CHEMICAL ENGINEERING TRANSACTIONS
VOL. 33, 2013
Guest Editors: Enrico Zio, Piero Baraldi
Copyright © 2013, AIDIC Servizi S.r.l.,
ISBN 978-88-95608-24-2; ISSN 1974-9791

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333136

Reliability Analysis of a Marine LNG-Diesel Dual Fuel Engine

Chengpeng Wan [a,b], Xinping Yan[a,b,c,d], Di Zhang[b,c,d], Shanshan Fu[a,b,c]

[a] School of Energy & Power Engineering, Wuhan University of Technology, 1040 Heping Road, Wuhan, Hubei, 430063, China
[b] Engineering Research Center for Transportation Safety (Ministry of Education), 1040 Heping Road, Wuhan, Hubei, 430063, China
[c] Intelligent Transport Systems Research Center, Wuhan University of Technology, Wuhan, Hubei, 430063, China
[d] Research and Development Base on Waterway Transportation Safety and Anti-pollution of CJRDC Ministry of Transport, 1040 Heping Road, Wuhan, Hubei, 430063, China
fred.zhangdi@gmail.com

In recent years, with the rapid development of world economy, energy consumption increases sharply, and the environment is deteriorating. So, Liquefied Natural Gas (LNG), a renewable clean energy (Tugnoli et al., 2010) which can be used as ship fuel, is drawing attentions from more and more countries in the world. However, the transformation of the marine LNG-diesel Dual-Fuel Engine (DFE) in China as a new researching is just in its infancy, and the technology of operability, economic and security of which is not mature yet. In view of this, taking the China inland's first transformed marine LNG-diesel dual-fuel engine GC6135ACz as an example, a risk assessment about the failure of this engine has been carried out based on an analytic hierarchy process, by which key risk factors for failure of dual-fuel engine have been obtained ultimately with expert survey data and certain risk control measures have been therefore put forward, so as to enhance the safety of marine LNG-diesel dual fuel engines.

1. Introduction

The marine LNG-diesel DFE is a complex system which is combined together by the cooperation of various different parts in order to function well. Furthermore, uncertainties are involved when evaluating the failure risk of a DFE that objective data collection would be usually infeasible. Thus, a subjective method is proposed in this study using Analytical Hierarchy Process (AHP) to deal with failure risk assessment of a marine LNG-diesel DFE.
In this study, the failure of a marine LNG-diesel DFE mainly comes from two parts, namely, system failure and machine element failure, and their sub-systems/elements are identified based on expert judgements and literature review by which a hierarchical structure for failure risk assessment is established.
An Analytical Hierarchy Process (AHP) method is implemented because it is a comprehensive framework which is designed to cope with intuitive, rational, and irrational data when dealing with multi-objective, multi-criterion and multi-actor decisions with and without certainty for any number of alternatives (Harker and Vargas, 1987). It is a method for deriving ratio scales used to integrate the elements of any problem. It organizes the basic rationality by breaking down a problem into its smaller constituent parts and then calls for simple pairwise comparison judgements to develop priorities in hierarchy.
The main aim of this paper is to study possible Risk Control Options (RCOs) to reduce the failure risk of marine LNG-diesel DFE by identifying the possible failure events and their major causes. In order to achieve the aim, this study proposes a method using AHP. The method is demonstrated with a case study based on a hierarchical structure constructed for modeling failures of a marine LNG-diesel DFE.

2. Failure modelling of LNG-diesel DFE

In this study performance degradations of components are considered as "failures". As far as a hierarchical

Please cite this article as: Wan C., Yan X., Zhang D., Fu S., 2013, Reliability analysis of a marine lng-diesel dual fuel engine, Chemical Engineering Transactions, 33, 811-816 DOI: 10.3303/CET1333136

structure is concerned, the failure of marine duel fuel engine is set in the top level. The elements in Level 2 are set to be System failure and Machine element failure. Each element in Level 2 is investigated based on its associated elements/factors given in Level 3 and Level 4. There are 32 causes in all in the bottom level. The specific elements and causes are shown in Table 4. These elements/factors are chosen because they are regarded as the most significant ones associated with major causes which lead to the failure of marine duel fuel engines. The selection of such elements is conducted based on extensive discussions with experts in the area and a recent study of the LNG-diesel DFE (Qian, 2007).

The specific causes of each failure event and the overall weight of each cause will be given in the Case study. The data is obtained based on the first refitted LNG-diesel dual fuel powered vessel on the Yangtze River. It's a ferryboat with two main engines typed GC6135ACz, of which rated power is 105.2 kW and rated speed is 1,500 rad/min.

