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Case Study on the Unavailability of a Ship Propulsion System under Aging Effects and Maintenance

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ABSTRACT: Unavailability of a ship propulsion system under aging effects and proper maintenance is estimated using GO-FLOW. GO-FLOW is an effective software tool for the unavailability analysis of complex systems. Aging effects are incorporated into GO-FLOW using a time-dependent technique and assuming a linear aging model. The results show that the aging effects and improper maintenance can potentially increase the frequency of accidents due to a malfunction of the propulsion system by a factor of three.

1 INTRODUCTION

Accidents due to the malfunction of the ship propulsion system may occur when the ship is in heavy traffic sea lane, or when the ship is under berth maneuvering. Aging effects increase the likelihood malfunction. In that respect, additional premium is applied for ships older than 15 years in the insurance of the cargo [1]. Since the demand forecasting of the number of ships as a function of time is difficult, there is a wide age distribution of available vessels. Figure 1 shows the age distribution of handy size bulkers worldwide as an example [2] and indicates that while the number available decreases with increasing age, in general, there are still more than 1400 handy size bulkers older than 25 years. Most these older ships are operated by minor marine transportation companies because major marine transportation companies usually sell the ships when the ship's age reaches 20 to 25 years. If an aging ship is operated by minor marine transportation company, there is a higher likelihood that the ship propulsion system is not maintained properly due to cost factors. Therefore, the unavailability of propulsion system of aging ship may not only be increased due to aging effects but also due to improper maintenance.

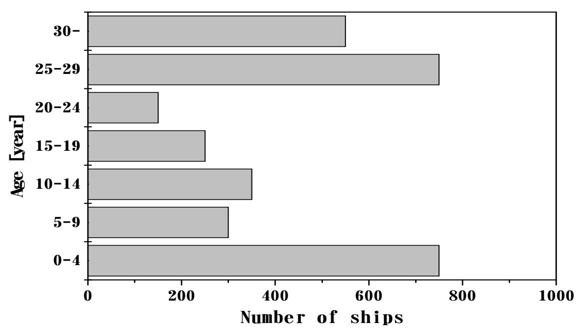

Figure 1. Age distribution of handy size bulkers in 2011.[2]

In general, to obtain system unavailability, failure rate of each component in the system is handled as constant value. However, to obtain system unavailability under aging effects, time-dependent failure rate of each component needs o be considered. Relatively few studies have been performed that take aging effects into account [6][7]. However, these papers did not treat ship propulsion system. Availability of ship propulsion system without accounting for aging effects has been estimated by Kiriya [8] using the GO-FLOW methodology [9] (also see Section 3). GO-FLOW is system analysis software which has a friendly Graphical User Interface (GUI) that allows constructing a system model without specifying equations. This study illustrates how aging effects as well as maintenance can be incorporated into GO-FLOW by using the time-dependent technique described in [4]. Sections 2 and 3, respectively, provide an overviews of the example propulsion system under consideration and its corresponding GO-FLOW model without considering aging effects. Section 4 describes how this model can be augmented to account for aging and maintenance with the methodology of [4]. The unavailability of the propulsion system under aging effect and improper maintenance is estimated using the augmented GO-FLOW in Section 5. Section 6 reports the results and Section 7 gives the conclusions of the study.

2 SHIP PROPULSION SYSTEM

In general, the ship propulsion system consists of fuel oil system (F.O. system), lubricating oil system (L.O. System), cooling system, main engine (M/E) system, and driveline system (see Fig.2) with the picture of the piston and cylinder. The main engine of the ship is large diesel engine with combustion chamber and inner mechanism, power transmission equipment, and fittings and accessories. The driveline system shown at the right hand side of Fig.2 delivers the driving force generated by the M/E to the propeller. The driveline system has a propeller, a shaft, intermediate shaft bearings, stern tube bearings, and stern tube seal bearings.

