Reliability Analysis Including External Failures for Low Demand Marine Systems

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Abstract: Marine systems fail not only due to equipment failure, but also because of external events like fire or flooding. Fire in the engine room, for example, can damage the main engine and it can lead to propulsion system failure regardless of the reliability of the main engine itself. Many redundancy requirements to vessels include these external events as a cause to system failure and they require physically separated redundancy in order to prevent system failure by a single fire or flooding. We need to consider external events, as well as equipment failure when analyzing the reliability of a marine system.

The main objective of this paper is to introduce a reliability analysis models for (i) equipment failure and (ii) external failure of low demand marine systems. A Markov model is suggested to calculate the hazardous event frequency (HEF) in this study. The paper also investigates the contribution of the two different types of failures (i & ii). The paper provides a case study of a fire pump in a passenger ship which analyses the contribution of each failure type.

Keywords: Reliability Analysis, Low Demand Marine System, Markov Model, External Failures, Redundancy, Safe Return to Port (SRtP), Dynamic Positioning (DP), Redundant Propulsion (RP), Hazardous Event Frequency (HEF).

1. INTRODUCTION

There are several redundancy requirements for vessels which have been issued by International Maritime Organization (IMO) and Classification Societies: IMO equipment class [1], Notations of Classification Societies for Dynamic Positioning (DP) system [2] and Redundant Propulsion (RP) [3], and Safe Return to Port (SRtP) regulation for passenger ships [4-6]. All redundancy requirements include external failures, as well as internal failures, because marine systems fail due to both types of failures. The former is a random hardware failure, which is relevant for reliability of equipment, while the latter is a failure caused by external events, which here are defined as fire and flooding [1-5]. For example, a fire in the vessel's engine room can damage the main engine and lead to loss of propulsion regardless of the reliability of the main engine itself. We therefore need to consider both types of failures when analyzing the reliability of a marine system. Even though reliability analysis methods and models for internal failures have evolved over several decades by various authors [7, 8], there are not much research on reliability analysis of external failures.

The main objective of this paper is to introduce a reliability analysis model and investigate the contribution of the two different types of failures of low demand marine systems: internal failure and external failure. If the effect of external failures is much greater than internal failures, then we need to pay much more attention to that kind of failures and study the feasibility of reliability analysis methods more in depth. On the other hand, if the effect of external failures is very small and negligible, then we may not need any further study on reliability analysis of external failures. The research in this paper investigates hazardous event frequency (HEF) of 1oo2 system to compare the impact of the two types of failures.

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An external failure is some kind of a common cause failure (CCF) and therefore one may argue that it could be included in the analysis of an internal failure as a CCF. However, an external failure may be a single failure as well as a CCF. For example, two independent fires may damage a redundant system at the same time. Considering an external failure as a CCF only is therefore an imperfect model and external failures should be included in the model as a single failure too.

One challenge of analyzing external failures is that, for some systems, a demand itself is a cause of system failure. A system may be damaged by a demand, and therefore it may fail to respond to the demand. For instance, if a fire occurs in a vessel and it damages the fire pump or other essential components for the firefighting system, the firefighting system cannot extinguish the fire. In this case, the fire is a demand, as well as a cause of system failure. This study focuses on these kinds of systems in the following sections.

The rest of this paper is organized as follows: the research method is described in Section 2. Section 3 and 4 introduce the Markov models for internal failure and external failure, and case studies for each kind of failures are given in Section 5. Finally, discussion and concluding remarks are presented in Section 6.

2. RESEARCH METHOD

The impact of external failure and internal failure should be compared by using an identical method and unit. An external failure is closely related to a demand, and therefore the demand rate should be included in the model when analyzing external failures. Various authors have shown that a Markov approach is suitable for reliability modeling, including for the demand rate [9-14], and Jin, et al. [14] have suggested a Markov model for internal failure of a 1oo2 system. This paper is based on this model for reliability analysis of internal failures because 1oo2 system is the most common redundant concept in marine systems. Assessing the impact of external failures has not been attempted by previous research and therefore this study suggests a Markov model for external failures of a 1oo2 system.

With those two Markov models of each type of failures, this study calculates HEF [13, 14] and studies the impact and contribution of each kind of failures.

3. MARKOV MODEL FOR INTERNAL FAILURE OF 1oo2 SYSTEM

3.1 Assumptions

It is assumed that the system components are exposed to dangerous undetected (DU) failures only. A dangerous detected (DD) failure is assumed to be revealed and repaired immediately, and therefore it is negligible. A DU-failure is discovered during a functional test, and the functional test and repair actions are assumed perfect. All failure rates are constant even when components are responding to a demand, and the system satisfies the Markov property [7]. The standard β factor model is used to model CCFs. It is also assumed that the two components are identical and the system composes passive standby with perfect switching.