3. Methodology

The following steps are developed in order to identify key factors ranked by different overall weights.

Step 1: Identify the standard to measure the pairwise comparison of different evaluation indexes, with the result of which, a pairwise comparison matrix can be established.

Step 2: Carry out the pairwise comparisons in each level of the hierarchical structure in terms of relative importance to failure of a LNG-diesel DFE and calculate the weighting vectors of the elements in the corresponding level.

Step 3: Check their consistency in order to achieve a convincing result.

Step 4: Estimate the overall weight of each element/factor in terms of failure risk and select the safety critical elements.

Step 5: Identify suitable RCOs according to results above, assess their effectiveness and list their priorities.

3.1 Establishment of comparison matrix

In order to conduct pairwise comparison among elements, this paper defines a simplified evaluation scale from 1 to 5. The importance degree is shown in table 1.

Table 1: Meaning of evaluation scale

Scale of importance	Meaning
1	Two factors are **Equally** important
2	Compared to the latter factor, the former one is more important, **Slightly**
3	Compared to the latter factor, the former one is more important, **Moderately**
4	Compared to the latter factor, the former one is more important, **Fairly**
5	Compared to the latter factor, the former one is more important, **Strongly**
reciprocal	When the latter factor is more important, it will be a reciprocal, that's $a_{ji} = 1/a_{ij}$

After the calculation of relative importance, the fuzzy pairwise comparison matrix is converted into a single-value comparison matrix. Suppose the quantified judgement on pairs of criteria C_i and C_j are represented by a $n \times n$ single-value comparison matrix *A*:

$$A = a_{ij} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{1}$$

Where, a_{ij} is the relative importance of criteria C_i and C_j.

3.2 Calculation of weights of each element in different levels

The weighting vector of a specific element *k* can be calculated through Eq. 2.

$$w_k = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \qquad (k = 1, 2, ..., n) \tag{2}$$

Where, a_{ij} is the entry of row i and column j in a comparison matrix of order n and W_k is the weighting vector of a specific element k in the pairwise comparison matrix.

3.3 Consistency check

When numerous pairwise comparisons are evaluated, their consistency has to be checked before a convincing result can be achieved. The AHP method provides a measure of the consistency for pairwise comparisons by introducing a consistency ratio (Anderson et al., 2003). The comparisons will be considered reasonable only if the consistency ratio is equal to or less than 0.10. An approximation of the ratio can be obtained using the algorithm described in Eq. 3.

$$CR = \frac{CI}{RI} \tag{3}$$

Where, CR is the consistency ratio and RI is the random index for the matrix size. The value of RI is given in Table 2 (Anderson et al., 2003), and CI is the consistency index that can be obtained from Eq. 4.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

Where, $\lambda_{\max}$ is the maximum weighting value of a $n \times n$ comparison matrix.

The weighting vectors need to be calculated for lower level criteria/element after the weighting vector calculation. The similar procedure is implemented for all the levels that the overall weight of each element is obtained by multiplying the weighting vectors of relevant associated upper level element.

3.4 Utility evaluation of RCOs

Combined with expert investigation, the effectiveness of each RCO is evaluated through Eq. 5.

$$W_{\mathrm{n}} = W_{\mathrm{k1}} \times \mathrm{S}_1 + W_{\mathrm{k2}} \times \mathrm{S}_2 + \cdot\cdot\cdot\cdot\cdot\cdot + W_{\mathrm{kn}} \times \mathrm{S}_{\mathrm{n}} \tag{5}$$

Where, W_n is the overall weight of RCO n; W_{kn} is the overall weight of element n; S_n is the average score of the effectiveness of RCO n, in terms of element n. The scoring standard of effectiveness is shown in Table 2.

Table 2: Scoring standard of effectiveness

Score	Definition
1	The RCO used is **least effective** in reduction of risks
3	The RCO used is **slightly effective** in reduction of risks
5	The RCO used is **effective** in reduction of risks
7	The RCO used is **greatly effective** in reduction of risks
10	The RCO used is **completely effective** in reduction of risks

4. Case study

Referring to the AHP structure of failure modeling, this section is to demonstrate how the proposed methodology can be applied to indentify key factors that influence the LNG-diesel DFE most. The data is obtained based on three domain experts and their details are shown as follows. Since the knowledge and experience of all three experts involved are considered as equivalent, the relative weight of every expert is assigned equally to merge their judgements.

Expert No.1: An experienced seafarer who worked as a chief engineer on a LNG carrier for more than 5 y.
Expert No.2: A professor engaged in LNG transportation for more than 6 y.
Expert No.3: A professor engaged in new energy powered ship for more than 6 y.