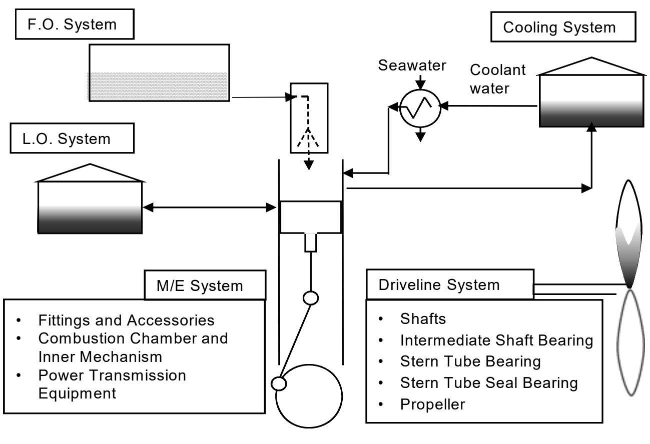

Figure 2. Outline of ship propulsion system

The F.O. system is the system that supplies the fuel oil to the main engine. Conceptual diagram for F.O. system is shown in Fig.3. The fuel oil is the crude petroleum stored at service tank (1). Sludge in the F.O. is removed with F.O. strainer (2). The F.O. is collected by the chamber via F.O. supply pump (3). The F.O. collected by the chamber is sent to F.O. heater via F.O. booster pump (4). Pressure of F.O. rises with the booster pump (5). The F.O. is heated up to appropriate temperature with FO heater (6). Sludge in the F.O. is removed with strainer, again (7). The F.O. is sent to the F.O. injection pump and put on high pressure (8). The F.O. is jetted from the fuel injection valve to the piston chamber (9). The numbers in parentheses correspond to those in Fig.3.

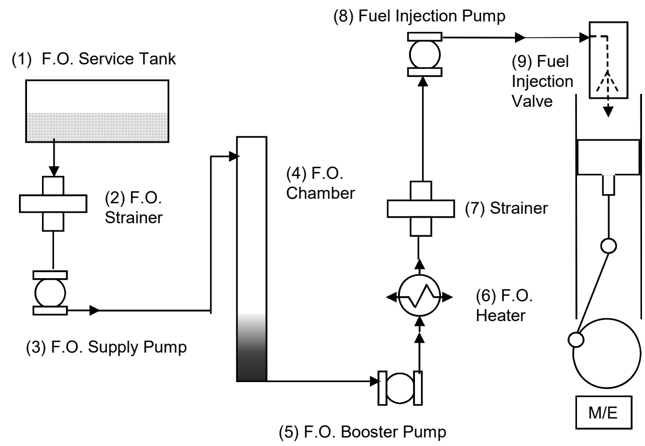

Figure 3. Conceptual diagram for F.O. system

The L.O system is a system that offers the lubricating oil to the operation part of the main engine block. Conceptual diagram for L.O. system is shown in Fig.4. The L.O. is stored in L.O. service tank (1) and L.O. gravity tank (2), and sent to the M/E. The L.O. at M/E is collected and sent to L.O. cooler (4) by L.O. pump (3). Then cooled L.O. is returned to the L.O. service tank.

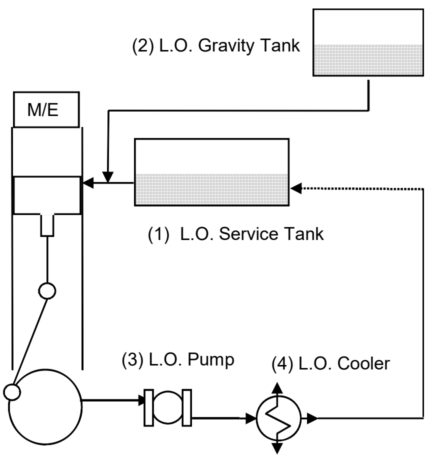

Figure 4. Conceptual diagram for L.O. system

The cooling system makes the coolant water circulate in the main engine block, and prevents the engine from overheating. The cooling system consists of freshwater (F.W.) cooling system and seawater (S.W.) cooling system. Conceptual diagram for cooling system is shown in Fig.5. The F.W. is stored in F.W. tank (1) as coolant for M/E. The F.W. is sent to F.W. cooler (3) by F.W. pump (2). At the F.W. cooler, F.W is cooled by seawater which comes from S.W. cooling system (see Fig.2). Then F.W. cools the M/E by passing over the inside of engine block. The warmed F.W. from M/E returns to F.W. tank. In the S.W. cooling system, seawater outboard is absorbed by S.W. pump (2) via the S.W. suction valve. The S.W. cools F.W. at F.W. cooler, and is exhausted to outboard.

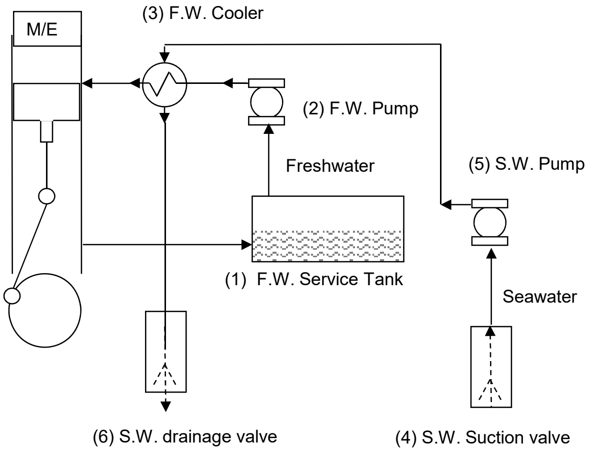

Figure 5. Conceptual diagram for cooling system

The M/E system and the driveline system are large, main subsystems of the ship propulsion system and there are no backups. On the other hand, F.O. system, L.O. system, and cooling system are small auxiliary subsystems and each of them typically consists of two or three trains.