3.2 System States

The Markov model has six system states from state 0 to state 5, and they are defined in Table 1. System components have three kinds of states: “Available”, “Functioning” and “Failure”. “Available” means that the component is able to respond to a demand, and “Functioning” means that the component is already responding to a demand. “Failure” means that the component is unable to respond to a demand because of a DU-failure [14].

Table 1 System States of Internal Failure

System State	Component State	Demand
5	2 Available	Non-demand
4	1 Available, 1 Functioning	On-demand
3	1 Available, 1 Failure	Non-demand
2	1 Functioning, 1 Failure	On-demand
1	2 Failures	Non-demand
0	2 Failures	On-demand

3.3 System Transitions

System transitions for internal failure of 1oo2 system are illustrated in Figure 1. State 5 is the initial state, where all components are able to respond without any demand. State 0 is the hazardous state where both of redundant components are failed by DU-failure with an occurrence of a demand. State 4 represents that one of the components responds to a demand without any failures. State 3 is the state where one of the components has DU-failure without demand, and state 2 is one DU-failure with a demand. Even though both of the components are failed in state 1, it is not a hazardous state because there is no demand. The transition rates of this Markov model are defined in Table 2.

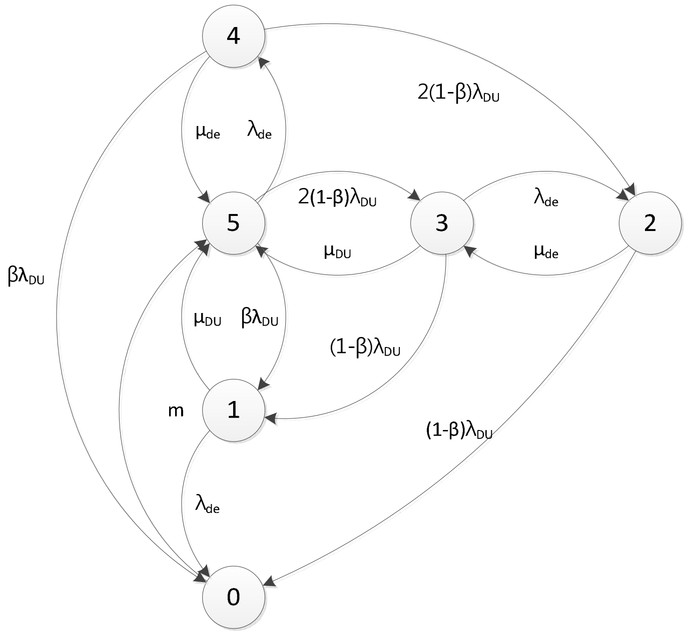

Figure 1 Markov Transition Diagram of Internal Failure

Table 2 Markov Transition Rates of Internal Failure

Transition Rates	Description
λ_{de}	Demand rate
μ_{de}	Demand duration rate
$(1-\beta)\ \lambda_{DU}$	Single DU-failure rate
$B\ \lambda_{DU}$	DU-CCF rate
μ_{DU}	DU repair rate
m	Renewal rate

4. MARKOV MODEL FOR EXTERNAL FAILURE OF 1oo2 SYSTEM

4.1 Assumptions

It is assumed that the system components are exposed to external failures only, and the external events are demands of the system, for instance a fire and a firefighting system. The fire is an external event which can lead to failure of the firefighting system and, at the same time, the fire is the demand of the firefighting system. If the system is not damaged by the external event (demand), the system successfully responds to the demand and the system is restored to an “as good as new” state after the demand duration. If the system is damaged by the external event, it is not possible to repair onboard, and the vessel should return to port to repair it. It is also assumed that the two components are identical and the system composes passive standby with perfect switching.

4.2 System States

The Markov model has five system states from state 0 to state 4, and they are given in Table 3. System components have three kinds of states, and they are same as in Section 3.2, except the “Failure” state. “Failure”, in this model, means that the component is unable to respond to a demand because of an external failure.

Table 3 System States of External Failure

System State	Component State	Demand
4	2 Available	Non-demand
3	1 Available, 1 Functioning	On-demand
2	1 Functioning, 1 Failure	On-demand
1	1 Available, 1 Failure	Non-demand
0	2 Failures	On-demand

4.3 System Transitions

System transitions for external failures of 1oo2 system are illustrated in Figure 2. State 4 represents the initial state where all components are able to respond without any demand. State 0 is the hazardous state where both components are failed by external failure with an occurrence of a demand. In state 3, the external event (demand) occurs, but it does not damage the system. The system therefore responds to the demand, and the system state moves to the initial state 4 after the demand duration. State 2 is the state where one of the components is damaged by the demand and the other is responding to the demand. After demand duration, the system state moves to state 1 where one of the components is able to respond and the other is not. It is not possible to move directly from state 4 to state 1, because the demand is the cause of the system failure. Moreover, in this model, there is no state where both components are failed without demand, like state 1 in Section 3.2, because of the same reason. One principle of this model is “no demand, no failure”.

