Using System Dynamics to Simulate the Management of Operation and Maintenance of Ship Machinery under a Port Availability Constraint

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Abstract - The total cost of ship machinery operation (C_T) must be kept at a minimum value while respecting the need for failure. This paper proposes a model to minimize the C_T by endeavouring the value of minimum Reliability Index (RI) of the machinery. The minimum RI is the level of reliability of machinery where we need to take maintenance action after some period of operation time. The changes of minimum RI causes the changes in the composition of C_T, including running cost (C_r), maintenance cost (C_m) and downtime cost (C_d). This paper discusses the operation of pumps which are installed in the cooling system of a ship's main engine. As constraint, the maintenance of the pumps is assumed to be only possible in one particular available port. This study utilizes System Dynamics (SD) to construct two kinds of proposed models of machinery operation. They are model 1, without forecasting and model 2, with forecasting of minimum RI. Model 1 results in minimum C_T, while model 2 reaches a C_T lower than the outcome of model 1.

Keywords: *optimization, pump operation, total operation cost, running cost, maintenance cost, downtime cost, minimum RI, port availability constraint for maintenance, System Dynamics, model 1, model 2.*

1. Introduction

Sustainable operation is the desire of the engineering departments of all shipping companies. Most efforts are aimed to reducing the interruptions of the ship service during voyages which can be caused by the problems of ship machinery. These problems induce downtime which causes unpredictable additional expenses, such as maintenance costs, downtime costs, etc. The objective of ship companies is to minimize expenses and gain profit. Understanding this, an appropriate maintenance strategy for ship machinery is required to realize reduced operation costs.

Preventive maintenance has being adopted as one of the strategies [1] to overcome machinery failure which can cause downtime of machinery systems. 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 paper proposes models for a maintenance strategy of ship machinery operated offshore which is assumed to have maintenance inflexibility since the maintenance action can not be carried out during voyages. The aim of this model is to manage the operation time and maintenance period of machinery in order to attain the minimum C_T. A reference study of cost optimization of marine machinery has been achieved by setting a limit value of RI [2]. While [3] and [4] have discussed the optimization of C_T of ship machinery by estimating the minimum value of RI as a work limitation which results in the minimum C_T for ship machinery. The other optimization of C_T appears in [5], [6] which analyses the operation of component/parts of ship machinery.

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. In the previous studies [3], [4], [5], maintenance could be

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conducted in all destination ports. This study considers the one port as a constraint, 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 affect configuration of C_r, C_m, and C_d. Based on this circumstance, a particular maintenance strategy is proposed to minimize the C_T.

The operation of pumps in the cooling system of the main engine of a ship are taken as a case study and modelled utilizing SD which initially was used to model management in the social sciences [10] and recently has being used in other fields including academic research and engineering [7] [8] [9]. This paper 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.

2. Problem Description

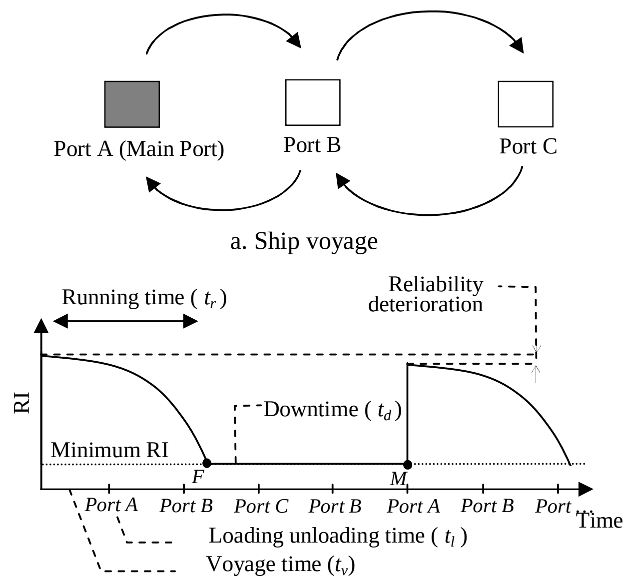
2.1 Working Principle of Cooling System of Main Engine

Ships need a working main engine. 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. The number 3 SW and CCFW pumps are small pumps used only for port operation when the generator set is operated while the main engine is stopped. These pumps provide a small capacity of cooling water for the air cooler, lubricating oil cooler, and jacket cooler of the generator set being operated.

