ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1137349

A METHOD FOR ESTIMATING PROPULSION RISK OF THE SHIP CASUALTY

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Abstract

Loss of the propulsion function by a ship is one of the most serious categories of hazardous events in sea transport. In specific external conditions it may lead to a loss of ship and environmental pollution. The consequences of propulsion loss by a ship are events classified by the International Maritime Organization as casualties or incidents. The probabilities of occurrence of the former events in a specific time unit constitute the propulsion risk of a ship. Determination of these probabilities is in practice confronted with difficulties connected with shortage of data. A method for estimating the risk caused by loss of a seagoing ship propulsion function is proposed. The estimation is fully based on the expert judgments. Expert is assumed to be well acquainted with the subject he is expected to formulate his judgment on. Expert should also be capable of formulating his judgment. This is connected with level of his education and the language used in the elicitation process, particularly as regards the parameters the expert is expected to estimate. This may be the language of numerical or linguistic values. Numerical values are better but are more difficult to articulate - also errors in judgments are more likely. To overcome this problem and to obtain a more accurate estimation, this study suggests using an analytic hierarchy process (AHP), which quantifies the subjective judgments and confirms the consistency of collected data. An example of the propulsion risk estimation of container carriers operating on the North Atlantic line allows to assess effectiveness of the method.

Keywords: *estimation, expert judgment, risk, ship propulsion system, analytic hierarchy process AHP, sea transport*

1. Introduction

The loss of propulsive power may be an effect of the propulsion system (PS) failures or of errors committed by the crew in the system operation process. In the safety engineering language we say that the propulsion loss probability depends on the reliability of the PS and of its operators.

The consequences of the propulsion function loss by a ship are events classified by the International Maritime Organization as casualties or as incidents [5]. The probabilities of occurrence of the former events in a specific time unit constitute the *propulsion risk of a ship* (PR). Determination of these probabilities is in practice confronted with difficulties connected with shortage of data. In such cases we have to rely on subjective estimations made by persons with practical knowledge in the field of interest, i.e. *experts*. The experts, on the other hand, prefer to formulate their opinions in the linguistic categories. This paper presents a method of the subjective estimation of propulsion risk by a seagoing ship, based on the expert judgments. It is adjusted to the knowledge of experts from ships' machinery crews and to their capability of expressing that knowledge. The method presented has been developed with an intention of using it in the decision making procedures in risk prediction during the seagoing ship operation.

2. Definition of the ship propulsion risk

The risk under investigation is connected with the loss by the PS of its capability of generating the driving force of a defined value and direction. In a formal model, that loss is an initiating event.

It has a form of a *catastrophic failure* (CF) of the PS. Catastrophic failure is defined as loss of the capability of performing by the object of its assigned function. Such event may cause *immediate* (ICF) or *delayed* (DCF) stoppage of the PS. In the latter case the stoppage is connected with renewal, which may be carried out at any selected moment. It is obvious that only the former case of the forced stoppage creates a risk of damage of ship – it is a hazardous event.

Following the IMO resolution (1997), five categories of ICF event consequences are distinguished. Their description is given in Tab. 1. They are divided into accidents and incidents. Occurrence of a consequence of specific category is an event. The set of events in the version presented in Tab. 1 is a complete system consisting of disjoint repertory consequences.

The consequences are connected with determined losses. They may pertain to people, artifacts and the natural environment. They are expressed in units of a physical and/or financial character. Detailed data on losses are very difficult to obtain, particularly those related to rare events, e.g. consequences of the C1 and C2 category accidents. The data cannot be obtained from experts, as in great majority they have not experienced events where such losses occur. We have to relate the risk only to the consequences of the ICF type propulsion function loss event. We define the PR as a probability of occurrence of the ICF event consequences during one year in a specific type of ships operating on a given shipping line.

Tab. 1. Categories of the ICF event consequences.

