

are referenced from prior research by Artana [35]. In this chapter, the conditions and data will be used as comparison for the result of SD simulation.

Figure 4–7 shows the evolving cost composition according to changes in the minimum RI. It can be seen how C_r , C_m , C_d and C_T behave similarly in both model 1 and model 2. In general, C_r decreases as the minimum RI increases because increases in the minimum RI shorten the value of t_r . The shorter the value of t_r , the more C_r will decrease. C_m obviously increases with the increasing of the minimum RI or shorter values of I_m . The shorter the value of I_m implies that more maintenance is needed. This causes more cost for maintenance. C_d shows a different

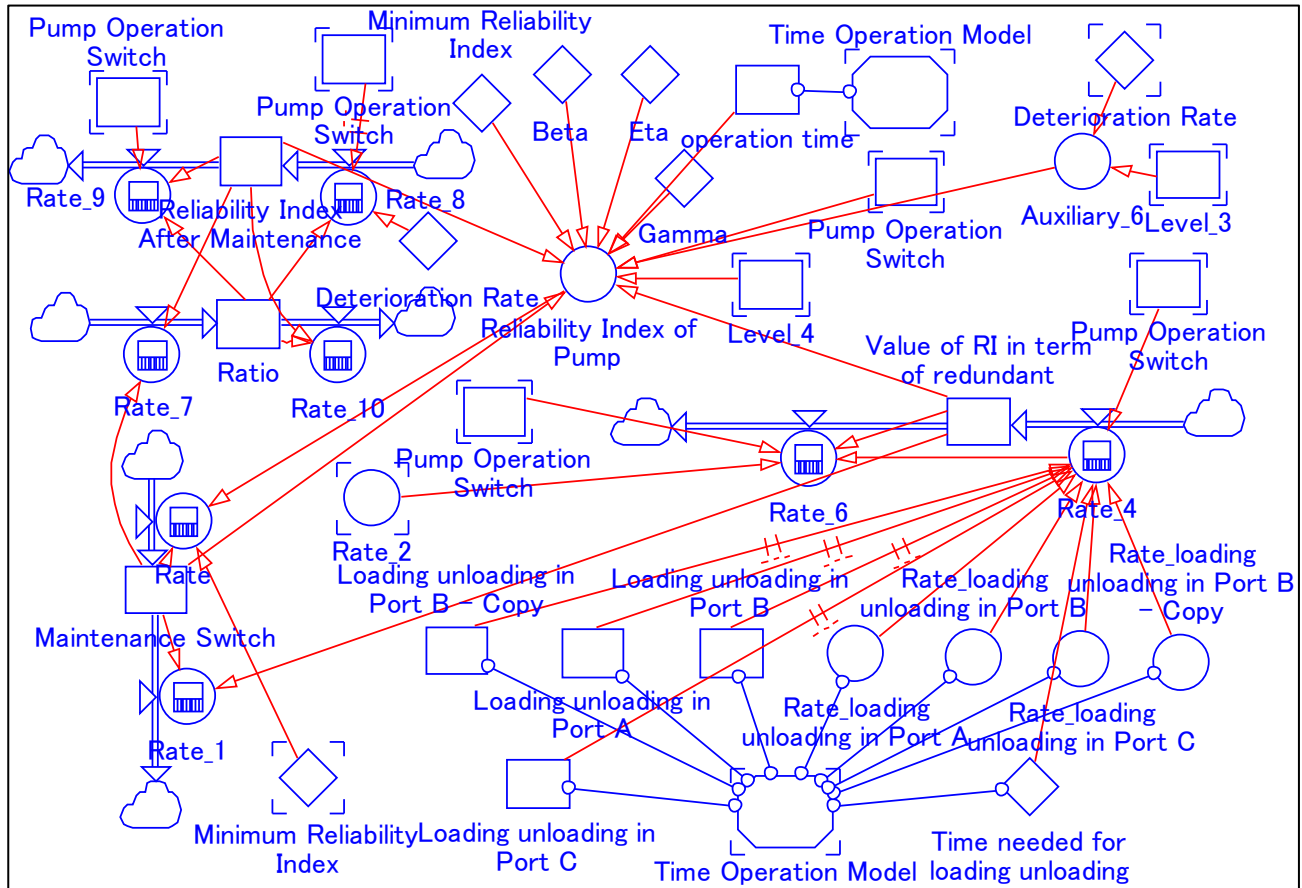


Figure 4–5 SD model of pump operation under port availability constraint

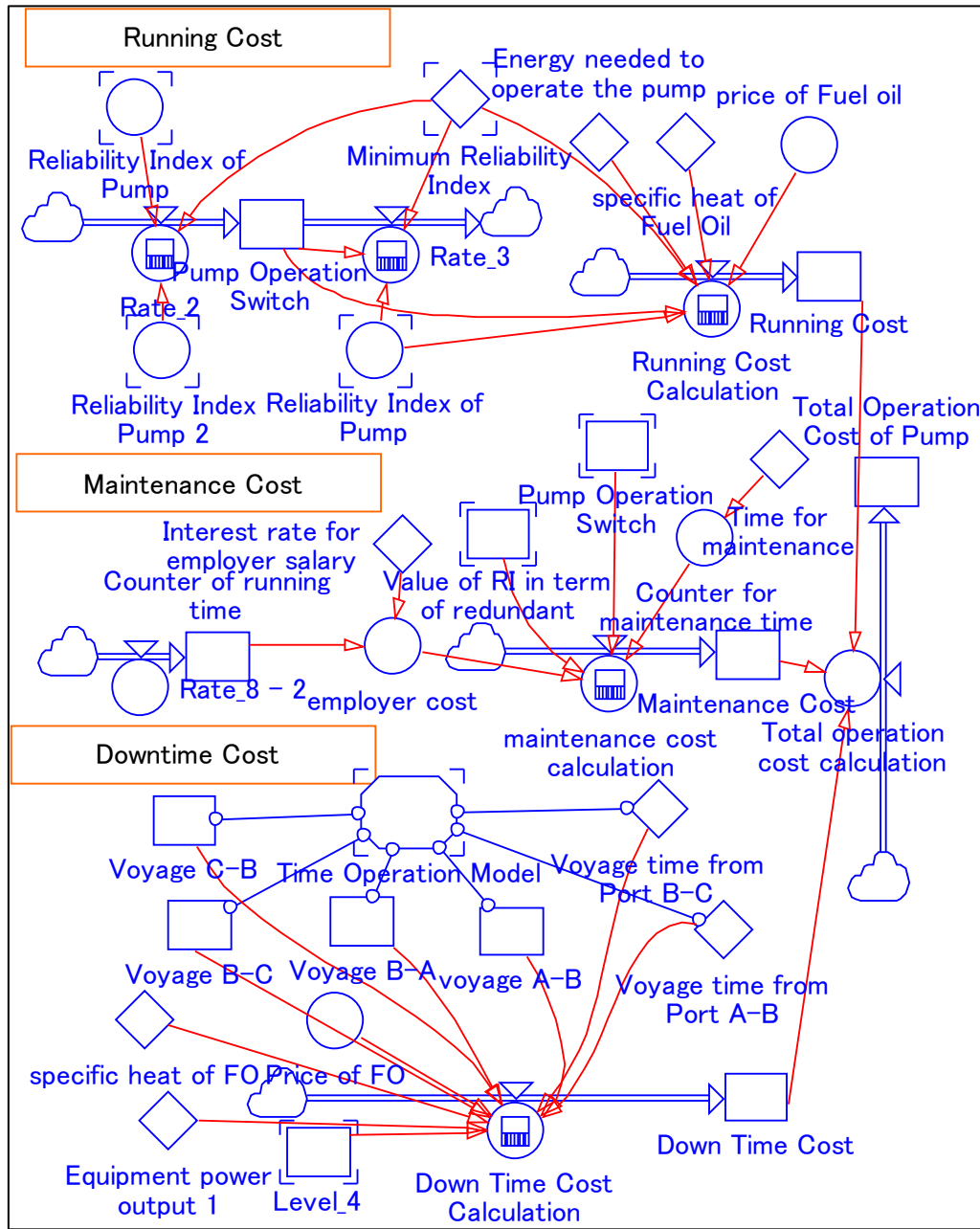
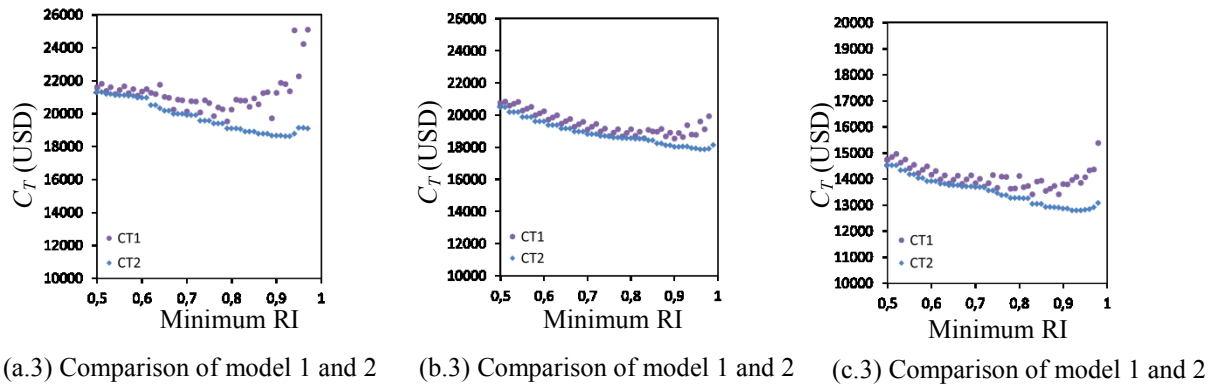
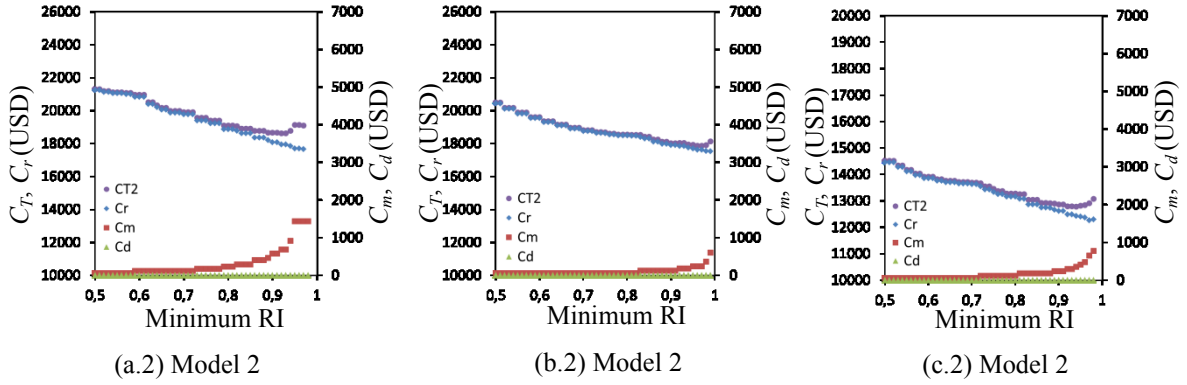
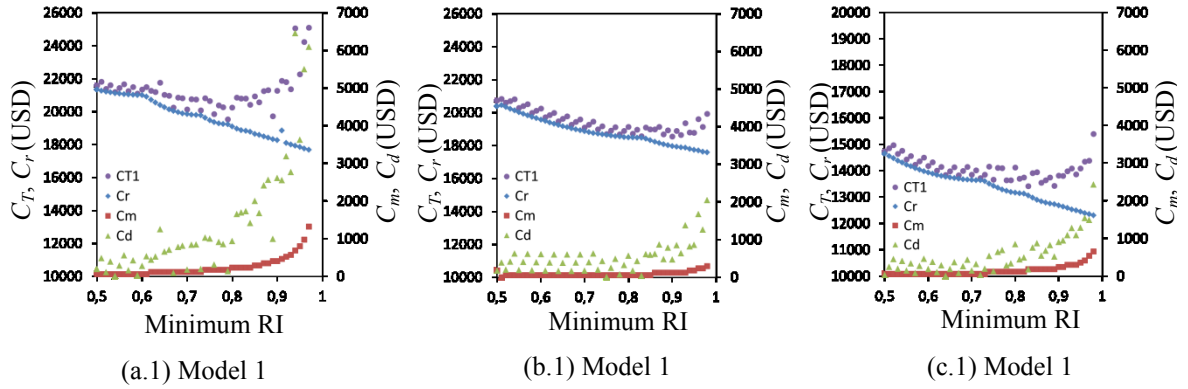