3 DESCRIPTION OF GO-FLOW

GO-FLOW is a success-oriented system analysis tool for evaluating system reliability and availability. GO-FLOW uses a set of standardized operators shown in Table 1 to describe the logic operation, interaction, and combination of physical equipment. A system is modeled by selecting operators and connecting them by signal lines. The signal represents some physical quantity or information. In GO-FLOW, three types of signals are connected to an operator; the main input signal(s), the sub-input signal(s), and the output signal. The intensity of a signal represents the probability of the actual or potential existence of a physical quantity or the probability of some information transmission or mission. The output signal intensity of each operator is shown in Table 1.

By using GO-FLOW, F.O. system of ship propulsion system described in Fig.3 was modeled as shown in Fig.6. In Fig.6, the signal is flow of F.O. and starts from Operator 1 which a signal generator (see Table 1). In GO-FLOW, system operation sequence is expressed in terms of a finite number of discrete time points (TP) and signal intensity (SI) of signal generator. Table 2 shows the sequence of operation for the system in Fig.6. No.1 F.O. service tank in Fig.6 is modeled with Operator 3 which is a Type 26 operator (see Table 1). Although Type 26 operator usually represents a normally closed valve as shown in Table 1, in conjunction with Operator 2 which is a signal generator (see Table 1) it is used to model the process of opening the valve of service tank that is closed at the initial state (TP 1 in Table 2). From Table 2, the SI of Operator 2 turns from 0 to 1 at TP2 and hence initiates the F.O. flow through Operator 3 which emulates the opening the valve. Then the F.O. flows to Operator 5. Operator 5 models No.1 F.O. strainer by Type 21 operator which represents a good/bad component. If the component does not work, F.O. is not supplied to downstream of the component. The F.O. system has two trains and each pump has selectable function. Therefore the signal at the upstream of the pump and downstream of the pump was connected by OR gate. Then, the GO-FLOW outputs the availability of the F.O system as the intensity of final signal. The final signal in Fig.6 is the input line of the Terminal.

Table 1. Operators in GO-FLOW methodology

Operator	Symbol	Model	Output Signal Intensity
Type 21		Two-State Component	$R_o(i) = S(i) \cdot P_g$
Type 22	OR	OR Gate	Probability that at least one input signal exists
Type 23	NOT	NOT Gate	$R_o(i) = 1 - S(i)$
Type 25		Signal Generator	Probability of a demand or time duration in hours
Type 26		Normally Closed Valve	$R_o(i) = S(i) \cdot O(i), \quad O(i) = O(i') + [1 - O(i')] \cdot V(i) \cdot P_g, \quad O(i_1) = P_p$
Type 27		Normally Open Valve	$R_o(i) = S(i) \cdot O(i), \quad O(i) = O(i') \cdot [1 - V(i) \cdot P_g], \quad O(i_1) = 1 - P_p$
Type 30	AND	AND Gate	Probability that all the input signal exist

*In this table, $S(i)$ is the main input signal, $V(i)$ is the sub-input signal, $R_o(i)$ is the output signal, P_g is the probability for successful operation, $O(i)$ is the probability for a valve to be in the open state, P_p is the probability for premature operation, i is the time point with subscript denoting the ordinal, i' is the time point immediately before the time point i.

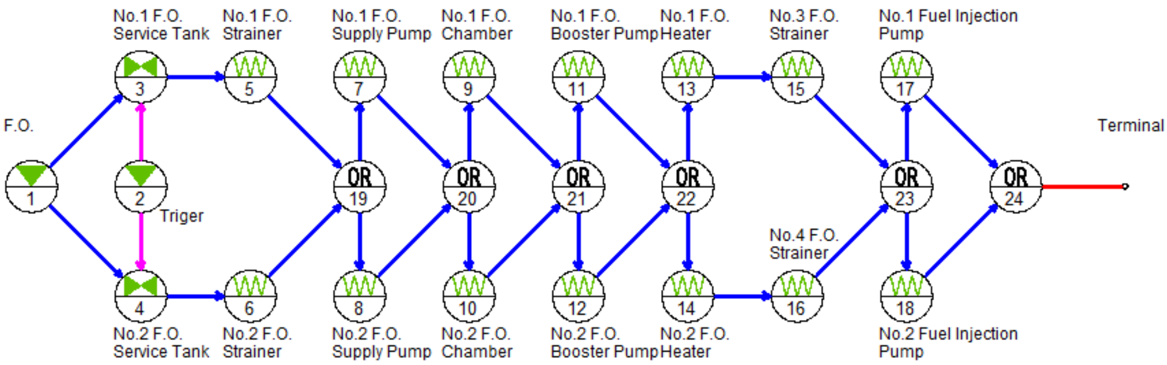

Figure 6. GO-FLOW chart of F.O. system

Table 2. Example of operation sequence

Time Point (TP)	Sequence	Signal intensity (SI) Operator 1	Operator 2
1	F.O flows from upstream.	1	0
2	Valve open.	1	1

Figure 7 shows GO-FLOW chart of L.O. system described in Fig.4. In Fig.7, the signal is flow of L.O. Then the signal intensity at Terminal in Fig.7 describes the availability of L.O. system.