2.2 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 both in series and parallel. 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 pump operation during a voyage is shown in Fig. 1.



a. Ship voyage

b. Reliability degradation of pump

Fig. 1. Overview of pump operation in ship voyage

The route of the ship voyage is from Port A – Port B – Port C and back again. Fig. 1.a shows the order of the voyage clearly. During the ship voyage, reliability degradation occurs until the reliability of the pump reaches the minimum RI at point F as shown in Fig. 1.b. At this point, the main pump has to be replaced by the standby pump in order to keep the cooling system of main engine working. Because Port A is the main port where maintenance service is available, the main pump can only be repaired when the ship arrives in Port A. This is marked by *M*. This study assumes that Port B and C do not provide maintenance service, and none is available on board.

2.3 Cost Breakdown

To optimize the minimum value of C_T one should thoroughly consider its composition, such as C_r, C_m and C_d. In Fig. 1, 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 following formula represents the cost calculation of C_T using C_r, C_m, and C_d as costs of composition.

$$C_T = C_r + C_m + C_d \quad (1)$$

Electric motors consume energy to drive pumps. C_r appears by converting this energy into a cost. Eq. 2 shows the equation of C_r. $P_{in}(t)$ is the energy required to operate the electric pump motor, O_p is the price of a specific unit of fuel, C_h is the specific heat of fuel oil and $\rho_v$is the density of fuel oil. The number of times maintenance occurs is symbolized by m, while ($m+1$) represents the number of I_m or the number of running terms of certain pumps.

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

$$C_r = \int_0^{t_{r_1}} \left(\frac{P_{in}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt + \int_0^{t_{r_2}} \left(\frac{P_{in}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt + \cdots + \int_0^{t_{r_{(m-1)}}} \left(\frac{P_{in}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt + \int_0^{t_{r_m}} \left(\frac{P_{in}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt$$

$$C_r = \sum_{i=1}^{i=(m+1)} \int_0^{t_{r_i}} \left(\frac{P_{in}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt \quad (2)$$

During the operation, C_r increases over the time because of performance degradation. [2] and [6] assume performance degradation in the modelling although it is not an exact interpretation. In this paper, the determination of performance degradation is approached by the increasing $P_{in}(t)$.

$$P_{in}(t) = P_o\left(1 + \left(1 - R(t)\right)\right) \quad (3)$$

C_m relies on the specific unit salary per engineer per unit of time (S_t), time required for maintenance (t_m) and extra cost (E) such as replacement of unrepairable components of a pump. The value of m depends on the value of minimum RI and I_m.

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

$$C_m = \left(\int_0^{t_{m_1}} S_t(t)\,dt + E_1\right) + \left(\int_0^{t_{m_2}} S_t(t)dt + E_2\right) + \cdots + \left(\int_0^{t_{m_{(m-1)}}} S_t(t)dt + E_{m-1}\right) + \left(\int_0^{t_{m_m}} S_t(t)dt + E_m\right)$$

$$C_m = \sum_{i=1}^{i=m} \left(\int_0^{t_{m_i}} S_t(t)\,dt + E_i\right) \quad (4)$$

C_d is expressed as the following equation.

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

$$C_d = \int_0^{t_{d_1}} \left(\frac{P_{out}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt + \int_0^{t_{d_2}} \left(\frac{P_{out}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt + \ldots + \int_0^{t_{d_{(m-1)}}} \left(\frac{P_{out}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt + \int_0^{t_{d_m}} \left(\frac{P_{out}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt$$

$$C_d = \sum_{i=0}^{i=m} \int_0^{t_{d_i}} \left(\frac{P_{out}(t).\,O_p}{\eta_c.\,C_h.\,\rho_v}\right)dt \quad (5)$$

Downtime occurs when the pump can not fulfil its performance requirement. In this paper, downtime starts from the failure until the ship arrives at port A, as the main port where maintenance is possible to be carried out. C_d represents the loss of production, i.e. the operation of a pump to produce liquid horse power (P_{out}). C_d is obtained by converting P_{out} by multiplying it with the cost per kilowatt.

