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Reliability Assessment of Repairable System through Expert Elicitation

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Abstract. The effect of unplanned downtime cannot be more over emphasized which can range from minor disturbance to catastrophic to plant operation. As much as possible the occurrence of failure has to be reduced or eliminated by putting more focus on planned downtime. This initiative can be accomplished by predicting the equipment failure accurately such that appropriate preventive actions can be planned and taken in order to minimize the failure as wells as the impact of equipment failure. However, accurate prediction depends highly on data availability and data scarcity remains one of the main challenges in applying reliability analysis. This paper presents the use of experts' tacit knowledge in the analysis to predict the probability of occurrence of system failure. This is done through the integration of expert elicitation, analytical hierarchical process (AHP) and least squared method to estimate the system failure distribution from which other reliability measures can be derived. The result showed statistical equivalence at 90% confidence level compared with estimation based on failure data proving the validity of the method in cases where failure data is unavailable.

1 Introduction

Effective maintenance management is essential and critical as a way to reduce the adverse effect of equipment failures and to maximize equipment availability. The increase in equipment availability means higher productivity which translates into higher profitability provided that the maintenance optimization does include cost reduction factor. This has led to increased research interest in the subject of optimizing maintenance management. It is estimated that 15% to 45% of total production cost are attributed to maintenance cost with 30% of total manpower involvement [1]. The total cost of maintenance is significant; however, the consequence of an inefficient maintenance management is far beyond the direct cost of maintenance where, in most cases, it is not easily quantifiable. The maintenance's high cost and low efficiency is one of the last costs saving frontier for companies to improve profitability and competiveness.

One of the ways to improve maintenance efficiency is to have a better prediction of the next failure occurrence so that all the resources involved can be optimized. There are a number of models to predict reliability and subsequently equipment failure, available in literatures, but there are gaps observed between researchers and practitioners of maintenance [2]. This is due to the fact that, most models are based on specific assumptions that rarely represent actual operating conditions. Another

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significant gap is the scarcity of data that makes statistical analysis difficult and inaccurate. This requirement presents a formidable challenge as, in practice, the scarcity of data to run statistical analyses is one of the main problems reliability analysis. Furthermore, this problem is expected to continue to persist since with improvement in maintenance and better maintenance strategy adopted, the less number of failures should occur [2]. The current research's purpose is to provide an alternative method to reduce this gap. The research is focusing on the development of reliability prediction model for repairable system based on expert elicitation in cases where failure data are limited or simply unavailable. A repairable system can be defined as a system which can be restored to satisfactory working condition by repairing or replacing the damaged components that caused the failure to occur rather than replacing the whole system [3]. The elicitation process used multiple experts as fundamentally, the more experts the better information can be gathered. This paper describes the methodology of multi-expert elicitation process, presents its technical basis and validates the proposed method through a case study.

2 Elicitation Process

In elicitation process, asking the right question and applying the right method to combine data from multiple expert is crucial for the results to be valid. In addition, the biasness in the results can be involuntarily introduced by the experts should they have some personal interest in the result [4]. Therefore, the elicitation questions have to be formulated such that they are easily understood without compromising the accuracy of the needed data. Formal and systematic elicitation process was applied in various applications such as nuclear safety [5], risk assessment [6] and human reliability assessment [7]. The different elicitation approaches are extensively discussed by O'Hagan et al. [8]

In addition to the elicitation process, another important factor is what criteria can be used to qualify an individual as the expert. Experts can be characterized by the effectiveness to use the knowledge to solve the system related problem with an acceptable success rate and acknowledge their limitation when the problem cannot be solved [9, 10]. The use of multiple experts during elicitation, especially for individual feedback, requires an appropriate method to efficiently combine their inputs. Razali and Salih [11] discussed the use of weight factors to combine two Weibull distributions. Clemen and Winkler [12], on the other hand, presented a more extensive combination method including linear and logarithmic aggregation. However, despite the simplified method of the combination of probability distribution, there are only few foundationally-based approaches to determine the weightage [12] available. One of the methods is through the use of Analytic Hierarchy Process (AHP) which is presented by Monti and Carenini [13] in their work to determine the inconsistency among the experts.

The current work presents the use of knowledge from multiple experts to predict the failure distribution of a pump operating in a gas processing plant with the application of linear aggregation (as shown in Eq. 1) and AHP. The elicitation process is as shown in Fig. 1.