Cat.	Name	Description
C1	Very serious casualty	Loss of the ship, loss of human life and/or heavy marine environment pollution.
*C*2	Serious casualty	Injuries or human health deterioration, ship grounding, touching a submarine object, contact with a solid object, lost seaworthiness due to defects, necessity of towing or assistance from the shore and/or marine environment pollution.
*I*1	Incident I	Prolonged hazard to the ship, people and environment which can cause a sea accident. After repair by the ship crew, the ship propulsion function is not fully restored (lower operational parameters).
*I*2	Incident II	As in *I*1, but after repair the ship propulsion function is fully restored.
*I*3	Incident III	Temporary hazard to the ship, people and environment which can cause a sea accident. No PS repairs needed.

3. Formal model of propulsion risk

The following assumptions are made as regards the ICF event probability:

– The investigated PS system may be in the active or stand-by usage state. The ICF failures may occur only in the active usage states, when it is in the shipping traffic. We shall exclude from the model the periods of stays in ship repair yards or in other places connected with renewals of the ship equipment.
– A formal model of the ICF type PS failures is the Homogeneous Poisson Process (HPP). This assumption is justified by the expert elicited data, which indicate that this type of failures occur fairly often, several times a year, but their consequences in general imply only a certain loss of operation time. More serious consequences, causing longer breaks in the normal operation of PS system, rarely occur. The exponential distribution of time between failures, taking place in the HPP model, is characteristic of a normal operation of many system classes, including also the ship systems [3, 7]. It is appropriate in the case when the modeled object failures and the operator errors are fully random abrupt failures but not gradual failures caused by the ageing processes and/or wear of elements. This corresponds with the situation when scrupulously performed inspections and renewals prevent the latter type of failure from occurring.

The PS system active usage time $t^{(a)}$ is strongly correlated with the ship operational times, mainly with the “at sea” state including “sailing”, “maneuvers” and “anchoring”. The numbers of

ICF failures per year elicited by experts are related to the calendar time *t*. The following approximation may be adopted for the PS system active usage time:

$$t^{(a)} = \kappa t \,, \tag{1}$$

where:
$t^{(a)}$ – active usage time,
t – calendar time of the system observation,
κ – time at sea factor ($\kappa \in \langle 0,1 \rangle$). Thus, the model ICF probability is the vector:

$$P\{k_{ICF}, t\} = P\{k_{ICF}, t^{(a)}\} = \left[\frac{(\lambda^{(a)} \kappa\, t)^k}{k!} e^{-\lambda^{(a)} \kappa t} : \; k = 1,2,3... \right], \tag{2}$$

where:
$P\{k_{ICF}, t^{(a)}\}$ – probability of occurrence of *k*-th *ICF* type failure within time interval $\langle 0, t)$,
k – number of ICF events,
$\lambda^{(a)}$ – intensity function of HPP (ROCOF), [1/h],
t – the time of probability prediction [h].

The consequence of an ICF event may be one of the five consequence categories listed in Tab. 1. The C1 and C2 consequences are significant in a risk model, as they are hazardous events. The other events are only incidents, which can cause some loss of operational time and some repair costs. We shall divide the consequences into two subsets corresponding to this subdivision of consequences, with the following designations:

$$\boldsymbol{C} = (C1 \cup C2),$$

$$\boldsymbol{I} = (I1 \cup I2 \cup I3),$$

where ***C*** is an accident subset, and ***I*** is an incident subset.

Only the subset ***C*** events will be further considered. Let's note that those events can occur only once in a given time interval. Their occurrence causes break in a normal ship operation as the ship is sunk or loses its seaworthiness and must undergo repairs. The events may occur after each subsequent ICF type PS failure. The occurrence takes place with a given conditional probability of ICF failure occurrence. We also assume that the probability does not depend on the ICF event serial number – it is the same for all the ICF events within a specific time interval *t*.

The PR is a probability of occurrence of the subset ***C*** consequences after an ICF type PS failure. It is determined by the following expression:

$$\Re\{C,t\} = P\{C/ICF\} \sum_{k=1}^{K} P\{k_{ICF}, t\} (1 - P\{C/ICF\})^{k-1}, \tag{3}$$

where $P\{k_{ICF}, t\}$, $k = 1,2,...$ is a probability of the *k*-th ICF failure in a time interval *t*, and $P\{C/ICF\}$ is a conditional probability of the subset ***C*** consequences after an ICF type failure.