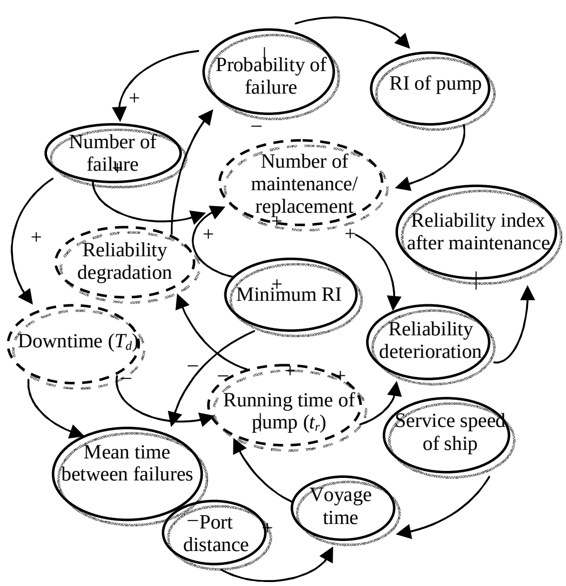
3. System Dynamics Model

SD is utilized to simulate the operation of a cooling pump of the ship's main engine. 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 behaviour through the utilization of a causal effect relationship diagram. This diagram shows the components which have a role inside the system. We will now discusses the causal effect relationship diagram and SD simulation model of the pump operation.

3.1 Causal Effect Relationship of Pump Operation

Causal effect relationship diagram is constructed to clearly see how the system operates. The positive feedback loop means there is positive relationship between the two connected system components. In contrast, a negative feedback loop means a negative relationship.

Fig. 2 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.

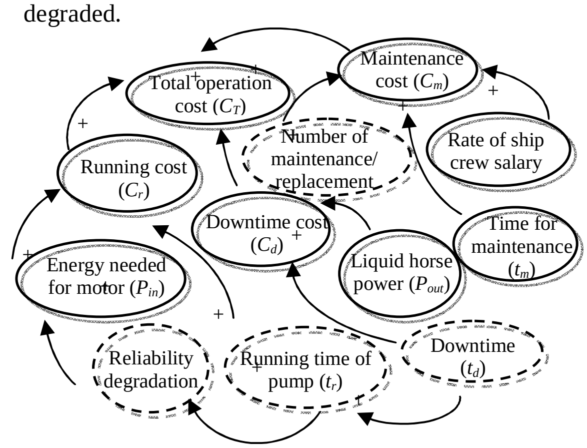


* (+) : positive relationship, (-) : negative relationship

* Dashed line means the same object in Fig. 2 and 3

Fig. 2 Ship machinery operation

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.



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

* Dashed line means the same object in Fig. 2 and 3

Fig. 3 Cost composition of ship machinery operation

Fig. 3 is a causal effect relationship diagram of the operational cost of a pump. 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.

3.2 System Dynamics Simulation Model

As mentioned in the introduction, this study proposed two models of optimization. Model 1 and model 2 simulate the optimization of pump operation in order to reach the minimum C_T. The following expressions describe the main concept of model 1 and model 2.

Model 1 :

$$\text{Pump 1} = \begin{cases} -\text{ switched to standby pump, if RI} < \text{minimum RI} \\ (pump\ 1\ is\ maintained\ after\ arrival\ in\ port\ A) \\ \\ -\text{ not switched, if } RI \geq \text{minimum RI} \\ (operation\ of\ pump\ 1\ is\ continued) \end{cases} \tag{6}$$

Model 2 :

$$\text{Pump 1} = \begin{cases} -\text{ switched to standby pump,} \\ \text{if forecast of RI in next port A} < \text{minimum RI} \\ (pump\ 1\ is\ maintained\ in\ port\ A) \\ -\text{ not switched to standby pump,} \\ \text{if forecast of RI in next port A} \geq \text{minimum RI} \\ (operation\ of\ pump\ 1\ is\ continued) \end{cases} \tag{7}$$