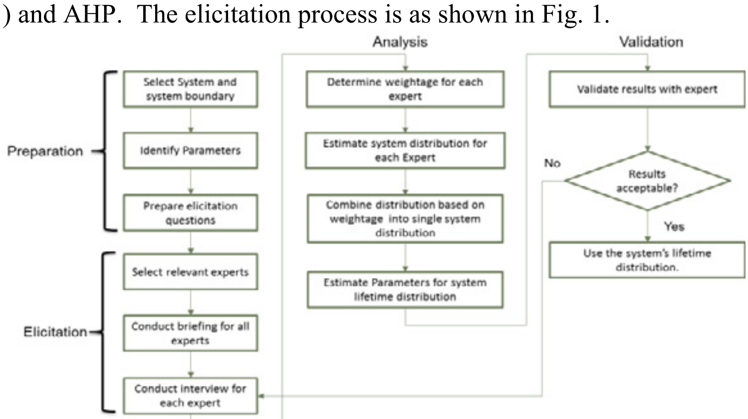


Figure 1. Elicitation Process

$$f(x) = w_1 f_1(x) + w_2 f_2(x) + \ldots + w_n f_n(x), \qquad w_i > 0, \sum_{i=1}^{n} w_i = 1 \tag{1}$$

where w_i is the weightage and $f(x)$ is the probability density function for each experts

The questions were prepared based on the system failure modes which would contribute to total failure distribution. The experts were asked to provide top five failure modes and the percentage of each failure mode occurred in the last one year. A snap shot the questionnaire is as shown in Fig. 2 (a) and (b).

List the top 5 failure modes of the process pump occurred in the last 1 year

1	SEVERE MECH SEAL LEAK	40	% of total failure
2	INSTRUMENTATION	15	% of total failure
3	LUBE OIL PROBLEM	25	% of total failure
4	MINIMUM FLOW VALVE FAILURE	20	% of total failure
5			% of total failure
	Sum	100	(sum should be 100%)

(a)

The chance of the following failure modes to occur after running X number of days of non-stop operation

		Highly likely (9 out of 10)	50/50 chance	Very unlikely (1 out of 10)	
1	SEVERE MECH SEAL LEAK	120	60	30	Days
2	INSTRUMENTATION	200	180	30	Days
3	LUBE OIL PROBLEM	250	180	60	Days
4	MINIMUM FLOW VALVE FAILURE	240	120	60	Days
5					Days

(b)

Figure 2. (a) Aggregation of each failure modes to the system failure (b) Data for 0.9, 0.5 and 0.1 probabilities for failure distribution of each modes

The data from Fig. 2(b) was used to estimate the cumulative distribution function for each of the failure modes. This was done using Microsoft Excel's solver function to find the minimum squared error to estimate the distribution parameters. The next step was to select the right expert which was based on a number of criteria including job function, number of years in the current job, professional certifications and background knowledge. Using these criteria and the pair wise comparison in AHP, the weightage contributions from each expert were determined. This is crucial as fundamentally, a more experience experts would contribute higher weightage to the overall system failure distribution [13].

3 Results and Discussions

In this study, five experts were selected who were working closely with the system. The rank or weightage for each of the experts after pair-wise comparison is as shown in Table 1 where the mechanical engineer with 5 years working at the current function had the highest score.

Table 1. Weightage contribution from experts

Experts	Job Function	Years at current function (years)	Weightage
Expert 1	Mechanical Engineer	1.5	0.13
Expert 2	Mechanical Engineer	3	0.26
Expert 3	Reliability Engineer	0.2	0.02
Expert 4	Shift Supervisor	4	0.17
Expert 5	Mechanical Engineer	5	0.42

The contribution of each failure mode to system failure from the experts' view is as depicted in Fig. 3 where there was a good agreement between the experts on the top 5 failures. However, in the proposed framework, the contribution from each failure mode was used to estimate the system failure distribution for the system based on each expert. The snapshot of the analysis is shown in Fig. 4 (a) and (b) for expert 5.