Figure 4-6 SD model of cost of machinery operation under port availability constraint

appearance between model 1 and model 2. In model 1, C_d tends to increase with increasing minimum RI or shorter I_m , while in model 2, C_d does not appear. Model 2 forecasts the value of RI of the pump during its operation. When the forecasting process states that, in the next main port, the RI will be less than the minimum RI, then maintenance should be carried out in the present main port before the ship leaves. This method prevents the appearance of downtime of pump and avoids C_d .

The forecasting method applied in model 2 gives a different value of C_T compared to model 1. Prevention of C_d which has been discussed above is the reason for this. As shown in Figure 4–7. a.3, b.3 and c.3, it can be clearly recognized that the value of C_T which changes with the value of minimum RI in model 2 is lower than in model 1. Additionally, the optimum value of C_T found in model 1 is costlier compared to the C_T found in model 2. The initial behavior of C_T of each pump decreases because the C_r seems to have a decreasing trend according to increases in the minimum RI. C_T decreases until reaching a minimum point and increases afterward. This is caused by increases in the C_m and C_d following increases of the minimum RI.

The results of the simulation suggest that the C_T of pump operation could be managed by choosing the level of minimum RI or the length of I_m . Minimum C_T could be obtained by operating the pump to the proper minimum RI or I_m . Figure 4–7 shows that the minimum RI which results in the minimum C_T vary according to each type of pump. The optimization of SW pumps 1 and 2 using model 1 obtains a minimum C_T in the amount of \$19,500 USD at 0.79 minimum RI, while the model 2 results a value of C_T in the amount of \$18,600 USD when the minimum RI is set at 0.92. The optimization for CCFW pumps 1 and 2, using model 1 and 2 results in minimum C_T at \$18,500 USD and \$17,800 USD when the minimum RI is 0.90 and 0.96 respectively. The JW pumps 1 and 2, result in C_T of \$13,400 USD and \$12,800 USD when the minimum RI is 0.83 and 0.94 in model 1 and 2 respectively. Model 2 clearly reduces the C_T in the operation of cooling pumps by utilizing the forecasting tool to prevent C_d . The simulation results of SW pump 3 and CCFW pump 3 do not appear in Figure 4–7. As mentioned in previous chapter, these small powered pumps are only operated in port. Their operation time is very short, so there is no maintenance during the 2.5 year simulation time. The value of their C_T is \$173 USD.



(a) SW pump 1 and 2, (b) CCFW pump 1 and 2, (c) JW pump 1 and 2

Figure 4–7 Results of simulation of pump operation under port availability constraint

Table 4-1 exhibits the comparison between the real data taken from Ship's planned maintenance system (PMS) and three kinds of optimizations. These optimizations are 1. Referred optimization [35], 2. Optimization A, the optimization which does not consider port availability for maintenance (see Chapter 3), and 3. Optimization B, the optimization which considers port availability for maintenance. It is revealed that optimizations can reduce the C_T and it becomes less than the initial C_T of Ship's PMS. The model 1 of optimization A has the value relatively near optimization [35], while model 2 obtains a lower C_T . An interesting result appears in the optimization B which has been conducted in this chapter by considering port availability for maintenance. Model 1 of optimization B obtains the most costly C_T and the lowest percentage of cost reduction compared to the other optimizations. The reason for this is that the downtime in this model is longer than in the other models. In real operation, the failure of a pump needs to wait until the ship has arrived at the main port while its function is replaced by the standby pump. The longer downtime impacts on the higher value of C_d and contribute to make C_T costlier.

Table 4-1 Result of optimization

| | Real data | Optimization [35] | Optimization A | | Optimization B | |
|-----------|-----------|-------------------|----------------|---------|----------------|---------|
| | | | Model 1 | Model 2 | Model 1 | Model 2 |
| CT (\$) | 70,740 | 50,763 | 50,226 | 49,642 | 51,829 | 49,631 |
| Reduction | | 28.24% | 29.00% | 29.82% | 26.73% | 29.84% |

Model 2 of optimization B obtains the lowest C_T and the highest cost reduction. The consideration on the port availability effects on the optimization of C_T in the SD model, especially C_d . The forecasting tool in model 2 prevents downtime to occur so C_d could be removed. Since the value of C_d in the model which considers the port availability for maintenance is relatively higher than other model, the forecasting tool results a higher impact on reducing the C_T . This is the reason for model 2 of optimization B to have the highest impact of cost reduction. The analysis of simulation result from this work clearly shows that model 2 which proposes forecasting tool brings a benefit for reducing C_T of main engine cooling pump. Although the reduced cost seems not so significant in the optimization A, but it shows a quite good improvement when model 2 is applied in case of port availability constraint which reach

29.84 % reduction of C_T .

Reduction rate of C_T may be more visibly improved if more variables which influence the C_d can be determined. In this paper, the determination of C_d is considered only on pump characteristics. In real conditions, there are some other factors that contribute to the C_d . Loss of time, loss of energy, failure propagation effect, additional work load of crew etc. These factors are quite difficult to be included in the cost. Improving the SD model by considering these other factors will bring us closer to the real conditions of C_d in pump operation. Other model developments could be an improvement in the determination of C_m . S_t and t_m should be determined in more detail, since t_m in this paper was considered to be the average time required for maintenance, while S_t could also be more defined depending on the type of ship or company. The value of C_r could possibly change depending on the oil price. In this study, it is assumed that C_r to be unchanged. It should be considered as well as the improvement of determination of performance degradation which also influences the C_r .

Table 4-2 Variation of service speed and port distance

| Parameters | Unit | Value |
|------------------------------------------|-------|-------------------------------------------------------------------------------------------------------|
| Ship service speed (V_s) | knots | 14.5 |
| Variation of V_s | knots | 10.0, 10.5, 11.0, 11.5, 12.0, 12.5, 13.0, 13.5, 14.0, 14.5, 15.0, 15.5, 16.0 |
| Initial Port distance | | |
| Port A – Port B | miles | 2,600 |
| Port B – Port C | | 3,500 |
| Variation of Port distance (A-B) - (B-C) | miles | 500 - 1,500; 1,000 - 2,000; 1,500 - 2,500; 2,000 - 3,000; 2,500 - 3,500; 3,000 - 4,000; 3,500 - 4,500 |

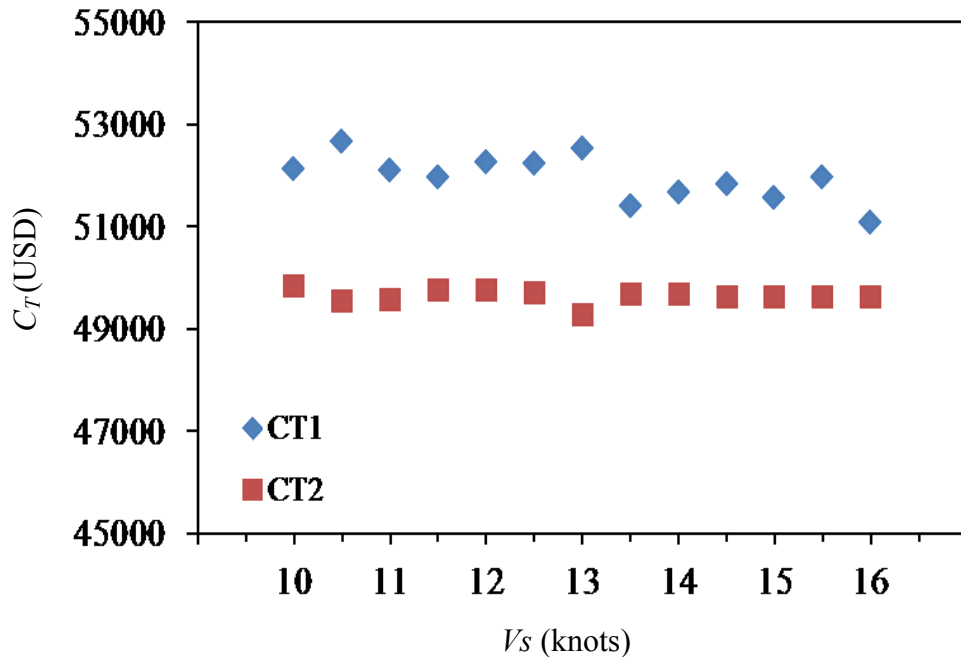
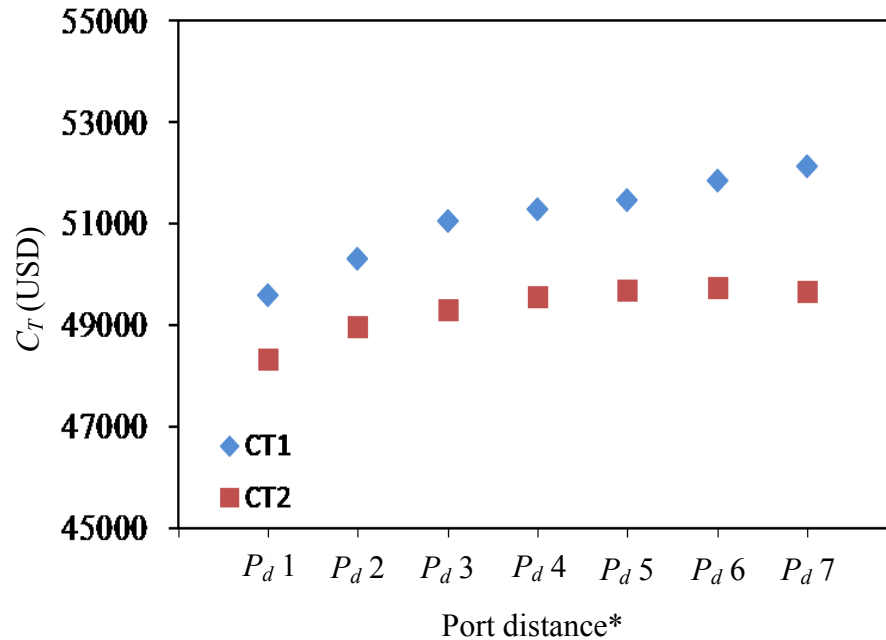


Figure 4–8 Variation of V_s

Further, the relationship between ship speed (V_s) and port distance (P_d) with C_T of main engine cooling pumps is taken into account in the optimization process. This is aimed to know how the changes on the ship speed and port distance influence the C_T . Table 4-2 contains the data inserted into the simulation regarding the variation of V_s and port distance. Figure 4–8 shows the optimization results for the different values of V_s . In model 1, V_s influences the C_T quite significantly. The lowest value of C_T is obtained when the ship is operated at 13.5 knot service speed. All of the results of model 2 clearly show that it reduces the C_T although its value does not change much by variation in V_s . Another significant relationship analysis was conducted by considering the port distance into the model. Figure 4–9 interprets the results of optimization. From this figure, it can be found that model 1 exhibits an increasing C_T according to the longer distance of ports. The same result is found in model 2. This is because the longer port distance increases the possibility of obtaining a bigger value of C_d . Additionally, the further the port distance, the longer the value of t_r and the higher the value of C_r . Model 2 gives the same benefit with all previous results that reduces the C_T . The result of the C_T shown by model 2 is lower than the one resulted by the model 1 in all of the variation of port distance. This result can be seen in Figure 4–9.