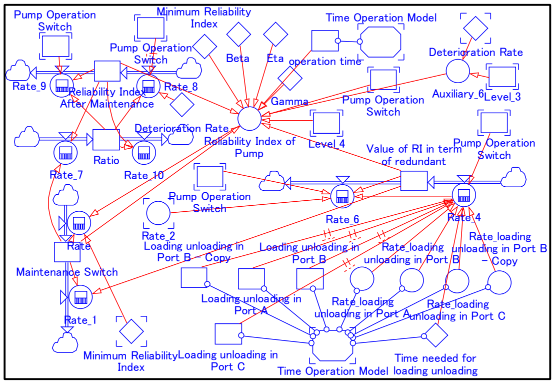


Fig. 4 Reliability analysis of pump operation

The causal effect relationship discussed previously is developed into the model in SD. Eq. 6 and 7 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 Fig. 4 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 Fig. 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".

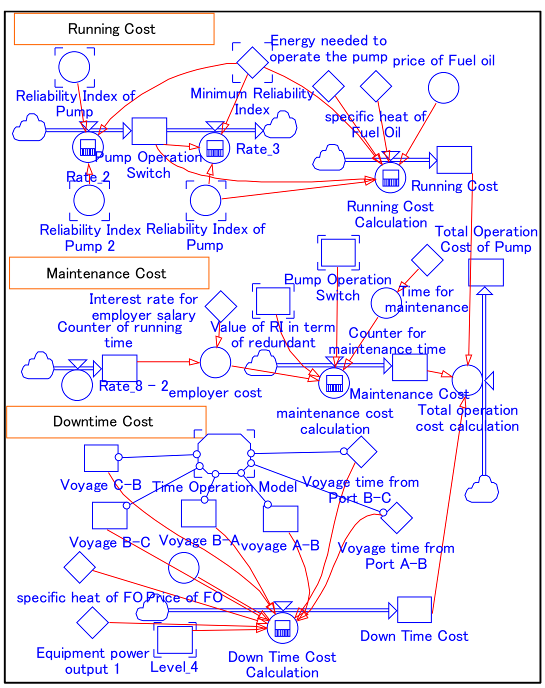


Fig. 5 Cost analysis of pump operation

4. Result and Analysis

SD simulates the model without forecasting (model 1) and with forecasting (model 2) both seen in Fig. 4 and 5. The data listed in Table 1 is inserted into model 1 and 2. The failure modeling of the main engine cooling pumps uses Weibull distribution which fits the best for the time to failure (TTF) obtained from the maintenance records [2].