4.1 Establishment of comparison matrix (step 1)

Take level 3 (below System failure) as a demonstration, the following matrix (shown as Figure 1) for this level can then be formed via Eq. 1, combined with merged expert judgements.

	Control system failure	Cooling system failure	Lubrication system failure	Dual fuel system failure	Ventilation system failure
Control system failure	1.00	2.50	1.67	1.00	1.00
Cooling system failure	0.40	1.00	0.75	0.42	0.75
Lubrication system failure	0.60	1.33	1.00	0.67	2.67
Dual fuel system failure	1.00	2.40	1.50	1.00	2.00
Ventilation system failure	1.00	1.33	0.38	0.50	1.00

Figure 1: Comparison matrix of level 3

4.2 Calculation of weights of each element in different level (step 2)
As shown in Table 3, the weights of this level's elements can be calculated using Eq. 2.

Table 3: Weights of each element in level 3

Elements	Control system failure	Cooling system failure	Lubrication system failure	Dual fuel system failure	Ventilation system failure
Weight	0.25	0.12	0.21	0.27	0.15
Rank	2	5	3	1	4

4.3 Consistency check (step 3)
Finally, Eq. 3 and Eq. 4 are used to check the consistency of this level's pairwise comparison as follows:

$$CR = \frac{CI}{RI} = \frac{\frac{5.1967-5}{5-1}}{1.12} = 0.043 < 0.1 \quad (6)$$

Similar process can then be implemented to lower levels and weighting vectors of all levels are obtained.

4.4 Estimation of overall weight of each element (Step 4)
By multiplying the weighting vectors of relevant associated upper level element, the overall weights of each element/factor are shown in Table 4.
As per the result of Table 4, nine (of thirty-two) influencing factors, namely, Piston ring abnormal wear, adhesive and broken, Oil pump fault, Reversal failure, Firing failure, Turbine fault, Pressure limiting valve fault, Fuel injector fault, Fresh (sea) water pump fault and Speed regulation fault are identified as the safety critical elements in terms of failure risk of a LNG-diesel DFE with respect to their comparatively high overall weights, which altogether take more 52% of the total weights.

Table 4: Overall weights

Aspects of failure modelling	Influencing factors	Overall weight *	Rank
Control system failure	Start-up failure	0.0319	15
	Firing failure	**0.0544**	**4**
	Reversal failure	**0.0600**	**3**
	Speed regulation fault	**0.0413**	**9**
Cooling system failure	Jam or leakage of fresh(sea) water piping	0.0324	14
	Fresh(sea) water pump fault	**0.0414**	**8**
	Fresh water valve damage	0.0162	24
Lubrication system failure	**Pressure limiting valve fault**	**0.0425**	**6**
	Oil pump fault	**0.0788**	**2**
	Sensor failure	0.0362	11

Table 4: Overall weights (continued)

Aspects of failure modelling		Influencing factors	Overall weight	Rank
Dual fuel system failure	Fuel oil system failure	Separator fault	0.0302	17
		Injection pump fault	0.0331	13
		Electronic governor fault	0.0216	20
		Oil supply piping damage	0.0173	23
		Fuel injector fault	**0.0417**	**7**
	Gas oil System failure	Natural gas pipeline damage	0.0100	30
		Gas injection valve fault	0.0061	32
		LNG processing system failure	0.0112	29
		ECU fault	0.0188	22
		Safety control system failure	0.0147	25
Ventilation system failure		Leakage of exhaust valves	0.0315	16
		Cracking of valve disk (rod)	0.0214	21
		Supercharger bearing damage	0.0135	26
		Turbine fault	**0.0461**	**5**
major motion components failure		Piston crown ablation	0.0370	10
		Piston ring abnormal wear, adhesive and broken	**0.0917**	**1**
		Connecting rod bending	0.0293	18
		Crankshaft fatigue damage	0.0332	12
major fixed components failure		Over wear of cylinder liner	0.0230	19
		Cavitation of cylinder liner	0.0116	28
		Crack and corrosive damage of cylinder cover	0.0127	27
		Bearing shell damage	0.0098	31

* Overall weight is a dimensionless value

4.5 Utility evaluation of RCOs (Step 5)

In terms of the safety critical elements of failure model, the following countermeasures are selected:

RCO 1: Strictly comply with the design specifications when refit a marine LNG-diesel DFE, and reinforce routine inspection and management to dual duel system.

RCO 2: Conduct maintenance work regularly according to the technical maintenance table, and adjust maintenance items and period according to the operating conditions of a marine LNG-diesel DFE and different environment.