* P_d is the distance from port A to B and port B to C. P_d 1 until 7 are defined as 500 and 1500, 1000 and 2000, 1500 and 2500, 2000 and 3000, 2500 and 3500, 3000 and 4000, 3500 and 4500 nautical miles respectively.

Figure 4–9 Variation of port distance

4.4 Conclusion

This study conducted an optimization of operation costs for main engine cooling pumps in a ship. The case study was carried out on SW, CCFW and JW pumps. Model 1 and model 2 were constructed to simulate the pump operation under a port availability constraint. The results of simulations in this paper were compared with the initial PMS, referred optimization [35] and cost optimization without considering port availability for maintenance (Chapter 3).

Looking at the results of simulations which considered the port availability constraint, model 1 had the highest minimum C_T compared to other optimization results because the C_d of the operation of pump with a port availability constraint is higher than in the other operation conditions. Model 2 with port availability constraint shows a significant reduction in C_T , much

more than the reduction of model 2 without port availability constraint. This shows that the forecasting tool has a great impact on cost reduction. From this analysis, it can be concluded that the forecasting tool in model 2 is recommended for the operation of pump under port availability constraints.

Improvements in the simulation model need to be conducted with considerations of environmental conditions of the ship voyage. Weather condition, wind direction, wave current etc. potentially influence the voyage conditions, like ship service speed. In present research, this was not included in the simulation mechanism. Future study can improve the pump's optimization model by taking this matter under consideration. Moreover, there is a tendency for the same types of pumps to be sometimes costlier or more economic when they are operated. Since the cooling system uses a standby mechanism, there is a model of improvement opportunity to manage which pump is preferable to be the main operating pump. This model improvement may further reduce the current optimum value of C_T because it may decrease the C_r and C_d .

Chapter 5

Development of Risk Based Maintenance (RBM) for Ship Machinery Operation

5.1 Introduction

The maintenance strategy of ship machinery should comply with the regulations of the ship classification society. General inspection is carried out every five years, when the ship is at dock. Some machinery is disassembled to examine its condition. This means that the real condition of ship machinery only can be known every five years on the general inspection dates. Unexpected machinery trouble can occur between the docking surveys. A corrective maintenance scheme is usually carried out when a symptom of machinery trouble first appears. If a severe symptom happens when the ship is under operation, it can lead to a catastrophic incident. Moreover, a maintenance tasks are sometimes difficult to carry out during ship passage because of limited spare parts availability or the requirement of shore base support [36].

This chapter implements a method called risk based maintenance (RBM) to estimate the risk of machinery failure during its operation between two docking surveys of ship. By applying RBM, a catastrophic failure of machinery can be minimized because the risk is kept at an acceptable level by applying preventative maintenance. The demand for doing maintenance is prioritized based on the magnitude level of the risk. This study also proposes a new model

development for RBM, a ship position estimation for times when the machinery runs under a high level of risk. Benefit of this proposal is that it increases maintenance planning based on additional information of risk and can be used to guide an engineer to prepare for times of high level of risks. This research outcome should help management remain in budget since the optimum operation and maintenance can be reached without the reliability of ship machinery degrading.

5.2 Implementation of risk based maintenance (RBM) in the operation of ship machinery

This chapter focuses on a case study of ship machinery, especially the pumps in the cooling system of the ship's main engine. Pumps are needed to support the main engine work. Pump failure could induce interruption on the cooling system as well as the main engine of a ship. This paper utilizes system dynamics (SD) simulation to construct a model of RBM on the pump operation. SD is a powerful tool developed by Forrester [38] for simulating a complex system. The history and recent utilization of SD has been discussed in Chapter 2 which has presented that it has being used in maintenance management such appeared in the previous studies by Handani, Fan and Baliwangi [3], [4], [5], [48], [49] [51]. In this study, SD models the proposed RBM technique comprised of five steps:

1. Preliminary identification
2. Risk assessment
3. Risk evaluation
4. Ship position estimation
5. Maintenance planning

The details of the steps of RBM will be discussed in the next subchapter. The outcome of this work is a maintenance planning which reduces the risk of failures of cooling pump in a ship's main engine, and identification of the ship position when the pump runs into high risk during the ships operation at sea.

This chapter will discuss each step of the process of RBM in the application of ship machinery operation. The steps of RBM in this chapter are shown in Figure 5-1.

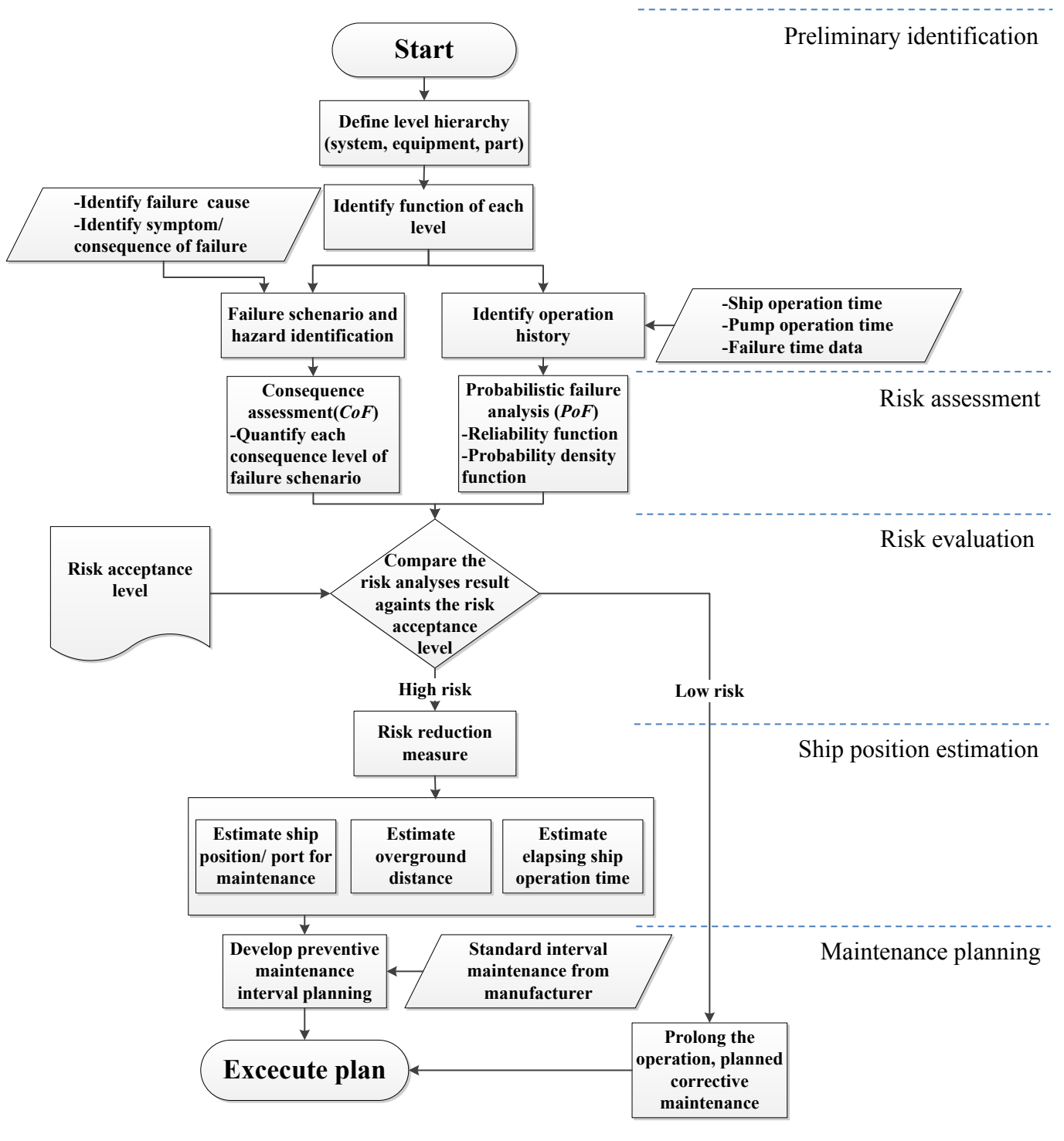


Figure 5-1 Overview of steps of the RBM

5.2.1 Step 1 : Preliminary identification

Preliminary identification is the first step of RBM. In this step, the focus system is analyzed in detail. The working principle and the potential failure mechanism of subsystems, machinery and parts of machinery are recognized based on the historical failure data and the result of literature study. In the ship, such information and data can be found in the ship operation log book. The failure of the smallest parts which comprise the machinery can be analyzed here. In preliminary identification, the information related to the machinery's symptoms and causes of failure are identified. This information is gathered in order to be used to know the failure scenario and hazard identification. Further, these machinery's symptoms and causes of failure are taken as input for subsequent analysis of the step of RBM. Figure 5-1 clearly shows the diagram including the structure of the preliminary identification.

Table 5-1 PDF and Reliability function of the failure distributions

| Distribution | PDF | R(t) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|
| Weibull 2 parameters | $f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta}$ (5-1) | $R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$ (5-2) |
| Gumbel max | $f(t) = \frac{1}{\sigma} e^{(-z-e^{-z})}$ (5-3) | $R(t) = 1 - e^{(-e^{-z})}$ (5-4) |
| Gumbel min | $f(t) = \frac{1}{\sigma} e^{(z-e^z)}$ (5-5) | $R(t) = e^{(-e^z)}$ (5-6) |
| <p>* β = shape parameter, η = scale parameter (weibull 2 parameters) σ = scale parameter, μ = location parameter (gumbel max and gumbel min) * $z = \frac{t-\mu}{\sigma}$</p> | | |

5.2.2 Step 2 : Risk assessment

5.2.2.1 Consequence of failure (*Cof*) analysis

The outcome of a failure can be defined as system performance loss, financial loss, human safety loss and environment loss. This paper adopted an equation from Khan [8] to determine the *Cof*. The form of the equation is presented as follows.