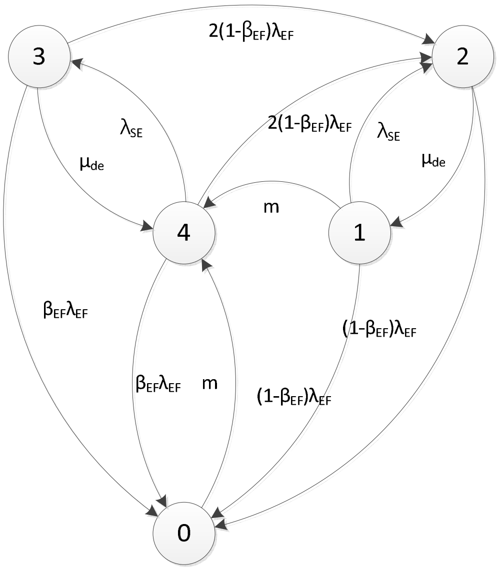

Figure 2 Markov Transition Diagram of External Failure

Table 4 Markov Transition Rates of External Failure

Transition Rates	Description
λ_{SE}	Survival rate by external event
μ_{de}	Demand duration rate
(1-β_{EF}) λ_{EF}	Single external failure rate
B_{EF} λ_{EF}	External CCF rate
m	Renewal rate

λ_{EF} represents the failure rate of a component by external events (demand), while λ_{SE} is a survival rate. They may be calculated as

$$\lambda_{EF} = \lambda_{de} \cdot EF \tag{1}$$

$$\lambda_{SE} = \lambda_{de} \cdot (1 - EF) \tag{2}$$

where EF denotes the conditional probability that the demand damages system given a demand occurs. Beta factor for external failure (β_{EF}) is a value which represents whether redundant components are physically separated or not. If the two redundant components are perfectly separated and not damaged by a single external event at the same time, β_{EF} equals to 0.

5. CASE STUDY

To test the models from the previous sections two different types of fire water supply systems are analyzed. One complies with the redundancy requirement with physical separation and the other does not. The case study calculates HEF of internal failures and external failures for each of the two systems and investigates the impact and the contribution to the overall reliability of each type of failures.

5.1 System Description

The main function of the fire water supply system is to provide water, in case of an occurrence of a fire, to extinguish the fire. The system consists of two fire pumps, the power supply system, power cables, the control system, control cables, water pipes, valves, and many necessary accessories. For the sake of simplicity, this case study only considers the two fire pumps with a 1oo2 configuration.

Two different types of fire water supply systems are given in Figure 3; "System A" is a physically separated system, while "System B" is a physically not-separated system. The physical separation is based on marine redundancy requirements [1-4]. They assume that physically separated components are not damaged by a single fire at the same time, while physically not-separated components fail simultaneously if a fire occurs in the compartment where they are located. Applying this physical separation affects the reliability of the system related to external failures, and therefore the research in this case study includes both of the systems in the case studies.

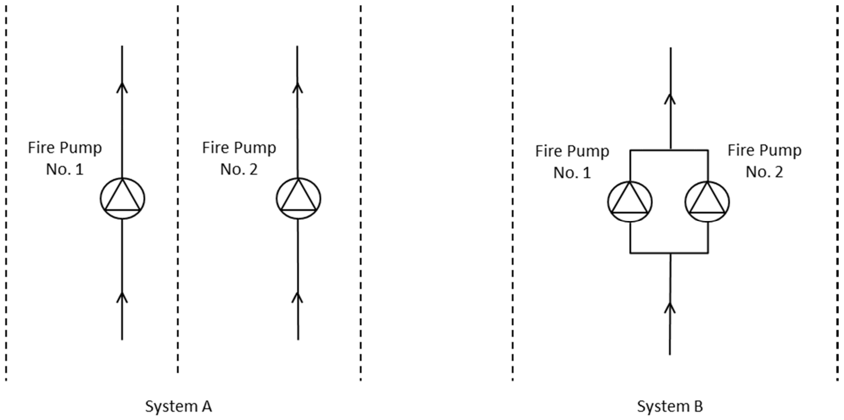

Figure 3 Two Types of Fire Water Supply Systems

5.2 Reliability Analysis for Internal Failure

Regarding internal failures, the two systems are identical, because the location of equipment does not affect the reliability of the system if they are operated in the same environment. Therefore, specifications and HEF of System A and System B are exactly the same when analyzing internal failures.