Fig.8 shows GO-FLOW chart of cooling system described in Fig.5. Upper side of the figure indicates flow of freash water in cooling system and lower sinde of the figure indicates flow of sea water in cooling system. The signal from upperside and signal from lower side are connected by an AND gate. The signal intensity at terminal in Fig.8 describes the availability of cooling system.

Fig.9 shows GO-FLOW chart of propulsion system. In Fig.9, Operator 1 modeled by an AND gate with three signals which are the availability of F.O. system, L.O. system and cooling system. Therefore, the intensity of output signal of Operator 1 describes availability of the auxiliary system in ship propulsion. The output signal becomes input to the subsequent operators which model the M/E system and the driveline system. Then the signal intensity at Terminal in Fig.9 describes the availability of L.O. system.

4 TIME-DEPENDENT TECHNIQUE

A GO-FLOW operator requires the probability for successful/failed operation as input (e.g. Type 21, 26, 27 in Table 1). In order to consider aging effects, this input parameter was derived from the time-dependent technique of [4] described in Section 4.1. Section 4.2 shows the implementation of the time-dependent technique for GO-FLOW. In the time-dependent technique, the unavailability of each component depends on its maintenance schedule. Section 4.3 shows how the maintenance schedule is managed in GO-FLOW.

4.1 *Time-dependent technique for aging components*

The technique used to model the time-dependent unavailability of aging components is based on the extended renewal equation [4]

$$\begin{aligned} w(t) &= \tilde{f}(t) + \int_{0^+}^{t} dt' f(t',t) \int_{0^+}^{t'} dt'' w(t'') g(t'',t') \\ &= \tilde{f}(t) + \int_{0^+}^{t} dt' w(t') \int_{t'}^{t} dt'' g(t',t'') f(t'',t) \,, \end{aligned} \quad (1)$$

where $w(t)dt$ is probability that the component fails within $(t, t+dt)$, $\tilde{f}(t)$ is first failure density (FFD) for the component at time t, $f(t',t)dt$ is probability component fails within $(t,t+dt)$ given that repair is completed at $t'<t$, and $g(t',t)dt$ is probability that repair is completed within $(t,t+dt)$ given that component fails within $(t',t'+dt')$}.

Under the assumptions that, 1) surveillance/tests are performed at times T units apart, 2) failures are detected only during surveillance/tests and cannot be detected at other times 3) surveillance/testing and repair times are negligible compared to T, and, 4) the component is restored to age 0 following surveillance/testing (i.e. through either minor maintenance such as tightening a valve or repair), it can be shown that, for a single component, the time-dependent unavailability $U(t)$ is given by [4],

$$U(t) = \int_{nT}^{t} dt' f(t',0) + \sum_{k=1}^{n} U(kT) \left[\exp\{-\int_{0}^{(n-k)T} dt' \lambda(t')\} - \exp\{-\int_{0}^{t-kT} dt' \lambda(t')\} \right]$$
$$nT < t \le (n+1)T \quad (n = 0,1,\cdots), \quad (2)$$

where $\lambda(t)$ is the failure rate for the component at time t.

In this study, the failure density of an aging component is assumed to be given by the Weibull distribution

$$f(t,t') = \begin{cases} \lambda_0 \exp\{-\lambda_0 (t-t')\} & \text{if } t-t' < \tau \\ \lambda_0 \dfrac{(t-t')^b}{\tau^b} \exp\{-\dfrac{\lambda_0 \tau}{b+1}[b + \dfrac{(t-t')^{b+1}}{\tau^{b+1}}]\} & \text{otherwise,} \end{cases} \quad (3)$$

where τ is the threshold time at which aging starts, λ_0 is the pre-aging constant failure rate, b is the Weibull shape parameter and t' is the time at which last repair is completed. The failure rate for this failure density is

$$\lambda(t) = \begin{cases} \lambda_0 & \text{if } t < \tau \\ \lambda_0 \left(\dfrac{t}{\tau} \right)^b & \text{otherwise.} \end{cases} \tag{4}$$