The above presented model is used in the expert investigations in maritime shipping conditions. Therefore, it is simple, adjusted to the data character so that can be acquired for its identification. The authors' experience indicates that it is unrealistic to try to acquire data on parameter estimation of more complex models, e.g. event tree or bi-parameter probability distributions.

4. Expert data acquisition and processing

In presented models the following parameters will be estimated:

- $\lambda^{(a)}$ – intensity function of HPP (ROCOF),
- κ – time at sea factor,
- $P\{C/ICF\}$ – probability of the subset ***C*** consequences with the condition of ICF event occurrence.

For the HPP, intensity function of failures (ROCOF) is determined by

$$\lambda = \frac{E[N(t)]}{t}. \tag{4}$$

Based on the theorem of the asymptotic behaviour of the renewal process [3]:

$$\lim_{t\to\infty}\frac{E[N(t)]}{t} = \frac{1}{T_o}, \tag{5}$$

where T_o is a mean time to failures MTTF, intensity function of HPP can be estimated by:

$$\lambda^{(a)} \approx \sum_{j=1}^{J} N_j(t) \Big/ \kappa_j t_j , \tag{6}$$

where:
N_j – annual number of the ICF type events elicited by j-th expert, [1/y],
κ_j – time at sea factor elicited by j-th expert,
t_j – calendar time of observation by *j-th* expert [h],
J – number of experts.

The $P\{C/ICF\}$ probabilities are determined by the pair comparision method. A linguistic variable LV has been adopted: *a chance of occurrence of the consequences of an ICF type ship propulsion system failure,* and its value LT-S*: very great, great, medium, little, very little.* A set of possible categories of those consequences, as described in Tab. 1, was introduced to experts and they were asked to estimate the chances of occurrence of those categories using the adopted LT-S values. The expert estimations were compared in pairs with the preferences given in Tab. 2. Those preferences were then processed to the form of probabilities by the AHP method [6, 10]. Processing the expert judgments to the form of probabilities is possible when the estimated set of consequence categories is a complete system of mutually exclusive events.

Tab. 2. Expert preference estimates acc. to [10]

Estimate	Preference
1	Equivalence
3	Weak preference
5	Significant preference
7	Strong preference
9	Absolute preference
Inverse of the above numbers	Inverse of the above described preference

Summarizing it, the following data are acquired from experts: $N(t)$, $t^{(m)}$ for time t and linguistic values of the adopted LV variable.

5. Case study

5.1. Estimation of the ICF event probability

The example discusses investigation of a PS consisting of a low speed piston combustion engine driving a fixed pitch propeller and auxiliary subsystems (including the electrical subsystem), installed in a container carrier ship, operating in the North Atlantic region. Experts were marine engineers with long experience (50 ship officers with a chief engineer or second engineer diploma). Special questionnaire was prepared for them containing definition of the investigated object, schematic diagrams of subsystems and sets of devices, precisely formulated questions and tables for answers. In the questionnaire, it was clearly stated that an ICF type failure may be caused by a device failure or by a crew action.

Out of 50 judgments elicited by experts, 3 were estimated as very unlikely (2 elicited numbers of the ICF events in a year were extremely underestimated and 1 was overestimated). They were eliminated and the remaining 47 judgments were further processed.

From the elicited data (Tab. 3) the occurrence probabilities of determined numbers of ICF event in 1 year were calculated. Fig. 3 presents results of those calculations. The numbers of probable ICF events in 1 year are equal 1, 2, …, 5. The maximum probability is 0.2565, which stands for 3 ICF events during 1 year, and the probability that such event will not occur amounts to 0.0821.

5.2. Estimation of consequence probability

Like in the case of the ICF probability estimation, the experts were marine engineers with long experience (30 persons). They estimated the odds of the occurrence of propulsion loss consequence categories, listed in Tab. 1. Those data were processed to the form of probabilities by the AHP method [1, 2, 10]. Fig. 4 presents the calculated conditional probabilities, under the condition of the ICF event occurrence, of the individual consequence categories.