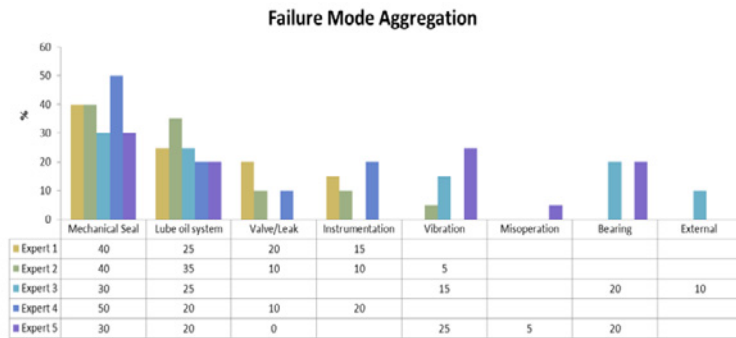
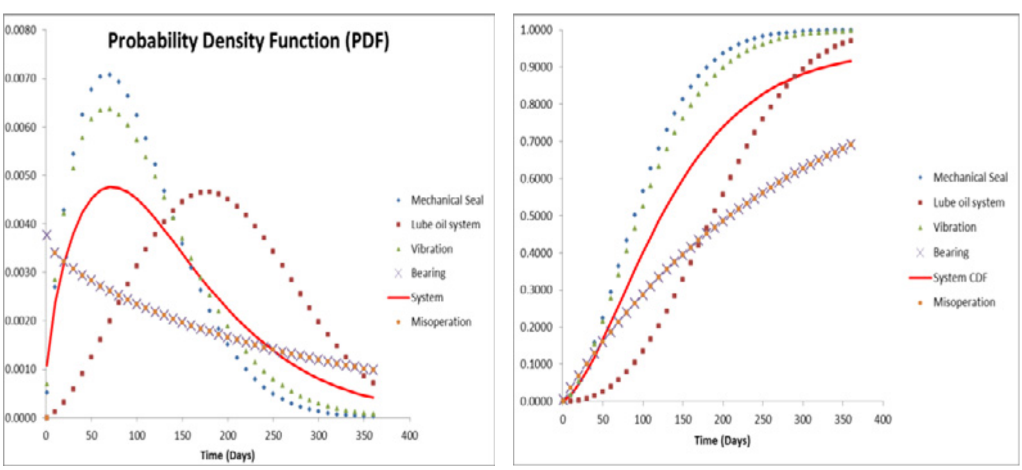


Figure 3. Failure mode aggregation from the experts

	Mechanical Seal		Lube oil system		Vibration		Bearing		Misoperation			
Time (Day)	PDF1	CDF1	PDF2	CDF2	PDF3	CDF3	PDF4	CDF4	PDF5	CDF5	System PDF	System CDF
1	0.0005	0.0003	0.0000	0.0000	0.0007	0.0004	0.0038	0.0039	0.0000	0.0000	0.0011	0.0010
10	0.0027	0.0158	0.0001	0.0005	0.0028	0.0177	0.0034	0.0357	0.0034	0.0357	0.0024	0.0182
20	0.0043	0.0511	0.0003	0.0026	0.0042	0.0534	0.0032	0.0687	0.0032	0.0687	0.0032	0.0464
30	0.0054	0.1000	0.0006	0.0071	0.0051	0.1004	0.0031	0.1001	0.0031	0.1001	0.0038	0.0815
40	0.0063	0.1587	0.0009	0.0145	0.0058	0.1552	0.0029	0.1301	0.0029	0.1301	0.0042	0.1218
50	0.0068	0.2241	0.0012	0.0252	0.0062	0.2150	0.0028	0.1589	0.0028	0.1589	0.0045	0.1657
60	0.0070	0.2933	0.0016	0.0394	0.0063	0.2777	0.0027	0.1866	0.0027	0.1866	0.0047	0.2119
70	0.0071	0.3640	0.0020	0.0574	0.0064	0.3414	0.0026	0.2133	0.0026	0.2133	0.0048	0.2593
80	0.0069	0.4341	0.0024	0.0792	0.0063	0.4046	0.0025	0.2389	0.0025	0.2389	0.0047	0.3069
90	0.0066	0.5020	0.0028	0.1049	0.0060	0.4661	0.0024	0.2637	0.0024	0.2637	0.0047	0.3540
100	0.0062	0.5664	0.0031	0.1343	0.0057	0.5249	0.0023	0.2875	0.0023	0.2875	0.0045	0.3999

(a)



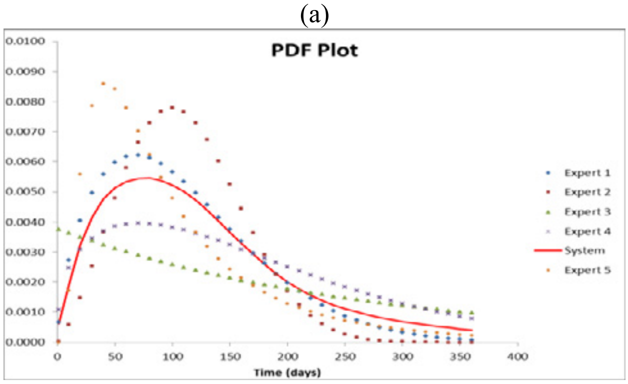
(b)

Figure 4. (a) Estimates of system probability distribution function (PDF) and cumulative distribution function (CDF) based on aggregation of failure modes (b) Plots of PDF and CDF for systems and each of the failure modes

Once the failure distribution from each expert was estimated, the final step was to combine the contribution from each expert based on the weightage determined through AHP. The results are as shown in Fig. 5 (a) and (b) where the system PDF was estimated.