Then the time-dependent unavailability is given by [3]

$$U(t) = R(nT)q(0,t) + \sum_{k=1}^{n} U(kT)R[(n-k)T]q(kT,t) \qquad nT < t \le (n+1)T \quad (n = 0,1,\cdots), \tag{5}$$

where

$$R(l) = \begin{cases} \exp(-\lambda_0 l) & \text{if } l < \tau \\ \exp\{-\dfrac{\lambda_0 \tau}{b+1}(b + \dfrac{l^{b+1}}{\tau^{b+1}})\} & \text{otherwise} \end{cases} \tag{6}$$

$$q(kT,t) = \begin{cases} 1-\exp\{-\lambda_0(t-nT)\} & \text{if } (n-k)T < \tau \\ 1-\exp\{-\lambda_0(t-nT) - \dfrac{\lambda_0}{(b+1)\tau^b}[(t-kT)^{b+1} - \tau^b]\} & \text{if } (n-k)T \ge \tau, t-kT < \tau \\ 1-\exp\{-\dfrac{\lambda_0}{(b+1)\tau^b}[(t-kT)^{b+1} - (n-k)^{b+1}T^{b+1}]\} & \text{otherwise.} \end{cases} \tag{7}$$

If the Weibull shape parameter b is set as 1, Eq. (7) corresponds to a linear aging model.

As indicated earlier, Eq. (2) and subsequently Eq. (5) is based on the assumption that surveillance is performed at times T units apart. In order to consider irregular surveillance, expanding Eq.(5) we have

$$\begin{aligned} U(t) = {} & R(nT)\cdot q(0,t) \\ & +U(T)\cdot R(nT-T)\cdot q(T,t) \\ & +U(2T)\cdot R(nT-2T)\cdot q(2T,t) \\ & +\cdots \\ & +U(nT-T)\cdot R(T)\cdot q(nT-T,t) \\ & +U(nT)\cdot R(0)\cdot q(nT,t). \end{aligned} \tag{8}$$

Under the assumption that each surveillance period is sequentially assumed to be $T_j (j=1,2,3, \ldots ,n)$ and $T_0=0$ is for the case of $n=0$, Eq.(8) is becomes

$$\begin{aligned} U(t) = {} & R(T_0+T_1+T_2+\cdots+T_n)\cdot q(0,t) \\ & +U(T_1)\cdot R(T_2+T_3+\cdots+T_n)\cdot q(T_1,t) \\ & +U(T_1+T_2)\cdot R(T_3+T_4+\cdots+T_n)\cdot q(T_1+T_2,t) \\ & +\cdots \\ & +U(T_1+T_2+\cdots T_{n-1})\cdot R(T_n)\cdot q(T_1+T_2+\cdots T_{n-1},t) \\ & +U(T_1+T_2+\cdots T_n)\cdot R(0)\cdot q(T_1+T_2+\cdots T_n,t). \end{aligned} \tag{9}$$

Then

$$\begin{aligned} U(t) = {} & R(\sum_{j=0}^{n} T_j)\cdot q(0,t) + \sum_{k=1}^{n-1}\{U(\sum_{j=1}^{k} T_j)\cdot R(\sum_{j=k+1}^{n} T_j)\cdot q(\sum_{j=1}^{k} T_j,t)\} \\ & + U(\sum_{j=1}^{n} T_j)\cdot R(0)\cdot q(\sum_{j=1}^{n} T_j,t) \qquad T_n < t \le T_{n+1} \quad (n=0,1,\cdots) \end{aligned} \tag{10}$$

where

$$R(\sum_{j=0}^{n} T_j) = \begin{cases} \exp(-\lambda_0 \sum_{j=0}^{n} T_j) & \text{if } \sum_{j=0}^{n} T_j < \tau \\ \exp\{-\dfrac{\lambda_0 \tau}{b+1}[b + \dfrac{(\sum_{j=0}^{n} T_j)^{b+1}}{\tau^{b+1}}]\} & \text{otherwise,} \end{cases} \tag{11}$$

$$R(\sum_{j=k+1}^{n} T_j) = \begin{cases} \exp(-\lambda_0 \sum_{j=k+1}^{n} T_j) & \text{if } \sum_{j=k+1}^{n} T_j < \tau \\ \exp\{-\dfrac{\lambda_0 \tau}{b+1}[b + \dfrac{(\sum_{j=k+1}^{n} T_j)^{b+1}}{\tau^{b+1}}]\} & \text{otherwise} \end{cases} \tag{12}$$

and

$$q(\sum_{j=1}^{k} T_j,t) = \begin{cases} 1-\exp\{-\lambda_0(t-\sum_{j=1}^{n} T_j)\} & \text{if } t-\sum_{j=1}^{k} T_j < \tau \\ 1-\exp\{-\lambda_0(\tau-\sum_{j=k}^{n} T_j) - \dfrac{\lambda_0}{(b+1)\tau^b}[(t-\sum_{j=1}^{k} T_j)^{b+1} - \tau^{b+1}]\} & \text{if } t-\sum_{j=1}^{k} T_j \ge \tau,\ \sum_{j=k}^{n} T_j < \tau \\ 1-\exp\{-\dfrac{\lambda_0}{(b+1)\tau^b}[(t-\sum_{j=1}^{k} T_j)^{b+1} - (\sum_{j=k}^{n} T_j)^{b+1}]\} & \text{otherwise.} \end{cases} \tag{13}$$

4.2 *Time-dependent probability for GO-FLOW operators*

Type 21 operator in Table 1 models a good/bad component. This operator has one input signal and one output signal line and requires a probability for successful operation. The output signal intensity is given by

$$R_o(i) = S(i)\cdot P_g \tag{14}$$

where $S(i)$ is input signal at time point i, $R_o(i)$ is output signal at time point i, P_g is the probability for successful operation. In order to consider aging effect of Type 21 operator, P_g is enabled for successful operation by

$$P_g = 1.0 - U(t) \tag{15}$$

where $U(t)$ is the time-dependent unavailability given by Eq. (10).