The consequence of the failure symptom recognized in the step of preliminary identification is quantitatively calculated by using Equation (5-7). The details on the usage of this equation appear in the case study in this chapter.

$$Cof = \sqrt{(0.25A^2 + 0.25B^2 + 0.25C^2 + 0.25D^2)} \quad (5 - 7)$$

where:

- A_i : system performance loss
- B_i : financial loss
- C_i : human safety loss
- D_i : environment loss

5.2.2.2 Probability of failure (*Pof*) analysis

The probability of a basic event failure of machinery found in the preliminary identification, is quantified. The record of machinery failure is utilized in order to know the probability of this failure occurring. This paper uses statistical analysis to find the failure distribution which best represents the characteristics of the time to failure data of the machinery. There are three distributions which appear in this paper, i.e.

1. Weibull two parameters,
2. Gumbel max, and
3. Gumbel min.

The probability density function (*PDF*) and reliability function of these three distributions are summarized in Table 5-1. In the final risk assessment, risk estimation is determined by combining the results of *Cof* and *Pof* analysis. Risk level of each piece of machinery is found by multiplying the results of *Cof* and *Pof* analysis as shown in the following expression.

$$Risk = Cof \times Pof \quad (5 - 8)$$

where :

Pof : probability of failure
Cof : consequence of failure

5.2.3 Step 3: Risk evaluation

The estimated risk which results from the previous step is compared with risk acceptance criteria. The machinery which exceeds the acceptance criteria is subject to maintenance to keep it at an acceptable risk level. The maintenance brings the reliability of machinery into a higher state so the *Pof* decreases. This decreasing *Pof* impacts on reducing the risk of machinery causing the risk becomes acceptable comparing to the risk acceptance level.

5.2.4 Step 4 : Ship position estimation

In this step, this study includes the position of the ship during her voyage when the estimated risk of the machinery is in the unacceptable risk level.

5.2.5 Step 5 : Maintenance planning

The recognized position of ship is important if engineer are to construct an appropriate maintenance plan for the ship machinery. This is related to when and where the maintenance should be best done. The planned maintenance will reduce the risk of machinery failure in order to bring the risk down to an acceptable risk level. The following equation is utilized to determine the maintenance planning in this study.

$$m_p = I_m - t_r \quad (5 - 9)$$

where

- I_m : interval time between maintenance
- t_r : elapsed running time

m_p is the maintenance planning which interprets the remaining operation time for maintenance. I_m is the interval between maintenance which complies with the risk acceptance criteria. t_r is the current operation time which indicates how long the machinery has been in operation. If t_r equals zero, $m_p = I_m$. This means that the machinery has never been operated since it was installed or since the last maintenance. When t_r equals to I_m , it means that the time for maintenance has coming. Determination of I_m and t_r are depend on the type of the failure distribution on which the failure of machinery is best represented, i.e. Weibull 2 parameters, Gumbel max and Gumbel min. They are defined as Equations (5-10), (5-11), (5-12), (5-13), (5-14), and (5-15) based on their type of failure distribution. The Equation can be seen as following forms.

5.2.5.1 Weibull 2 parameters

$$I_m = \eta \cdot \left(-\ln \left(R_{I_m}(t) \right) \right)^{\frac{1}{\beta}} \quad (5 - 10)$$

$$t_r = \eta \cdot \left(-\ln \left(R_{t_r}(t) \right) \right)^{\frac{1}{\beta}} \quad (5 - 11)$$

where :

- η : scale parameter
- β : shape parameter
- R_{I_m} : reliability at proposed I_m
- R_{t_r} : reliability at t_r

t : operation time

5.2.5.2 Gumbel max

$$I_m = \mu - \sigma \cdot \ln \left(-\ln \left(1 - R_{I_m}(t) \right) \right) \quad (5 - 12)$$

$$t_r = \mu - \sigma \cdot \ln \left(-\ln \left(1 - R_{t_r}(t) \right) \right) \quad (5 - 13)$$

where :

μ : location parameter

σ : scale parameter

R_{I_m} : reliability at proposed I_m

R_{t_r} : reliability at t_r

t : operation time

5.2.5.3 Gumbel min

$$I_m = \mu + \sigma \cdot \ln \left(-\ln(R_{I_m}(t)) \right) \quad (5 - 14)$$

$$t_r = \mu + \sigma \cdot \ln \left(-\ln(R_{t_r}(t)) \right) \quad (5 - 15)$$

where :

μ : location parameter

σ : scale parameter

R_{I_m} : reliability at proposed I_m

R_{t_r} : reliability at t_r

t : operation time

5.3 Case study: development of RBM for the cooling system of the ship's main engine

The case study focuses on the pumps which are installed in the cooling system of a ship's main engine. This system has an important role in keeping the main engine at a working temperature. A breakdown in any part of the cooling system could disturb the main engine. One of the most important parts of the cooling system are the pumps, because they transfers the coolant fluid into the cooling system. This chapter will discuss the application of the proposed development of RBM method in the case study of the operation of the cooling pumps of a ship's main engine. The RBM method discussed in this subchapter is based on the structure of RBM on the previously shown in Figure 5–1 which illustrates the whole step of RBM process. Further, the SD is utilized to build simulation of RBM. Figure 5–2 shows the total model of RBM in SD. This SD model of RBM is constructed of pieces of sub models i.e. 1. Preliminary identification, 2. Risk assessment, 3. Risk evaluation, 4. Maintenance planning, including 5. Ship position estimation. The following description will discuss in detail about each step of the SD model of RBM.

Table 5-2 Properties of the analyzed pumps of the cooling system of ship's main engine

| Pump Name | Number installed | Capacity x head | rpm | Power |
|-----------|------------------|-------------------------|------|-------|
| | | (m ³ /h x m) | | (kW) |
| SW pump | 3 | 285 x 15 | 1800 | 18,5 |
| CCFW pump | 4 | 190 x 25 | | 22 |
| JW pump | 2 | 65 x 30 | | 11 |

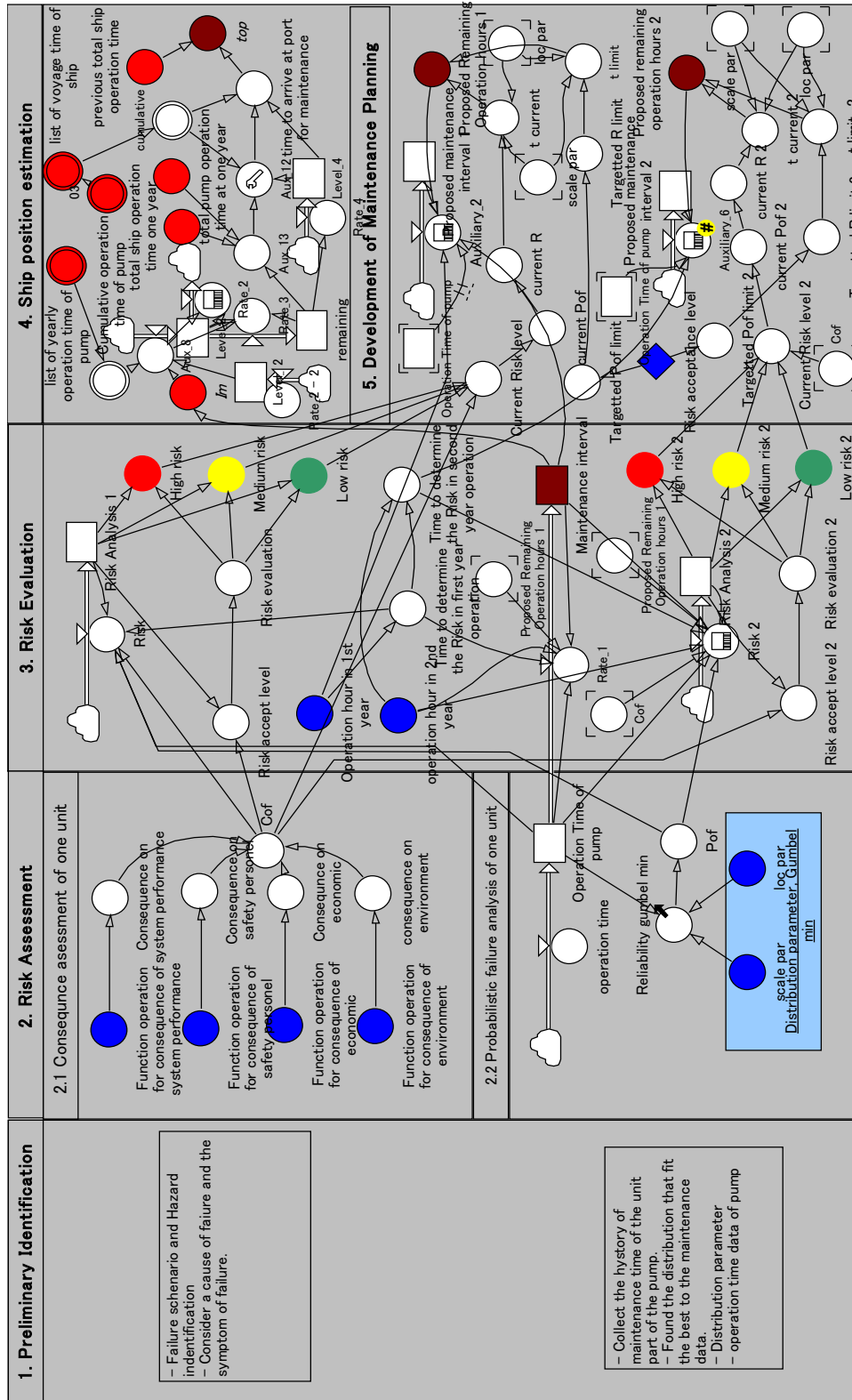


Figure 5-2 SD model of RBM

5.3.1 Preliminary identification

There are three types of pumps analyzed which have typical properties as shown in the Table 5-2. The total number of pumps is nine units comprised of sea water (SW) cooling pumps (4 units); central cooling fresh water (CCFW) pumps (3 units); jacket water (JW) pumps (2 units). The pumps' failure modes are identified. The common failure causes and symptoms of the pumps are studied from the pump operation history and reference studies. The overview of some failure causes and symptoms in the operation of cooling pumps are shown in Figure 5–3. This figure shows the possible causes which contribute for each of the symptoms appearing in the operation of cooling pump.

In Figure 5–3 which is modified from Bloch and Mobley [53], [54], the relation of the common causes (C1 ~ C10) and the possible resulting symptoms (S1~S16) are clearly shown. Out of all the pump parts, the mechanical seal, the O-ring, the shaft and the discharge valves are the parts which experience the most trouble based on the records of the ship operation history. Considering the tendency results of the data, this paper focuses on these common failures appearing in the above mentioned pump parts.