Failure data of the fire pump and other parameters for System A and System B are given in Table 5. The failure rate of the fire pump is from the OREDA handbook[15] and the beta-factor is calculated from IEC61508 [16] with expert judgment. The test interval of the fire pump is from the guideline of IMO [17] and the repair time is assumed to be negligible. The demand rate is from historical data of IMO [18] and the demand duration rate is based on the IMO requirement of fire pumps [19]. Renewal time is based on expert judgment.

Table 5 Specifications for Internal Failure

Notation	System A	System B	Description
λ_{DU}	7.10×10^{-7} per hour	7.10×10^{-7} per hour	DU-failure rate
B	0.02	0.02	Beta factor
μ_{DU}	1.39×10^{-3} per hour	1.39×10^{-3} per hour	DU repair rate
λ_{de}	1.05×10^{-6} per hour	1.05×10^{-6} per hour	Demand rate
μ_{de}	2 per hour	2 per hour	Demand duration rate
m	1.39×10^{-2} per hour	1.39×10^{-2} per hour	Renewal rate

According to Jin, et al. [14], the $HEF(t)$ is equal to the visit frequency to state 0, from any other state:

$$HEF(t) = \sum_{i=1}^{5} P_i(t) \cdot a_{i0} \qquad (3)$$

where $P_i(t)$ is the probability that the system is in state i at time t, and a_{i0} is the transition rate from state i to state 0. $HEF(t)$ therefore means how often hazardous events occur for a given system design and demand rate [14]. HEF for internal failure may be obtained by solving (3) with Markov models in Figure 1. The calculation result is given in Table 6.

Table 6 HEF for Internal Failure of System A and B

System	HEF
System A (Physically Separated)	9.86×10^{-8} per year
System B (Physically Not-Separated)	9.86×10^{-8} per year

5.3 Reliability Analysis for External Failure

Regarding external failures, the two systems have one significant difference; whether the components are located in separated compartments or not. It is reflected on the value of β_{EF}. The external failure rate and the external survival rate can be calculated from (1) and (2). The demand rate, demand duration, and renewal time is the same as in Section 5.2. The conditional probability, EF, is derived from historical data for the ratio of fire origin location [20] and the area of each fire pump room [21]. All the other specifications and parameters are same for System A and System B as given in Table 7.

Table 7 Specifications for External Failure

Notation	System A	System B	Description
λ_{SE}	1.05×10^{-6} per hour	1.05×10^{-6} per hour	Survival rate by external event
λ_{EF}	2.04×10^{-9} per hour	2.04×10^{-9} per hour	External failure rate
B_{EF}	1	0	Beta factor for external failure
λ_{de}	1.05×10^{-6} per hour	1.05×10^{-6} per hour	Demand rate
μ_{de}	2 per hour	2 per hour	Demand duration rate
m	1.39×10^{-2} per hour	1.39×10^{-2} per hour	Renewal rate

HEF for external failure of System A and System B may be obtained by the same way with Section 5.2, and the calculation result is given in Table 8.

Table 8 HEF for External Failure of System A and B

System	HEF
System A (Physically Separated)	1.35×10^{-9} per year
System B (Physically Not-Separated)	1.79×10^{-5} per year

6. DISCUSSION AND CONCLUDING REMARKS

This paper introduces Markov models with HEF for both internal failures and external failures of marine systems, and two case studies have been carried out: one for internal failures and the other for external failures. Each of these case studies has calculated HEF for a physically separated system and a physically not-separated system. The study shows some interesting results.

First, for the physically separated system, the HEF of internal failures is about 100 times as high as that of external failures. On the contrary, for physically not-separated system, the HEF of internal failures is about 100 times as low as that of external failures. However, we cannot conclude that we do not need to consider external failures for physically separated systems nor that internal failures are meaningless to include for physically not-separated systems, because this case study has analyzed only a small part of the entire system. The contribution of each type of failures may vary when the entire system's components are included in the model. Instead, the case study provides a good ground for the necessity to pay much more attention to external failures with a feasible reliability analysis method.

Second, the HEF values are very small in these case studies. The reason for this is as follows: (i) the HEF value is neither a failure frequency nor a demand frequency, but a combination of them. It is a frequency of occurrence for both equipment failure and demand. The HEF value therefore may be very small compared to the failure rates or demand rates. (ii) This paper only covers fire pumps in the fire water supply system, which is a very small part of the entire system. Reasonable HEF values are expected if the entire system is included in the analysis. Future work should include all components of the fire water supply system into the analysis model investigating the sensitivity of contribution of two types of failures.

Last, this paper analyzes internal failure and external failure through its own respective models. One model is for internal failure and the other is for external failure. Merging them into a single model and investigating the results should be further addressed.

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