Tab. 3. Basic results of propulsion system investigation

Averaged expert elicited data	$\overline{N}(1\,y)=2.5$, $\sigma[N(1\,y)]=1.1325$, $\overline{\kappa}100=83.9575\,\%$, $\sigma[\kappa\,100]=7.2441\,\%$
Risk model parameters	$\sum_{1}^{47} t = 411720\,h$, $\lambda^{(a)} = 3.3992 \cdot 10^{-4}\ 1/h$, $\overline{\kappa} = 0.8396$

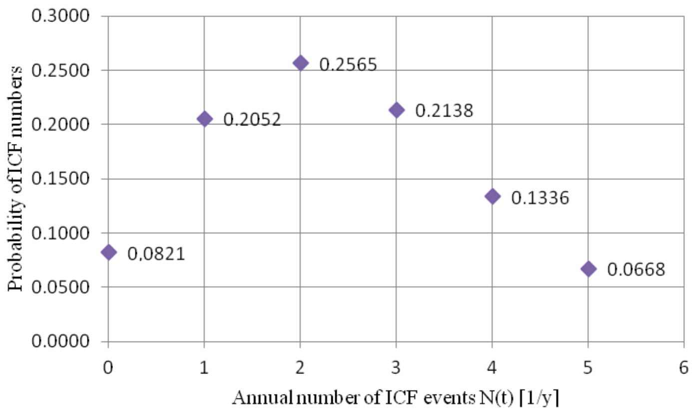

Fig. 3. Distribution of ICF event number probability

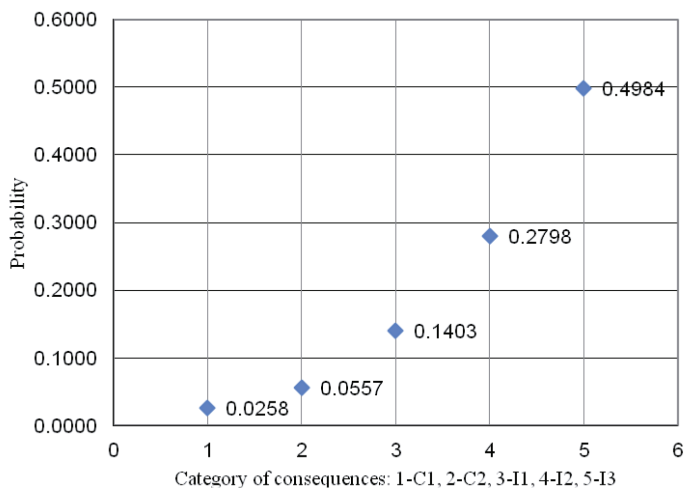

Fig. 4. Conditional probability of ICF event's consequences

5.3. Propulsion risk

Figure 5 shows the PR values for the cases of annual ICF type failure numbers from 1 to 5. That risk is a probability of an ICF type event occurrence with consequences in the form of a very serious casualty or serious casualty, in a period of 1 year of active operation of a container carrier on the Europe – North America line. The PR depends on the number of ICF events in a year. It is the highest in the case of five such events in that period of time. The maximum value of propulsion risk is 0.0628.

The PR value increases along with the annual number of ICF failures. The intensiveness of that increase falls when ICF number growths – this may be explained by the course of probability of that numbers (Fig. 3) determined from the Poisson distribution.

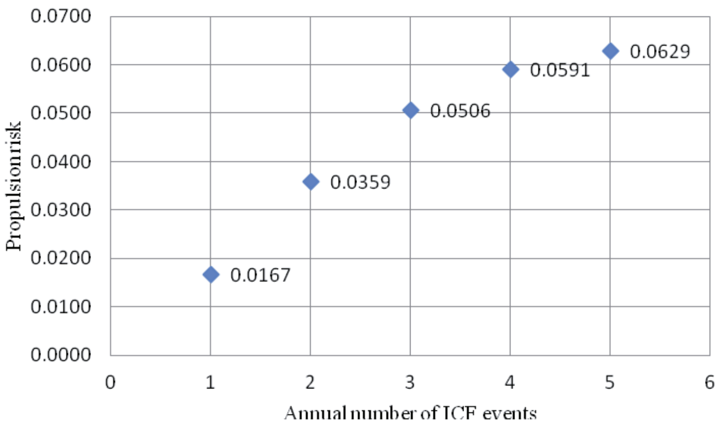

Fig. 5. Propulsion risk of investigated ship

The value of total risk – the alternative of all risks connected with five numbers of ICF events during a year – is 0.2249. It is obvious that such risk cannot occur in reality. However, it is an indicator that may be useful in the operational practice. It reflects not only a risk connected with consequences of one potential number of possible propulsion loss.