5.3.2 Risk assessment

5.3.2.1 *Cof* analysis

The possible symptoms of failure found in the preliminary analysis are taken into account in order to quantitatively measure the consequence of failure. Actually *Cof* analysis can be performed in terms of some types of loss as shown in the Equation (5-7). The symptoms of failure recognized in the previous step indicate that the consequences of the failure of the cooling pump can be measured by considering an assessment of the system performance loss conducted in this study. This study does not perform analysis on human safety, environmental effects or financial consequences. Performance loss indicated by the symptoms of failure in Figure 5–3 is classified into their level by utilizing performance function which is provided in the Table 5-3. After finding the A_i for each symptom, the result of *Cof* analysis is obtained by inserting the value of A_i into Equation (5-7).

| | | Failure symptoms | | | | | | | | | | | | | | | |
|-----------------|--------------------------------------------------|------------------|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| Part name | Failure causes | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 |
| Mechanical seal | Entrained air by seal leaks | C1 | • | • | • | | | | • | • | | • | | | • | | |
| | Improper mechanical seal | C2 | | | | | | • | | | | | | • | | | |
| O-ring | Excessive compression/ pressure/ temperature | C3 | • | • | | | | | | | | | | • | | | |
| | Rough sealing surfaces | C4 | • | • | | | | | | | | | | • | | | |
| Shaft | Bent shaft | C5 | | | | • | • | • | • | • | • | | | • | | • | • |
| | Parts loose on the shaft | C6 | | | | | | | • | • | | | | | | | |
| | Shaft running off center because of worn bearing | C7 | | | | | | | | | | | | • | | | |
| | Excessive wear at internal running clearances | C8 | • | • | | | | | • | | • | | | | | | |
| Discharge valve | Leakage valves | C9 | • | • | | | | | | | | | | | | | |
| | Discharge valve failed to open/ partially open | C10 | • | • | • | | | | • | | | • | • | | | | |

Figure 5–3 Failure causes and symptoms of cooling pump of main engine. Constructed after modification from Bloch and Mobley [53], [54]

Table 5-3 Performance function. Modified after Khan [8].

| Level | Description | Function (A_i) |
|-------|-----------------------------------------------------------------------------------------------------------------------------------|--------------------|
| I | Very important for operation of cooling pump ~Failure would cause the pump to stop functioning | 8-10 |
| II | Important for good pump operation ~Failure would cause impaired performance and adverse consequences | 6-8 |
| III | Required for good pump operation ~Failure may affect the pump performance and may lead to subsequent failure | 4-6 |
| IV | Optional for good performance ~Failure may not affect the performance immediately but prolonged failure may cause pump to fail | 2-4 |
| V | Optional for operation of cooling pump ~ no effect to the performance of cooling pump if failure happened | 0-2 |

SD model shown in Figure 5-4 is a part of SD model of RBM which performs *Cof* analysis. The highest value of A_i is inserted into the number 1 unit of the SD model. The highest value of A_i is used because it has the highest possibility to induce more serious consequences greater than the result of A_i from other causes of failure. In this model, the Equation (5-7) is used at number 2 unit of the SD model (see Figure 5-4). The results of *Cof* analysis are then shown at the number 2 unit of the SD model. Table 5-5 summarizes the results of the *Cof* analysis for all of the parts of cooling pump in focus. It clearly shows that entrained air by seal leaks (C1), excessive compression/ pressure/ temperature and rough sealing surface (C3 and C4), bent shaft (C5) and discharge valve failed to open (C10) result in the most catastrophic consequences, i.e. pump loses prime after starting (S14), mechanical seal damage/ leaks excessively (S13), coupling fails (S16), no liquid delivery (S4) respectively.

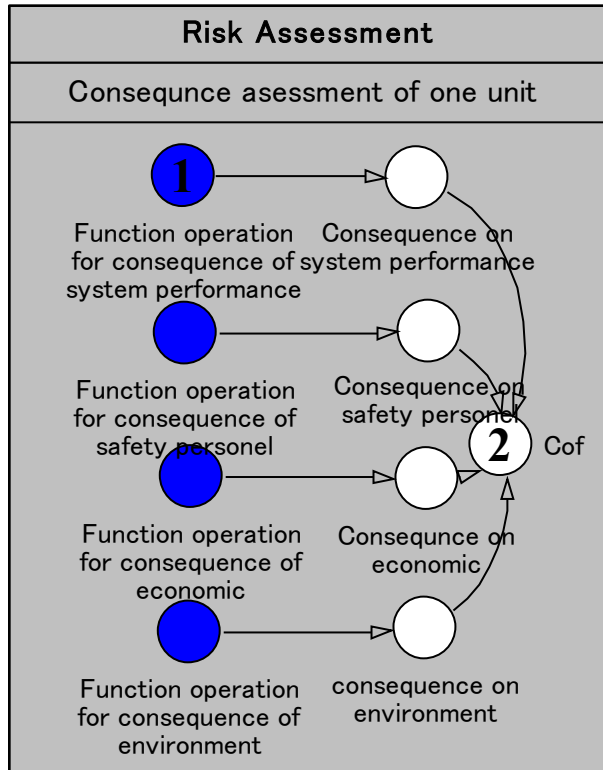


Figure 5-4 SD model of *Cof* analysis

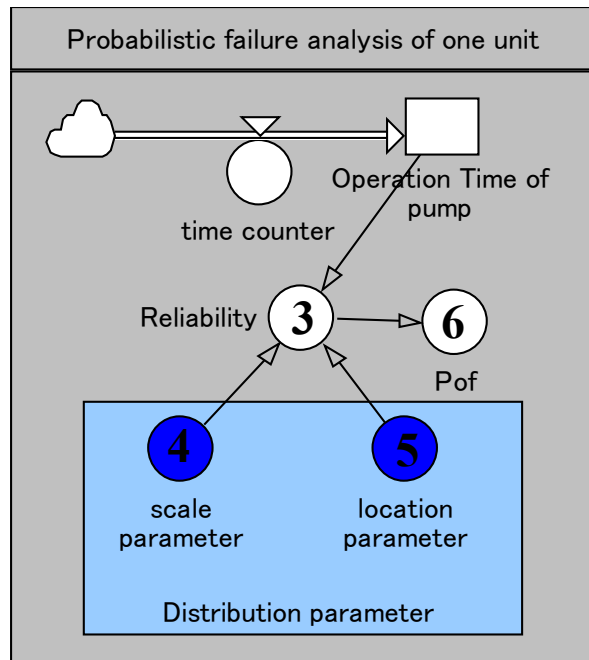


Figure 5-5 SD model of *Pof* analysis

5.3.2.2 *Pof* analysis

This study analyses the operation history of the cooling pumps of a ship's main engine under 16 years of operation from 1997 until 2012. Failure time history has been recorded and analyzed. Table 5-4 depicts the failure distribution for all of the analyzed parts of the cooling pumps. The failure distributions listed in Table 5-4 is the distribution that best fits into the data of failure time. The quantitative *Pof* analysis utilizes these failure distributions by inserting the related equation and distribution parameters into the SD model of RBM. The SD model of *Pof* analysis appears in Figure 5-5. In this model, reliability function in Table 5-1 is inserted into the number 3 unit of the model, while the distribution parameters listed in the Table 5-4 are inserted into numbers 4 and 5. The result of *Pof* analysis comes up in the number 6 unit of model. The results of *Pof* analysis for all of the analyzed parts of the analyzed pump are completely presented in Table 5-6.

As pump operation time goes on, the failure probability of the parts of the pump increases, in the same time followed by the degradation of reliability [4]. The RBM technique enables us to know the risk of pump failure by considering increases in the probability of failure. Risk estimation of the pump failure is determined by multiplying the result of the *Cof* and *Pof* analysis. The number 7 unit of the SD model in Figure 5-6 calculates the risk estimation of cooling pump failure. In this paper, the result of risk estimation is shown in two different periods of t_r . This is purposed to give clearer understanding on the changing value of *Pof* as well as the risk of failure during pump operation. Table 5-6 lists the results of the risk estimation for the first year of operation and the second year period of operation. In the first year, the t_r of SW pumps and CCFW pumps are 1336 and 1177 hours and in the second year operation are 4569 and 3852 hours respectively. Risk of JW pumps are estimated at the second and third year of operation, i.e. at 1660 and 2890 hours, because the t_r of JW pumps per year are less than the other cooling pumps. The third year of operation is used in the simulation of JW pumps in order to show more reduction of risk. This data was taken from the real operation history of the analyzed pumps take from the focused ship. In Figure 5-6, the data is inserted into numbers 8 and 9 units of the SD model for first year and second or third year operation respectively. From these units of SD model, the data of operation time (first and second/third year) is used for determining the risk in the subsequent unit SD model shown in Figure 5-6.

Table 5-4 Failure distribution of the analyzed parts of the cooling pumps

| Pump name | Part Name | Distribution Name | Distribution Parameter | | | |
|-----------|-----------------|-------------------|------------------------|-----------|--------|------------|
| | | | σ | | μ | |
| SWP 1 | Mechanical seal | Gumbel max | σ | 2727.7145 | μ | 6090.5733 |
| | O ring | Gumbel max | σ | 3591.3595 | μ | 13099.3139 |
| | Shaft | Gumbel max | σ | 916.9122 | μ | 11555.8849 |
| | Discharge valve | Gumbel min | σ | 1826.0322 | μ | 34357.5373 |
| SWP 2 | Mechanical seal | Gumbel max | σ | 3167.5149 | μ | 8720.3298 |
| | O ring | Gumbel min | σ | 1655.4744 | μ | 21848.7532 |
| | Shaft | Gumbel max | σ | 583.4896 | μ | 13353.7449 |
| | Discharge valve | Gumbel min | σ | 1016.2718 | μ | 37105.1991 |
| SWP 3 | Mechanical seal | Weibull 2 Par. | β | 5.9175 | η | 14893.2709 |
| | O ring | Weibull 2 Par. | β | 6.2210 | η | 25786.8388 |
| | Shaft | Weibull 2 Par. | β | 7.9968 | η | 27817.3633 |
| | Discharge valve | Gumbel max | σ | 2252.0440 | μ | 31945.4698 |
| CCFW 1 | mechanical seal | Gumbel min | σ | 2917.4479 | μ | 18831.2752 |
| | O ring | Gumbel min | σ | 835.0361 | μ | 19902.5203 |
| CCFW 2 | mechanical seal | Gumbel min | σ | 1526.7017 | μ | 11268.6248 |
| | O ring | Gumbel min | σ | 742.2342 | μ | 18790.0776 |
| CCFW 3 | mechanical seal | Gumbel max | σ | 9432.8196 | μ | 20488.8841 |
| | O ring | Gumbel min | σ | 4563.1935 | μ | 32716.6392 |
| CCFW 4 | mechanical seal | Gumbel min | σ | 877.9233 | μ | 11886.6141 |
| | O ring | Gumbel max | σ | 4040.7997 | μ | 16061.7769 |
| JWP 1 | mechanical seal | Gumbel min | σ | 250.0669 | μ | 5848.3950 |
| | O ring | Gumbel max | σ | 583.4896 | μ | 4353.7450 |
| JWP 2 | mechanical seal | Gumbel min | σ | 683.8604 | μ | 7735.6860 |
| | O ring | Gumbel max | σ | 625.1674 | μ | 4879.0125 |

5.3.3 Risk evaluation

In this step, SD simulation of RBM calculates the risk estimation of the operation of the cooling pump of the ship's main engine. After risk estimation has been conducted, risk evaluation is presented to classify the risk of failure into the low, medium and high risk. Risk evaluation determines the need of the cooling pumps to be maintained in order to bring down high risk to an acceptable level. In this step, risk acceptance criteria need to be set to give the minimum risk level of cooling pumps during operation. This study uses the Pof_{limit} which is obtained from the conversion of the risk acceptance limit. Because the level of Cof in Table 5-5 is 4 and 5, the result of the conversion value for the Pof_{limit} is 1.0E-02 as obtained from DNV-RP-G101 [55]. The risk is classified in unit model number 11 after the value of Pof_{limit} has been set in unit number 10 of the SD model. The result of risk classification appears in units 12, 13 and 14 in Figure 5–6. In the constructed SD model, the red, yellow and green colors of the units respectively represent high, medium and low levels of risk.