	Expert 1		Expert 2		Expert 3		Expert 4		Expert 5			
	PDF1	CDF1	PDF2	CDF2	PDF3	CDF3	PDF4	CDF4	PDF5	CDF5	System PDF	System CDF
1	0.0007	0.0004	0.0000	0.0000	0.0038	0.0038	0.0011	0.0008	0.0000	0.0000	0.0006	0.0005
10	0.0027	0.0170	0.0006	0.0024	0.0036	0.0370	0.0025	0.0181	0.0017	0.0047	0.0019	0.0120
20	0.0041	0.0514	0.0015	0.0124	0.0035	0.0727	0.0031	0.0462	0.0056	0.0418	0.0032	0.0379
30	0.0050	0.0967	0.0025	0.0325	0.0034	0.1070	0.0035	0.0791	0.0079	0.1106	0.0042	0.0753
40	0.0056	0.1496	0.0037	0.0636	0.0032	0.1401	0.0037	0.1151	0.0086	0.1938	0.0048	0.1202
50	0.0060	0.2076	0.0048	0.1059	0.0031	0.1719	0.0039	0.1529	0.0084	0.2793	0.0051	0.1698
60	0.0062	0.2684	0.0058	0.1589	0.0030	0.2026	0.0039	0.1919	0.0078	0.3605	0.0053	0.2222
70	0.0062	0.3305	0.0067	0.2213	0.0029	0.2321	0.0040	0.2314	0.0070	0.4347	0.0054	0.2763
80	0.0061	0.3923	0.0073	0.2912	0.0028	0.2606	0.0039	0.2709	0.0062	0.5010	0.0055	0.3308
90	0.0059	0.4528	0.0077	0.3662	0.0027	0.2880	0.0039	0.3101	0.0055	0.5595	0.0054	0.3851
100	0.0057	0.5108	0.0078	0.4438	0.0026	0.3143	0.0038	0.3488	0.0048	0.6108	0.0052	0.4381

(a)



(b)

Figure 5. (a) Estimates of system probability distribution function (PDF) based on aggregation from experts (b) Plots of PDF for system and each of the experts

The distribution fitting revealed that the system failure distribution can be best described by Weibull distribution with parameters, β = 1.54 and η = 173 days. This result was then compared with distribution analysis of the same system using the actual system failure times. The contour plot, as shown in Fig. 6, shows that the results are statistically equivalent at 90% confidence level.

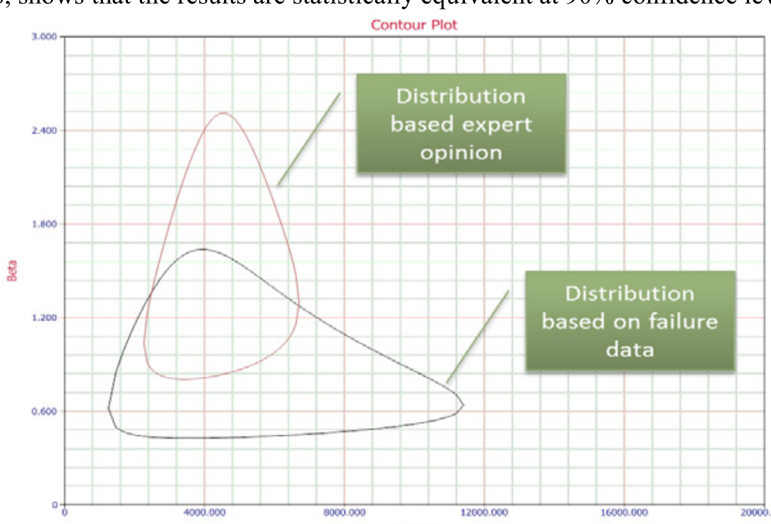


Figure 6. Result comparison between proposed elicitation framework and traditional analysis

4 Conclusions

This study proposed and validated an expert elicitation framework in estimating the system failure distribution from which other reliability measures can be derived in cases where failure data is limited or unavailable. The result showed statistical equivalence at 90% confidence level compared to traditional analysis. However, priority should still be given to analysis based on failure data and computerized maintenance management system (CMMS) should be employed to capture system history due to limitation of inherent uncertainty in expert's opinion and AHP method. The framework can be applied to augment the results from CMMS to fulfil our quest to have a reliable reliability analysis.

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