RCO 3: Increase the personnel training, in order to improve the crew quality。

RCO 4: Select suitable working mode of a marine LNG-diesel DFE according to different condition.

Through weighted average of experts data, the result of utility evaluation can be obtained, show as below.

Table 5: Utility evaluation of RCOs

Risk elements	RCO 1	RCO 2	RCO 3	RCO 4
Piston ring abnormal wear, adhesive and broken	3.67	8.67	5.00	3.33
Oil pump fault	2.33	6.67	4.33	3.33
Reversal failure	2.67	6.00	5.00	3.33
Firing failure	6.00	8.67	8.33	8.67
Turbine fault	4.33	7.33	7.00	7.33
Pressure limiting valve fault	3.00	4.33	3.67	6.00
Fuel injector fault	8.67	9.33	7.00	8.67
Fresh(sea) water pump fault	3.33	4.00	5.00	4.00
Speed regulation fault	9.33	5.33	5.00	4.00
Overall Effectiveness	2.2186	**3.4490**	2.7369	2.5242
Rank	4	**1**	2	3

According to the results above, weight of RCO 1 can be calculated via Eq. 5.

W_1=0.0917×3.67+0.0788×2.33+0.0600×2.67+0.0544×6.00+0.0461×4.33+0.0425×3.00+0.0417×8.67+0.0414×3.33+0.0413×9.33= 2.2186

The results shown in Table 5 reveals that the best RCO to reduce failure risk of a marine LNG-diesel DFE is RCO 2 (Conduct maintenance work regularly according to the technical maintenance table, and adjust maintenance items and period according to the operating conditions of a marine LNG-diesel DFE and different environment.), followed by other three RCOs.

5. Conclusion

Various factors may influence the operational safety of a marine LNG-diesel DFE. The developed approach using AHP identifies the safety critical elements and the best RCO in terms of failure risk. The proposed method is further demonstrated and validated in a case study that the safety critical elements and the best RCO of a marine LNG-diesel DFE in terms of failure risk are studied. This paper provides a subjective approach for stakeholders involved in failure risk of a marine LNG-diesel DFE. The results of this study provide useful information for the marine engineers in order to reduce the failure risk of marine LNG-diesel DFEs and ensure the safety of them.

Acknowledgements

The authors would like to thank the EU FP7-PEOPLE-2012-IRSES project “Research Network on Flexible Risk Assessment and Decision Science” (REFERENCE) No. 314836, NSFC project No. 51209165 for their financial support to this research, and also Chinese National Petroleum Corp. (CNPC) for their assistance in the data collection.

References

Anderson, D.R., Sweeney, D.J., Williams, T.A., 2003, An Introduction to Management Science: Quantitative Approaches to Decision Making, 10th Edition. South-Western, Nelson, Canada.

Harker, P.T., Vargas, L.G., 1987, The Theory of Ratio Scale Estimation: Saaty’s Analytic Hierarchy Process. Management Science, 33(11), 1383-1403.

Pillay, A., Wang, J., 2003, Technology and Safety of Marine Systems. Elsevier Ocean Engineering Book Series. Elsevier, Amsterdam, the Netherlands.

Satty, T.L., 1980, The Analytic Hierarchy Process. McGraw Hill International, New York, USA.

Shang, J.S., Tjader, Y., Ding, Y., 2004, A Unified Framework for Multi-Criteria Evaluation of Transportation Projects. IEEE Transactions on Engineering Management, 51(3), 300-313.

Sii, H.S., Wang, J., 2003, A Design-Decision Support Framework for Evaluation of Design Options/Proposals using a Composite Structure Methodology based on the Approximate Reasoning Approach and the Evidential Reasoning Method. Journal of Process Mechanical Engineering, Part E (Proceedings of the Institution of Mechanical Engineers), 17(1), 59-76.

Tugnoli, A., Paltrinieri, N., Landucci, G., Cozzani, V., 2010, LNG regasification terminals: Comparing the inherent safety performance of innovative technologies. Chemical Engineering Transactions, 19, 391-396, DOI: 10.3303/CET1019064

Ugboma, C., Ugboma, O., Ogwude, I.C., 2006, An Analytic Hierarchy Process (AHP) Approach to Port Selection Decisions – Empirical Evidence from Nigerian Ports”. Maritime Economics and Logistics, 8, 251-266.

Qian Y.N., 2007, Marine Diesel Engine, Dalian Maritime University Press, Dalian, P. R. China.

Zhang D., Yan X.P., Yang Z.L., Wang J., 2012, A subjective approach for evaluating navigational risk of Yangtze River, PSAM 11 & ESREL 2012, 3, 2348-2357.