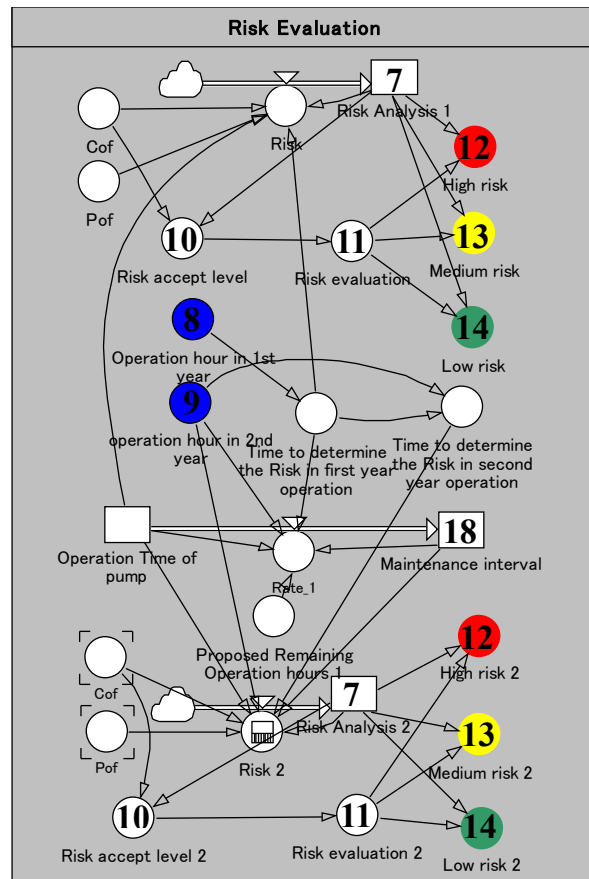


Figure 5–6 SD model of risk evaluation

The results of the SD simulation listed in the Table 5-6 show that there is no maintenance needed for any of the analyzed pump parts in the first year of operation, since the value of Pof is under the Pof_{limit} . During the second year of operation, there is maintenance/replacement for mechanical seal of SWC pump 1 and 2. The parts that needs maintenance/replacement are indicated by italicized writing in the Table 5-6. The Pof value of these parts reaches the Pof_{limit} when they enter the second year operation time. Maintenance is indicated by the changing value of m_p , which becomes longer by the end of the second year of operation, i.e. 2920 hours into 3940 hours and 2550 hours into 3200 hours respectively for mechanical seal of SW pump 1 and 2. This means that the maintenance has been done which can be assumed that I_m equals to m_p just after the maintenance accomplished. In the end of second year operation, it can be seen that the value of m_p is longer than in the first year of operation.

5.3.4 Ship position estimation

Previously, risk estimation has been quantified followed by risk evaluation which determines the level of risk. In this step, the position of the ship is taken into account when a high level of risk occurs in any of the cooling pumps during their operation. SD model of ship position estimation is proposed to allow this step to work. The construction of the model is based on real data of the ship voyage history over the past 16 years. The SD model of ship position estimation is shown in Figure 5–7. Some types of required data for ship position estimation such as I_m , yearly pump operation and yearly ship voyage time are inserted into this SD model, units 19, 20 and 21 respectively.

The outcome of this proposed model is the total ship voyage time after arrival at port for pump maintenance (t_{op}) which is calculated in the number 22 unit of the SD model in Figure 5–7. t_{op} is the time spent during voyages until the ship reaches a port where the value of Pof of the pump exceeds the maximum Pof_{limit} . The detailed results of the proposed model are shown in Table 5-7 in the column of ship position estimation. It shows clearly, when the ship should be maintained, at what over ground distance (OG dist.), and where the port/ anchorage of maintenance should be. In the column of port/ anchorage, the italicized type means that the ship is moored in the port while the normal type means that the ship is anchored. The name of port is the place where the maintenance is proposed to be done.

Table 5-5 Result of *Cof* analysis

| Pump | Part name | Causes | Symptoms | <i>Cof</i> |
|--------|-----------------|--------|----------|------------|
| SWP 1 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| | Shaft | C5 | S16 | 5 |
| | Discharge valve | C10 | S4 | 5 |
| SWP 2 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| | Shaft | C5 | S16 | 5 |
| | Discharge valve | C10 | S4 | 5 |
| SWP 3 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| | Shaft | C5 | S16 | 5 |
| | Discharge valve | C10 | S4 | 5 |
| CCFW 1 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| CCFW 2 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| CCFW 3 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| CCFW 4 | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| JWP 1* | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |
| JWP 2* | Mechanical seal | C1 | S14 | 4.5 |
| | O-ring | C3, C4 | S13 | 4 |

Table 5-6 Result of SD simulation in the first and second year of pump operation

| Pump | Part name | 1 st year operation | | | 2 nd year operation | | |
|--------|-------------------|--------------------------------|----------|------------|--------------------------------|----------|------------|
| | | <i>Pof</i> | Risk | m_p (hr) | <i>Pof</i> | Risk | m_p (hr) |
| SWP 1 | <i>Mech. seal</i> | 2.20E-07 | 9.88E-07 | 2920 | 7.16E-11 | 3.22E-10 | 3940 |
| | O-ring | 3.24E-12 | 1.30E-11 | 6280 | 2.14E-05 | 8.55E-05 | 3050 |
| | Shaft | ≈ 0 | ≈ 0 | 8820 | ≈ 0 | ≈ 0 | 5590 |
| | Disc. valve | 1.40E-08 | 7.00E-08 | 24620 | 8.23E-08 | 4.11E-07 | 21390 |
| SWP 2 | <i>Mech. seal</i> | 3.39E-05 | 1.53E-04 | 2550 | 3.27E-06 | 1.47E-05 | 3200 |
| | O-ring | 4.16E-06 | 1.66E-05 | 12900 | 2.93E-05 | 1.17E-04 | 9660 |
| | Shaft | ≈ 0 | ≈ 0 | 11130 | ≈ 0 | ≈ 0 | 7890 |
| | Disc. valve | ≈ 0 | ≈ 0 | 31100 | 1.24E-14 | 6.22E-14 | 27860 |
| SWP 3 | Mech. seal | 6.36E-07 | 2.86E-06 | 5510 | 9.19E-04 | 4.13E-03 | 2280 |
| | O-ring | 1.01E-08 | 4.02E-08 | 10970 | 2.11E-05 | 8.44E-05 | 7740 |
| | Shaft | 2.86E-11 | 1.43E-10 | 14310 | 5.33E-07 | 2.66E-06 | 11080 |
| CCFW 1 | Disc. valve | ≈ 0 | ≈ 0 | 27160 | ≈ 0 | ≈ 0 | 23930 |
| | Mech. seal | 2.35E-03 | 1.06E-02 | 4230 | 5.87E-03 | 2.64E-02 | 1560 |
| | O-ring | 1.82E-10 | 7.30E-10 | 14880 | 4.49E-09 | 1.80E-08 | 12210 |
| CCFW 2 | Mech. seal | 1.35E-03 | 6.06E-03 | 3070 | 7.74E-03 | 3.48E-02 | 390 |
| | O-ring | 4.95E-11 | 1.98E-10 | 14200 | 1.82E-09 | 7.27E-09 | 11520 |
| CCFW 3 | Mech. seal | 4.32E-04 | 1.94E-03 | 4900 | 2.93E-03 | 1.32E-02 | 2230 |
| | O-ring | 9.96E-04 | 3.98E-03 | 10550 | 1.79E-03 | 7.15E-03 | 7870 |
| CCFW 4 | Mech. seal | 5.04E-06 | 2.27E-05 | 6670 | 1.06E-04 | 4.77E-04 | 4000 |
| | O-ring | ≈ 0 | ≈ 0 | 8710 | 1.22E-09 | 4.88E-09 | 6040 |
| JWP 1* | Mech. seal | 5.32E-08 | 2.39E-07 | 3040 | 7.28E-06 | 3.28E-05 | 1810 |
| | O-ring | ≈ 0 | ≈ 0 | 1800 | 4.61E-06 | 1.84E-05 | 570 |
| JWP 2* | Mech. seal | 1.39E-04 | 6.23E-04 | 2930 | 8.37E-04 | 3.76E-03 | 1700 |
| | O-ring | ≈ 0 | ≈ 0 | 2260 | 3.47E-11 | 1.39E-10 | 1030 |

*Calculation of *Pof*, Risk estimation and m_p for JWP is carried out at 2nd and 3rd year of operation, i.e. 1660 and 2890 hours

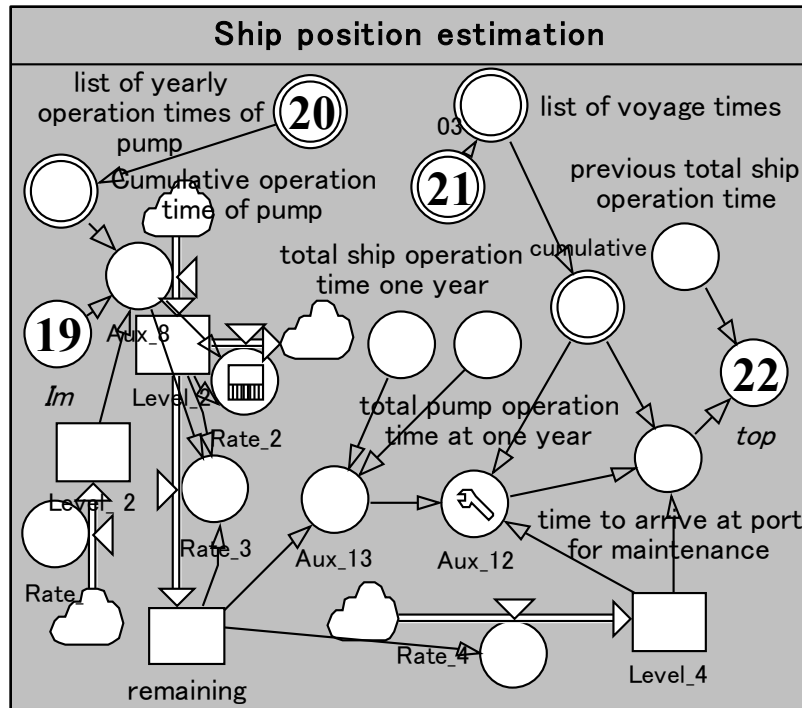


Figure 5–7 SD model of ship position estimation

5.3.5 Maintenance planning

Maintenance planning is carried out after risk evaluation and ship position estimation. Figure 5–8 shows the SD model of the maintenance planning. In this step, the cooling pumps have been prioritized for maintenance based on the level of risk of failure. As shown in Table 5-6, m_p for each pump is clearly defined. m_p is important, especially for the ship engineer, in order to make a priority list of time remaining until maintenance of the cooling pumps of the ship’s main engine is necessary. In this paper, m_p is calculated by Equation (5-9) which is determined from I_m and t_r . Equation (5-9) is inserted into the number 17 unit of the SD model, while I_m and t_r are calculated by using Equations (5-10) ~ (5-15) and inserted into the units 15 and 16 of the SD model respectively.