Full risk record can be described as a vector of the "number of ICF events, risk" pairs (k_{ICF}, $R_k\{C, t\}$). It needs to be underlined that risk depends on the considered time interval. The above quoted data pertain to 1 year of PS observation. The risk will decrease for a shorter reference time interval. It will also decrease for a smaller coefficient κ of time at sea.

6. Summary

A method of subjective ship system risk estimation has been developed in this paper. The estimation method is based exclusively on the judgments elicited by experts – experienced marine engineers. The method is adjusted to the expert educational level and language used in the elicitation process. To obtain a more accurate estimation, this study suggests using an analytic hierarchy process (AHP), which quantifies the subjective judgments and confirms the consistency of collected data. An example of the propulsion risk estimation of container carriers operating on the North Atlantic line allows to assess effectiveness of the method.

The propulsion risk estimation results given in section 5 are fairly acceptable in terms of the order of magnitude. The subset ***C*** events occur now in approx. 2% cases of the ship population per 1 year. This pertains to ships of gross register tonnage above 500 GT [4, 9]. The results are also qualitatively adequate – the identified trends of changes of the investigated quantities are in line with logic of the respective events.

It has to be taken into account that subjective investigation results may (but not necessarily) be charged with greater error than objective results acquired in real operation process. The adequacy of such investigation depends on proper selection of experts, their motivation and type of questions asked. The questions should never exceed the experts' experience-based knowledge and the right to disclose it. The fuzzy methods are particularly useful in the expert investigations.

The method presented here may be used for the ship propulsion risk prediction. It may also prove to be useful for other systems, not only aboard ships, particularly in the cases of shortage of objective data for estimation of the probability of hazardous events and their consequences.

Further study would be focused on the data acquisition techniques and the data processing methods, which are extremely crucial in the subjective investigations.

References

[1] Brandowski, A., Frackowiak, W., Nguyen, H., Posiadlo, A., *Subjective Propulsion Risk of a Seagoing Ship Estimation*, Proceedings of ESREL Conference, Valencia 2008.
[2] Brandowski, A., *Estimation of the Probability of Propulsion Loss by a Seagoing Ship*, Polish Maritime Research, Gdansk 2009.
[3] Gniedienko, B. W., Bielajew, J. K., Solowiew, A. D., *Metody matematyczne w teorii niezawodnosci*, Wydawnictwa Naukowo-Techniczne, Warszawa 1968.
[4] Graham, P. *Casualty and World Fleet Statistics as at 31.12.2008*, IUMI Facts & Figures Committee 2009.
[5] IMO Code *for the Investigation of Marine Casualties and Incidents*, IMO Resolution A.849 (20), London 1997.
[6] Kwiesielewicz, M., *Analityczny hierarchiczny proces decyzyjny. Nierozmyte i rozmyte porownywanie parami*, Instytut Badan Systemowych PAN, Warszawa 2002.
[7] Modarres, M., Kaminskiy, M., Krivtsov, *Reliability Engineering and Risk Analysis*, Basel: Marcel Dekker Inc., New York 1999.
[8] Nguyen, H., *The Application of the AHP Method in Ship System Risk Estimation*, Polish Maritime Research, Vol. 16, No. 1, pp. 78–82, Gdansk 2009.
[9] Podsiadlo, A., *Analiza uszkodzen okretowych silnikow napedu glownego statkow*, Internal Study of Gdynia Maritime University, Gdynia 2008.
[10] Saaty, T. L., *The Analytic Hierarchy Process*, New York, McGraw-Hill 1980.