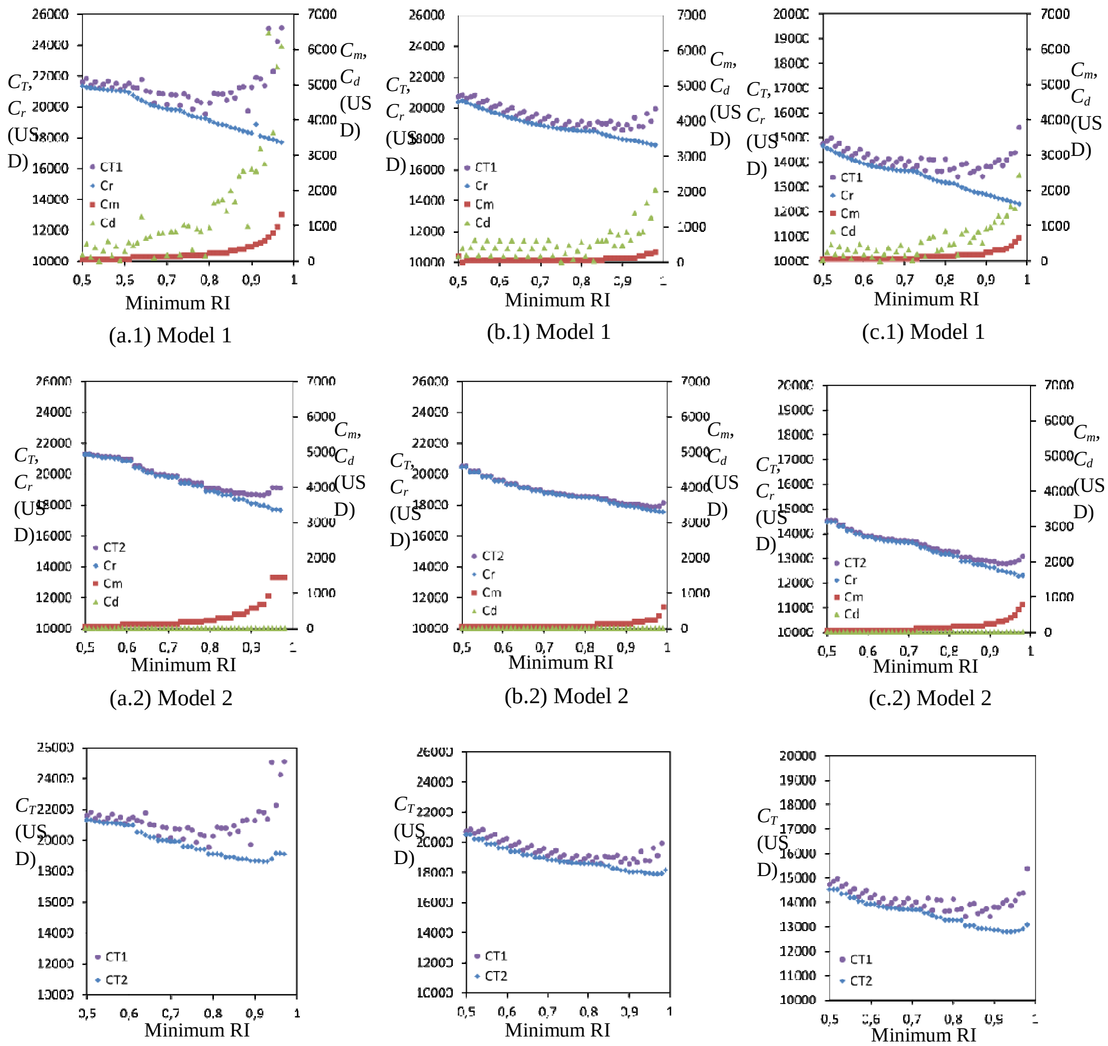
Table 1. Data Simulation

Parameters	Unit	Value
Ship service speed (Vs)	Knots	14.5
Variation of Vs	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	miles	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
Power of pump motor		
SW pump 1 and 2	kW	20
SW pump 3	kW	15
CCFW pump 1 and 2	kW	20
CCFW pump 3	kW	15
JW pump 1 and 2	kW	14
Simulation time (interval between docking)	years	2.5
Rate of reliability deterioration	%	0.05
Time duration at port	hours	3
Weibul Distribution parameters (β; η; γ):		
SW Pump 1		1.15; 20,485.41; 44.86
SW Pump 2		1.02; 19,702.74; 289.76
SW pump 3		1.63; 24,714.96; 328.03
CCFW Pump 1		2.19; 25,268.25; 0.00
CCFW Pump 2		1.79; 26,073.25; 0.00
CCFW pump 3		2.37; 31,136.30; 1,303.36
JW pump 1		1.22; 22,379.71; 243.17
JW pump 2		1.57; 24,616.98; 711.35

This distribution is determined by three parameters namely β(shape parameter), η(scale parameter) and γ(location parameter). The Weibull distribution has a probability density function and a reliability function as in equation 8 and 9 respectively.

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

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



(a.1) Model 1 (b.1) Model 1 (c.1) Model 1

(a.2) Model 2 (b.2) Model 2 (c.2) Model 2

(a.3) Comparison of model 1 and 2 (b.3) Comparison of model 1 and 2 (c.3) Comparison of model 1 and 2

Fig. 6 Simulation result. (a) SW pump 1 and 2, (b) CCFW pump 1 and 2, (c) JW pump 1 and 2

The results of the simulations are shown in Fig. 6. This figure shows the simulation results of the three analysed 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 [2]. In this chapter, the conditions and data will be used as verification for the result of SD simulation.