In this study, the maintenance planning also provides the I_m for all of the studied cooling pumps as presented in the Table 5-8. In order to compare the results of I_m in this study, the

standard I_m published by the pump manufacturer is used [56]. Table 5-8 provides the list of the I_m standard for all of the parts of the analyzed pumps except for the discharge valve because the pump company does not publish it. The standard I_m for the discharge valve is left blank since there is no reference for this part. In pump operation, I_m standard is not always exactly applied because it is an approximation value. From the Table 5-8, it can be seen that there are differences between standard and result of simulation. This result emphasizes that in reality, I_m can vary based on the operation condition of the pump, such as type of fluids, temperature, pump operation mode and environmental condition.

Based on the comparison of the I_m results with the I_m standard, a significant difference can be seen for the O-ring of JWP 1 and 2. Some possible reasons of this discrepancy are described as follows:

1. High fluid temperature, since JW pump is operated in the high temperature loop of the cooling system of main engine
2. Fluid working pressure in the JW pump is the highest of all cooling pumps (see Table 5-2)
3. There are only two JW pumps installed, fewer than the other cooling pumps. This condition may cause the JW pumps to work harder.

Overall comparison, it can be seen in Table 5-8 that most of the I_m resulting from the SD model has quite a similar value to the standard from the pump manufacturer. Some disparity may appear in an acceptable value. Special focusses on the quite big discrepancy comes from the result of the O-ring of JW pump while some explanations on environmental condition that may induce this differences have been given as acceptable reason. It can be concluded from this, that the SD model of RBM in this chapter presents a reasonable outcome. SD model presented in this study results in not only I_m but also shows the m_p and ship position estimation which gives us the t_{op} , OG. dist., and port of mooring/ anchorage for maintenance. This outcome is very beneficial for the ship engineer in that it allows for a better maintenance strategy for the cooling system of a main engine. This result helps to improve the current view of an engineer to face a maintenance management problem in the ship machinery.

Table 5-7 Result of SD simulation on ship position estimation

| Pump | Part name | Ship position estimation | | |
|--------|-----------------|--------------------------|----------------------|------------------------|
| | | t_{op} (hr) | OG. dist. (miles) | Port/ anchorage |
| SWP 1 | Mechanical seal | 2805 | 47769 | <i>Nagasaki</i> |
| | O-ring | 5259 | 90166 | Ishigaki offing |
| | Shaft | 6923 | 118644 | <i>Kushiro</i> |
| | Discharge valve | 17549 | 301989 | Great bitter lake |
| SWP 2 | Mechanical seal | 2555 | 43739 | Tsu offing |
| | O-ring | 9688 | 166338 | <i>Osaka</i> |
| | Shaft | 8513 | 145932 | <i>London</i> |
| | Discharge valve | 21012 | 354462 | <i>Takamatsu</i> |
| SWP 3 | Mechanical seal | 4684 | 80818 | <i>Muroran</i> |
| | O-ring | 8410 | 143971 | Panama canal |
| | Shaft | 10854 | 186472 | <i>Recife</i> |
| | Discharge valve | 19165 | 326146 | <i>Brisbane</i> |
| CCFW 1 | Mechanical seal | 4440 | 76369 | Suez canal |
| | O-ring | 13360 | 230357 | <i>Curacao</i> |
| CCFW 2 | Mechanical seal | 3546 | 60260 | <i>Tokyo</i> |
| | O-ring | 12732 | 218816 | <i>Tokyo</i> |
| CCFW 3 | Mechanical seal | 4968 | 85418 | Kagoshima offing |
| | O-ring | 9582 | 164629 | <i>Nagasaki</i> |
| CCFW 4 | Mechanical seal | 6655 | 114413 | El ballah by pass west |
| | O-ring | 8145 | 139189 | <i>Tokyo</i> |
| JWP 1 | Mechanical seal | 8601 | 147550 | <i>Barcelona</i> |
| | O-ring | 6373 | 109326 | <i>Naples</i> |
| JWP 2 | Mechanical seal | 8410 | 143971 | Panama canal |
| | O-ring | 7158 | 122389 | <i>Tokyo</i> |

Table 5-8 Comparison of I_m result and I_m standard

| Pump | Part name | Comparison of I_m (hr) | |
|--------|-----------------|--------------------------|----------------|
| | | I_m result | I_m standard |
| SWP 1 | Mechanical seal | 4260 | 5000 |
| | O-ring | 7620 | 15000 |
| | Shaft | 10160 | 12000 |
| | Discharge valve | 25960 | - |
| SWP 2 | Mechanical seal | 3880 | 5000 |
| | O-ring | 14230 | 15000 |
| | Shaft | 12460 | 12000 |
| | Discharge valve | 32430 | - |
| SWP 3 | Mechanical seal | 6850 | 5000 |
| | O-ring | 12310 | 15000 |
| | Shaft | 15650 | 12000 |
| CCFW 1 | Discharge valve | 28500 | - |
| | Mechanical seal | 5410 | 5000 |
| | O-ring | 16060 | 12000 |
| CCFW 2 | Mechanical seal | 4250 | 5000 |
| | O-ring | 15380 | 12000 |
| CCFW 3 | Mechanical seal | 6080 | 5000 |
| | O-ring | 11730 | 12000 |
| CCFW 4 | Mechanical seal | 7850 | 5000 |
| | O-ring | 9890 | 12000 |
| JWP 1 | Mechanical seal | 4700 | 5000 |
| | O-ring | 3460 | 12000 |
| JWP 2 | Mechanical seal | 4590 | 5000 |
| | O-ring | 3920 | 12000 |

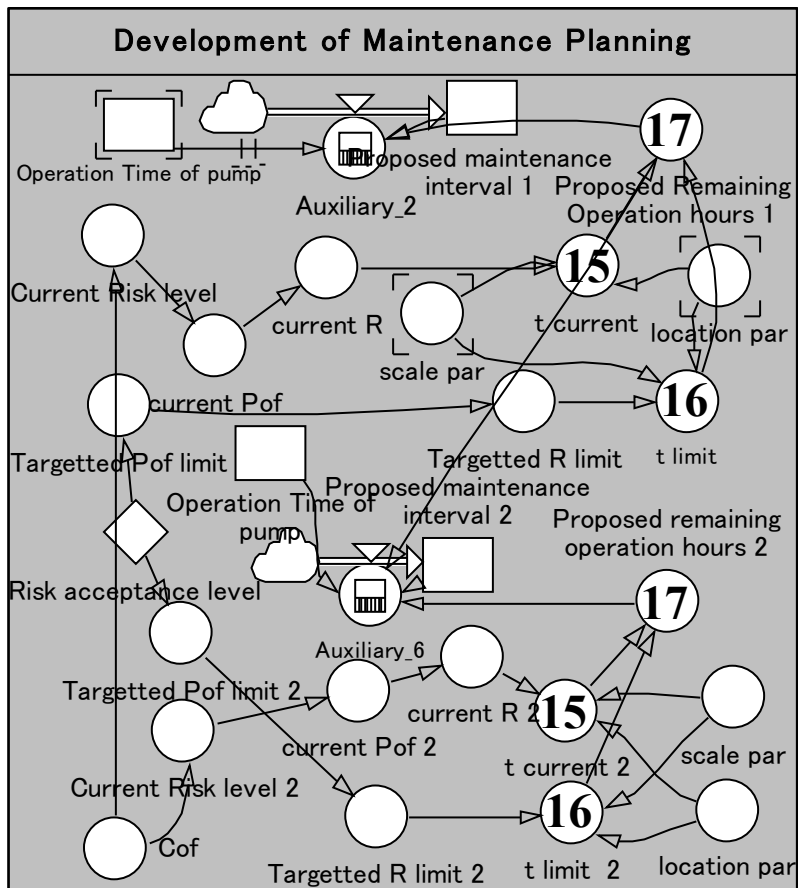


Figure 5–8 SD model of maintenance planning

5.4 Summary

This study presents a new development of the RBM method for application in the field of marine machinery operation. SD simulation is utilized to construct a model of RBM with a case study that focusses on the parts of the SW pumps, CCFW pumps and JW pumps. SD model of RBM as shown in Figure 5–2, is built up by adding together SD model of 1. Preliminary identification, 2. Risk assessment, 3. Risk evaluation, 4. Ship position estimation, and 5. Maintenance planning.

The outcomes achieved by this SD model of RBM are Pof , Cof , 1st year and 2nd year estimation of risk, maintenance planning (m_p) and interval time between maintenance (I_m), while the ship position estimation of the proposed model development of RBM, gives a clear interpretation on the position, passage time and covered distance of the ship when the machinery

runs into a high level of risk. These results should improve the existing maintenance strategy for the management of the ship company. Given the results of the ship position estimation and maintenance planning, they enable the ship engineer to better construct a maintenance strategy for the cooling system of the ship's main engine.

Focusing on the analyzed parts in this case study, it is obvious that the I_m of similar pump parts in different pumps have quite different values. Cooling pump operation conditions causes this disparity. Although differences appear, the I_m results are in line with the I_m standard obtained from the pump manufacturer. There are only two parts that show an odd value of I_m i.e. O-ring of JW pump 1 and 2, but they are tolerable since the operation conditions of JW pumps are severe compared to the other pumps. It is possible to make the I_m shorter.

Study improvement may be possible by extending the history data of failure time and failure mode of the cooling pump. In this study, limited data meant that only a few failure modes could be analyzed. More failure time data is needed in order to collect more type of failure modes. These improvements may develop the current SD model of RBM to become more complex. Focused equipment is also possible to be added since there are some other important components which also have an important function in the cooling system of the ship's main engine. Improvement of the SD model of RBM in marine machinery operation is possible by taking these matters under consideration for future work.

Chapter 6

Conclusion

An effort to increase the profit of ship operation is obtained by gaining more revenue and cutting expense as well as emphasizing efficiency of operation. Focusing on the machinery operation could be one way to accomplish this purpose. Cost of machinery operation is an important aspect which corresponds with economic ship operation, but attention must also be made to safety from machinery failure as well. This research analyzes a quantitative simulation model of cost optimization of ship machinery operation. The optimization process is a complex matter since many factors must be considered to efficiently analyze ship machinery. The modeling process deals with the machinery operation conditions, ship voyage pattern, reliability analysis, and cost composition which is comprised of running cost (C_r), maintenance cost (C_m) and downtime cost (C_d). This thesis demonstrates that utilization of a method called system dynamics is useful when analyzing a complex behavioral problem. The system dynamics allowed us to see how the optimum operation cost was obtained, as well as the cost composition correlates with other aspects of ship machinery operation. The behavior of cost composition over time, can be observed as changes in corresponding variables occur. This thesis proves that the system dynamics is a powerful and user friendly tool that is helpful to analyze data to find the optimization of ship machinery operation.