Type 26 operator in Table 1 models a normally closed valve, which is opened by sub-input signal. This operator has one input signal, one sub-input signal, and one output signal line. The output signal intensity is given by

$$\begin{aligned} & R_o(i) = S(i)\cdot O(i) \\ & O(i) = O(i') + [1.0 - O(i')]\cdot V(i)\cdot P_g \end{aligned} \tag{16}$$

where $V(i)$ is sub-input signal at time point i, i' is time point immediately before the time point i, $O(i)$ is probability for valve in open state, P_g is the success probability for opening valve operation. In order to consider aging effect of Type 26 operator, P_g is given by Eq.(15). For initial time point, $O(1)$ is given by

$$O(1) = P_p \tag{18}$$

where P_p is probability for premature operation.

Type 27 operator in Table 1 models a normally open valve, which is closed by sub-input signal. This operator has one input signal, one sub-input signal, and one output signal line. The output signal intensity is given by

$$\begin{aligned} R_o(i) &= S(i) \cdot O(i) \\ O(i) &= O(i') \cdot [1.0 - V(i) \cdot P_g] \end{aligned} \tag{16}$$

where P_g is the success probability for closing valve operation. In order to consider aging effect of Type 27 operator, P_g is given by Eq.(15).

4.3 *Maintenance period*

Time-dependent unavailability of each component depends on the maintenance schedule. In order to implement and manage the maintenance schedule in GO-FLOW, each GO-FLOW operator was allocated a unique 3digit number and the maintenance schedule for each operator was linked with this 3digit number (which we call the maintenance code) as will be illustrated below. Then, each operator's unavailability as given in Eq. (15) was calculated by the time-dependent technique using this maintenance schedule.

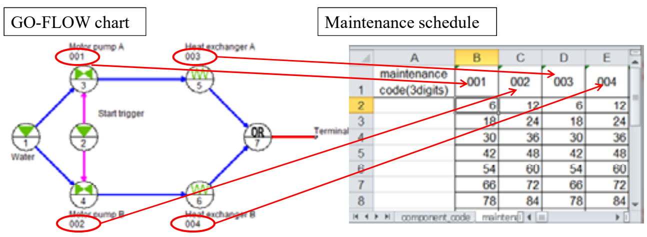

Figure 10. Example of GO-FLOW chart and maintenance schedule

Fig.10 shows example of GO-FLOW chart which models a two-train heat removal system (Systems A and B) and the maintenance schedule for each operator. For example, Operator 3 in Fig.10 (Motor Pump A) is assigned 001 as the maintenance code and its maintenance schedule is described in Column 001. In column 001, times when the maintenance of Motor Pump A is executed is shown in months. This time also indicates the age of Motor Pump A. The table in Fig.10 shows that the first maintenance of Motor Pump A was executed at its age of six months, and the maintenance after that was executed at every 12 months. The maintenance schedule for Heat Exchanger A which maintenance code is 003 has same maintenance schedule as the Motor Pump A. On the other hand, Motor Pump B with maintenance code 002 and Heat Exchanger B with maintenance code 004 were maintained every 12 months. Therefore, the timing of maintenance for Systems A and B have gap which described in Fig.11. Using this maintenance schedule function, GO-FLOW could consider the gap of the maintenance timing and changing maintenance period.

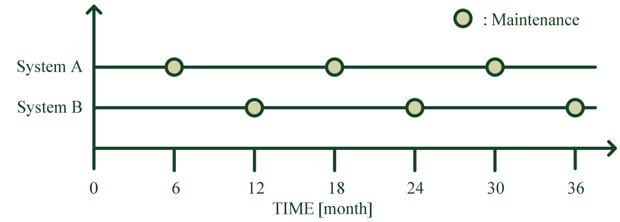

Figure 11. Example of timing of maintenance for system A and B

5 CASE STUDY

In this section, three cases of GO-FLOW simulation for unavailability of ship's propulsion system are considered with aging effect and maintenance modeled as described in Section 4. Case 1 has no aging effects. In Case 2, the variation of the unavailability of ship propulsion system under aging effects is simulated. Case 3 assumes that the ship is sold at age 20 years and the maintenance period was changed.