Fig. 6 shows the evolving cost composition according to changes in the minimum RI. We can see 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 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.

Table 2. Comparison of Optimization Result

	Real data	Optimization [2]	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%

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 Fig. 6. a.3, b.3 and c.3, we can clearly recognize 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 behaviour 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 after this are 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. Fig. 6 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 Fig. 6. As previously mentioned in Chapter 2, 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.

Table 2 exhibits the comparison between the real data taken from Ship's planned maintenance system (PMS) and three kinds of optimizations. These optimizations are (1) Optimization resulting from [2], (2). Optimization A, the optimization which does not consider port availability for maintenance, 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 [2], while model 2 obtains a lower C_T. An interesting result appears in the optimization B which was conducted in this paper 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 model. 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.

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 we recognizes 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 C_d can be more accurately 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 world crude oil price. In this study, we assumed it to be unchanged. It should be considered as well as the improvement of determination of performance degradation which also influences the C_r.

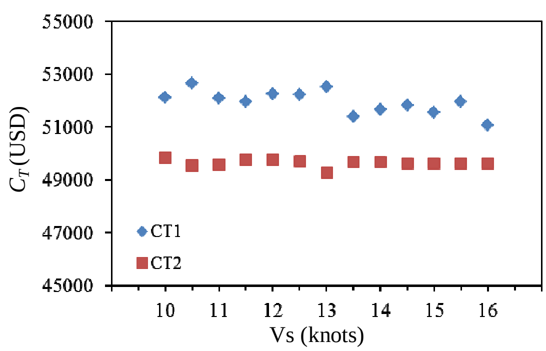
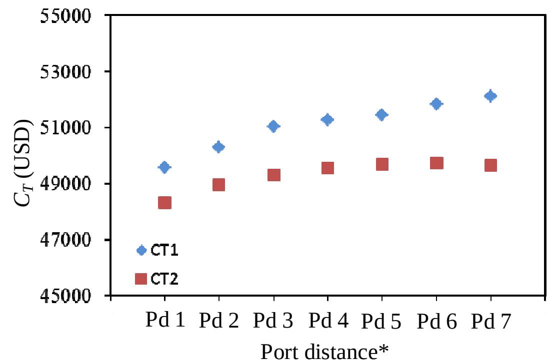


Fig. 7 Variation of Vs

The relationship between ship speed (Vs) and C_T of main engine cooling pumps is taken into account in the optimization process in this paper. Fig. 7 shows the optimization results for the different values of Vs. In model 1, Vs 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 Vs. Another significant relationship analysis was conducted by considering the port distance into the model. Fig. 8 interprets the results of optimization. From this figure, model 1 exhibits an increasing C_T according to the longer



* Pd is the distance from port A to B and port B to C. Pd 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.

Fig. 8 Variation of port distance

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.

5. 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, optimization resulted from [2] and cost optimization without considering port availability for maintenance.

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 our research, this was not included in the simulation mechanism. We can improve the pump's optimization model by taking this matter under consideration in future work. 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.

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Nomenclature

AI : availability index
CCFW : central cooling fresh water pumps
C_d : downtime cost
C_h : specific heat of fuel oil
C_m: maintenance cost
C_r: running cost
C_T : total operation cost
E_i : extra cost of maintenance
I_m : interval between maintenance
JW : jacket water pumps
m : number of maintenance
O_p : specific unit of FO price
P_{in} : energy required to operate the electrical motor
PMS : planned maintenance system
P_o : Initial P_{in}
P_{out} : liquid horse power
RI : reliability index
SD : System Dynamics
SW : sea water cooling pumps
S_t : specific unit salary for engineer per unit of time
t_d : downtime
t_l : loading unloading time
t_m : time required for maintenance
t_r : running time
t_v : voyage time
V_s : service speed of ship
β : shape parameter
η : scale parameter
γ : location parameter
ρ_v : density of fuel oil