The goals of this research stated in Chapter 1 have been realized. *First*, a model for the

management of ship machinery operation has been created by a utilizing system dynamics simulation model. In Chapter 2, this thesis present how the operation of ship machinery can be interpreted into a cause and effect diagram in order to clarify the interrelationship between aspects that correlate in the system. Chapter 3 continues the work of the previous chapter to build a stock and flow diagram to create a model of machinery operation as well as a cost optimization model. The model demonstrates not only a simulation method dealing with ship operation under maintenance inflexibility at sea, but also considers the constraints of port availability for machinery maintenance. *Second*, the cost optimization model was included in Chapter 3. System dynamics model presents the behavior of C_r , C_m and C_d during machinery operation by considering minimum reliability index (RI) which governs the optimization process. In this case study, the simulation of the machinery in the cooling system of a ship's main engine which involves the SW pump, CCFW pump, and JW pump was conducted using SD simulation models 1 and 2. Looking at the results of the SD simulation, the optimization using model 1 obtained a minimum C_T which was nearly the same as the previous research. Model 2 had optimization results better than model 1. In applying model 2 to the pump's operation, a good strategy for determining when and where maintenance needed to be carried out had to be found. This decision relied on the I_m which could be derived from the minimum RI of the optimization result. With this information model 2 gave important information about appropriate minimum RI and I_m in order to acquire the lowest C_T as the most economical operation of pump.

This study has also presented an optimization of operation costs for main engine cooling pumps in a ship dealing with not only maintenance inflexibility which sometimes depends on access to shore based facilities or the availability of spare parts onboard, but also a port availability constraint. The case study was carried out on SW, CCFW and JW pumps. Model 1 and model 2 were constructed to simulate the operation of the pump. In Chapter 4, the simulations and their results were compared with the initial PMS, referred optimization, and cost optimization without considering port availability which were discussed in Chapter 3. Following the results of the simulations which considered the port availability constraint, model 1 had the highest minimum C_T compared to other optimization results because the C_d of the operation of pump with a port availability constraint is higher than in the other operation conditions. Model 2 with port availability constraint shows a significant reduction in C_T , much more than in the

reduction of model 2 without port availability constraint. This shows that the forecasting tool has a great impact on cost reduction. From this analysis, it can be concluded that the forecasting tool of model 2 is recommended for the operation of pumps under port availability constraints. Analyzing the cost optimization model proposed in this study, discussion may lead to further model improvement. Possible future improvements and suggestions of cost optimization are discussed as bellow.

1. Simulation results of optimization in the proposed model 2 obviously show that the minimum RI for each analyzed pump is different even though they are the same type and have the same properties. From these differences it can be identified that the I_m of each pump also exhibits a different value. This may be an important consideration for ship crews which have been applying annual maintenance using the same interval period for the same type of pumps.
2. Voyage pattern such as ship service speed, ship departing and arriving schedule are potentially influenced by weather conditions such as wind direction, wave current etc. Further study can be conducted to improve the pump's optimization model by taking weather into consideration, since this is another important factor which affects ship operation.
3. There is a possibility to operate the same types of pumps in a way to be more economic. Since the cooling system uses a standby mechanism, there is a model of improvement opportunity to manage which pump is preferable to be the main operating pump. This model improvement may further reduce the current optimum value of C_T because it may decrease the C_r and C_d .

Third, besides analyzing the cost optimization, this study presents a new development of the RBM method for application in the field of marine machinery operation. This work considers risk of failure to be an important aspect in developing a cost optimization model. SD simulation was used to construct a model of RBM with a case study that focused on the parts of the SW pumps, CCFW pumps and JW pumps. SD model of RBM shown in Figure 5–2 is built up by adding together SD model of, 1. Preliminary identification, 2. Risk assessment, 3. Risk evaluation, 4. Ship position estimation, and 5. Maintenance planning. The outcomes achieved by this SD model of RBM are Pof , Cof , 1st year and 2nd year estimation of risk, maintenance planning (m_p), and interval time between maintenance (I_m), while the ship position estimation of

the proposed model development of RBM, gives a clear interpretation on the position, ship operation time and covered distance of the ship when the machinery runs into a high level of risk. These results should improve the existing maintenance strategy of the management of the ship company. Given the results of the ship position estimation and maintenance planning, the ship engineer should be better able to construct a maintenance strategy for the cooling system of the ship's main engine. Focusing on the analyzed parts in this case study, it is obvious that the I_m of similar pump parts in different pumps have quite different values. Cooling pump operation conditions cause this disparity. Although differences appear, the I_m results are in line with the I_m standards obtained from the pump manufacturer. There are only two parts that show an odd value of I_m i.e. O-rings of JW pumps 1 and 2, but they are tolerable since the operation conditions of JW pumps are severe compared to the other pumps. This may have caused the I_m to become shorter.

Improvements for the development of the RBM model should be looked into.

1. Extend the data history of failure times and failure modes of the cooling pumps. In this study, limited data meant that only some failure modes could be analyzed. More failure time data is needed in order to collect more types of failure modes. These improvements may develop the current SD model of RBM to become more complex. Especially when extending this model into other ship machinery systems which may give us more types of failure history.
2. It is also possible to focus on other equipment since there are some other important components which also have important functions in the cooling system as well as other support systems of the ship's main engine. Improvement of the SD model of RBM in marine machinery operation should take these and other matters into consideration in future work.

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Appendix A

Data of ship and machinery operation time

Table A-1 Yearly operation time of ship's main engine

| Year | Date | Main engine | | | |
|------|------------|---------------------------|-----------------------|-------------------------|------------------------|
| | | Cumulative operation hour | Yearly operation hour | Domestic operation hour | Oversea operation hour |
| | 01/10/1997 | 0 | - | - | - |
| 1997 | 01/04/1998 | 700 | 700 | 700 | - |
| 1998 | 01/04/1999 | 3000 | 2300 | 1000 | 1300 |
| 1999 | 01/04/2000 | 5300 | 2300 | 1000 | 1300 |
| 2000 | 01/04/2001 | 7610 | 2310 | 1010 | 1300 |
| 2001 | 01/04/2002 | 9869 | 2259 | 959 | 1300 |
| 2002 | 01/04/2003 | 12229 | 2360 | 1060 | 1300 |
| 2003 | 01/04/2004 | 14437 | 2208 | 908 | 1300 |
| 2004 | 01/04/2005 | 16450 | 2013 | 1013 | 1000 |
| 2005 | 01/04/2006 | 18531 | 2081 | 1081 | 1000 |
| 2006 | 01/04/2007 | 20004 | 1473 | 973 | 500 |
| 2007 | 01/04/2008 | 21501 | 1497 | 997 | 500 |
| 2008 | 01/04/2009 | 22521 | 1020 | 1020 | - |
| 2009 | 01/04/2010 | 24040 | 1519 | 1519 | - |
| 2010 | 01/04/2011 | 25173 | 1133 | 1133 | - |
| 2011 | 01/04/2012 | 26200 | 1027 | 1027 | - |
| 2012 | 01/04/2013 | 27197 | 997 | 997 | - |

Table A-2 Yearly operation time of cooling pumps

| Year | Sea water cooling pump | | Central cooling fresh water pump | | Jacket water pump | |
|------|------------------------|---------------------------|----------------------------------|---------------------------|-----------------------|---------------------------|
| | yearly operation hour | cumulative operation hour | yearly operation hour | cumulative operation hour | yearly operation hour | cumulative operation hour |
| 1997 | 1336 | 1336 | 1177 | 1177 | 430 | 430 |
| 1998 | 3233 | 4569 | 2675 | 3852 | 1230 | 1660 |
| 1999 | 3233 | 7803 | 2675 | 6527 | 1230 | 2890 |
| 2000 | 3233 | 11036 | 2678 | 9205 | 1235 | 4125 |
| 2001 | 3233 | 14269 | 2665 | 11869 | 1210 | 5335 |
| 2002 | 3233 | 17503 | 2690 | 14559 | 1260 | 6595 |
| 2003 | 3233 | 20736 | 2652 | 17211 | 1184 | 7779 |
| 2004 | 3133 | 23869 | 2603 | 19815 | 1087 | 8865 |
| 2005 | 3133 | 27003 | 2620 | 22435 | 1121 | 9986 |
| 2006 | 2967 | 29969 | 2468 | 24903 | 817 | 10802 |
| 2007 | 2967 | 32936 | 2474 | 27377 | 829 | 11631 |
| 2008 | 2800 | 35736 | 2355 | 29732 | 590 | 12221 |
| 2009 | 2800 | 38536 | 2480 | 32212 | 840 | 13060 |
| 2010 | 2800 | 41336 | 2383 | 34595 | 647 | 13707 |
| 2011 | 2800 | 44136 | 2357 | 36952 | 594 | 14300 |
| 2012 | 2800 | 46936 | 2349 | 39301 | 579 | 14879 |

Table A-3 Yearly Mooring and anchoring time

| Year | Mooring + anchoring time (hours) | Notes |
|------|----------------------------------|-------------------------|
| 1997 | 3308 | Domestic |
| 1998 | 6100 | Oversea (round trip) |
| 1999 | 6100 | Oversea (round trip) |
| 2000 | 6090 | Oversea (round trip) |
| 2001 | 6141 | Oversea (round trip) |
| 2002 | 6040 | Oversea (round trip) |
| 2003 | 6192 | Oversea (round trip) |
| 2004 | 6387 | Oversea (Caribbean sea) |
| 2005 | 6319 | Oversea (round trip) |
| 2006 | 6927 | Oversea (Australia) |
| 2007 | 6903 | Oversea (Australia) |
| 2008 | 7380 | Domestic |
| 2009 | 6881 | Domestic |
| 2010 | 7267 | Domestic |
| 2011 | 7373 | Domestic |
| 2012 | 7403 | Domestic |

List of Publications

1. Handani, D. W., Ishida, K., Nishimura, S., Hariyanto, S., “Optimum Maintenance Strategy and Risk Prioritization of Ship Machinery Component Using System Dynamics Simulation and Analytical Hierarchy Process (AHP)”, Proceeding of International Symposium on Marine Engineering (ISME), pp. D9-2, Kobe, October 2011
2. Handani, D. W., Ishida, K., Nishimura, S., Hariyanto, S., “System Dynamics Simulation for Constructing Maintenance Management of Ship Machinery”, Proceeding of IEEE Conference on Industrial Engineering and Engineering Management (IEEM), Singapore chapter, pp. 1549-1553, December 2011
3. Handani, D. W. and Uchida, M., “Simulation on Optimum Operation of Ship Main Engine Support System by Using System Dynamics”, Proceeding of IEEE Conference on Industrial Engineering and Engineering Management (IEEM), Hong Kong chapter, pp. 1935-1939, December 2012
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5. Handani, D. W. and Uchida, M., “Using System Dynamics to Simulate the Management of Operation and Maintenance of Ship Machinery under a Port Availability Constraint”,

International Journal of Supply Chain and Management, vol. 2, no. 4, pp. 76-84, December 2013

6. Handani, D. W. and Uchida, M., “Modeling Optimum Operation of Ship Machinery by Using System Dynamics”, Journal of Japan Institute of Marine Engineering, vol. 49, no. 1, pp. 132-141, January 2014
7. Handani, D. W. and Uchida, M., “Development of Risk Based Maintenance (RBM) Method in the Operation of Ship Machinery”, under review in the World Maritime University (WMU) Journal of Maritime Affairs.