5.1 *Case 1*

To simulate the variation of unavailability before aging effects, the GO-FLOW chart of ship propulsion system described in Fig.9 was used. In this model, Type 21 and Type 26 GO-FLOW operators and Eq.(10)-(13) for $T_j<\tau$ are needed. Failure rate for each component was taken from Ship Reliability Investigation Committee's (SRIC) database [2] which is compiled from the engine room failure reports of 265 merchant ships. The choice of the maintenance period is described in Section 5.1.1 and results of the simulation are described in Section 5.1.2.

5.1.1 *Choice of the maintenance period*

In general, auxiliary components of engine room are maintained by engineers during navigation. For example, in the case of the two-train system such as described in Fig.3, System B can be maintained when System A is under operation. The component that could be only maintained when the ship is moored at the pier is M/E. The ship is entered in the dock once a year, and all components of engine room are inspected and maintained as required. Therefore, the components of ship propulsion system were divided into three groups: Group 1includes components which are maintained during navigation, Group 2 includes components which are maintained at the port, and Group 3 includes components which are maintained only at the dock. In this study, all components of F.O. system, L.O. system, and cooling system were classified as Group 1, and all components of driveline system and components of M/E system except fittings and accessories were classified into Group 3. The fittings and accessories of

M/E system were classified as Group 2. Maintenance period for Group 3 (T3) was set to 1 year and maintenance period for Group 2 (T2) was set to 1 month which was estimated from average navigation times. Maintenance period for Group 1 depends on ability of the engineer. It is estimated that ability of an engineer in a major marine transportation company is high and ability of an engineer in a minor company is lower. Therefore, maintenance period for Group 1 (T1) was chosen as T1=2weeks for a major company and T1= 4 weeks for a minor company.

5.1.2 *Results*

Using the approach described above, the variation of unavailability of ship propulsion system was calculated by GO-FLOW. Figure10 shows the unavailability of ship propulsion system as a function of time. From Fig.10, it can be seen that the unavailability oscillates with a period of every 2 weeks and the average unavailability increases during the year. This oscillation is caused by the maintenance of Group 1 components. The trend of increasing unavailability is due to the unavailability of Group 3 components which are maintained every year when the ship is in the dock as indicated above. Therefore the peak in the unavailability is just before the ship enters the dock. This unavailability just before the dock (UBD) is 0.034 as shown in Fig.10. On the other hand, if the maintenance period for Group 1 iss set to 4 weeks, UBD increases to 0.061 as shown in Fig.11.

5.2 *Unavailability under aging effect*

As described in Section 5.1, to simulate the unavailability of ship propulsion system, SRIC data base was used for failure rate of each component. To calculate unavailability of ship propulsion system under the aging effect, Eq(11), (12), and (13) require the value of τ which is the threshold time for the start of aging effect and the value of *b* which is the Weibull shape parameter for aging component model. The choicer of these parameters is described in Section 5.2.1. Section 5.2.2 presents the results.

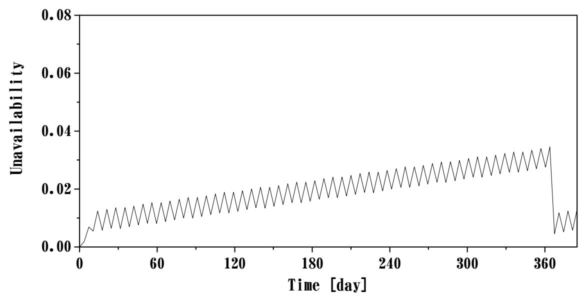

Figure 10. Unavailability of the ship propulsion system (T1=2weeks)

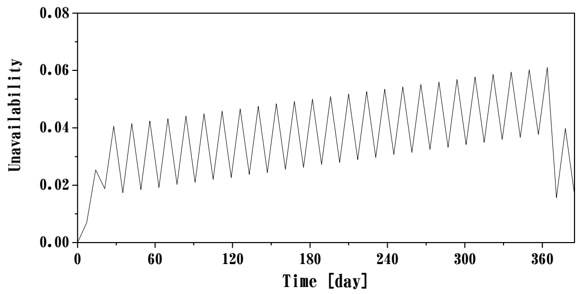

Figure 11. Unavailability of ship propulsion system (T1=4weeks)

5.2.1 *Setting of aging parameter*

In the insurance on the cargo of a ship, overage additional premium is applied if the ship is 15 years or older.. However, aging parameters are not available for all components in the SRIC database. Therefore, τ for all components of the ship propulsion system was set as 10 years and 15years to account for the possible variation in τ. The aging model was treated as linear (i.e. *b* =1) [5]. Also, maintenance period for each component group was set as $T1 = 2$ weeks, $T2 = 1$ month, and $T3 = 1$ year.

5.2.2 *Results*

Figure12 shows the variation of the unavailability of the ship propulsion system until just before entering dock. In this figure, the result of $\tau = 10$ years was drawn by solid line and the result of $\tau = 15$ years was drawn by dotted line. The value of UBD before aging starts is assumed to be 0.03 (see Section 4.1.2). At the age of 35 years, the value of UBD for the case of $\tau = 10$ years is 0.078 and the value of UBD for the case of $\tau = 15$ years was 0.060. Naturally, the UBD of $\tau = 10$ year case for which aging stars early is larger than the UBD of $\tau = 15$ years. Therefore, τ was set to 10 years conservatively for the simulation in Section 5.3.

5.3 *Unavailability under changing maintenance period*

From the result of Section 5.1, it is seen that the value of pre-aging UBD for 4 week maintenance period for Group 1 is 0.061. On the other hand the result of Section 5.2show that the value of UBD at 20 years after the aging starts is 0.060. From these two results, it is clear that proper maintenance is important to keep low unavailability of the ship propulsion system in an aging ship. However, it is possible that an aging ship is sold from a major marine transportation company to minor company. In the minor company, the maintenance period for Group 1 components was assumed to be 4 weeks (see Section 4.1) Therefor the maintenance period for Group 1 was changed from 2weeks to 4 weeks at the age of 20 years at which point the ship is assumed to sold to the minor company.

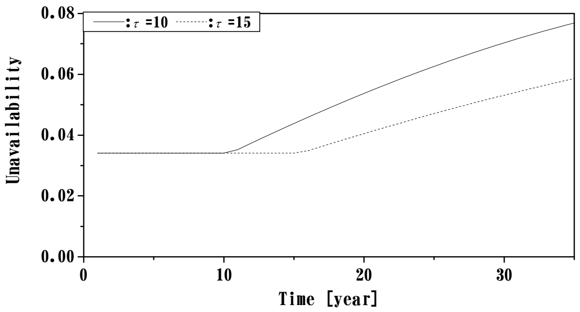

Figure 12. Unavailability of ship propulsion system at just before dock

Figure13 shows UBD of the ship propulsion system when maintenance period T1 was changed from 2 weeks (solid line) from 4 weeks (dotted line) at 20 years. The value of UBD increases rapidly as expected from 0.054 to 0.085 at age 20 years and to 0.107 at age 35 years.

6 DISCUSSION

From the results of the case studies presented in this paper the value of pre-aging UBD was found to be 0.034 (see Section 5.1.2) which implies that a malfunction can occur in about 30 voyages (1000/34=29.4). In this study, navigation time for one voyage was assumed to be 1 month, however, the number of voyages per year was estimated to be 8 rather than 12, because the ship is moored at the port at the end of in each voyage and enters dock once a year. Therefore, the maximum number of navigation days per year was estimated to be 250 days. Based on this reasoning, that pre-aging ship has the possibility of a propulsion system malfunction once every four years. Table 3 shows the resulting frequency of malfunction as a function of age of a ship which is sold from a major company to a minor company at age 20 years. From the Table 3, it is seen that a 35 years old ship has the possibility of malfunction once in about 10 voyages vs. about 30 years for a new shp. This result show that the aging effects and improper maintenance can potentially increase the frequency of accidents due to a malfunction of the propulsion system by a factor of 3. It should be mentioned that this results is based on the assumption that aging effects of the all the component of the ship propulsion system start at age ten years.

Table 3 Frequency of malfunction for aging ship

Age [year]	Unavailability	Frequency of malfunction [voyage time]	Mean time between failures [year]
0 - 10	0.034	29.4	3.7
20	0.054	18.5	2.3
21	0.085	11.8	1.5
35	0.107	9.3	1.2

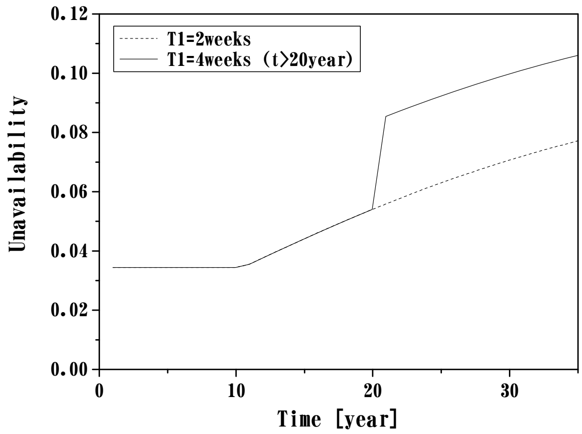

Figure 13. UBD of ship propulsion system which maintenance period T1 was changed from 2 weeks to 4 weeks at age 20 years.

7 CONCLUSION

This study examines the unavailability of ship propulsion system under aging effects and maintenance using an augmented GO-FLOW methodology to account for time-dependent failure rates. The results show that the aging effects and improper maintenance can potentially increase the frequency of accidents due to a malfunction of the propulsion system by a factor of 3 in 35 years.

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