Design for Reliability of Complex System with Limited Failure Data; Case Study of a Horizontal Drilling Equipment

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Abstract: In this paper, a methodology is developed for reliability evaluation of electromechanical systems. The method is applicable in early design phase where there is only limited failure data available. When experimental failure data is scarce, generic failure data are searched from some related reliability data banks. In this method, Reliability Block Diagrams (RBD) is used for modeling the system reliability. Monte Carlo Simulation technique is employed to simulate the system for reliability and availability calculation. Current methodology contains the reliability importance analysis and reliability allocation to optimize the reliability. Evaluating reliability of complex systems in reverse engineering (competitive) design phase is one of the applications of this method. As a case study, a horizontal drilling equipment is used for assessment of the proposed method. According to the results, motor sub-system and hydraulic sub-system are the critical elements from reliability point of view. A comparison of the results is done with the results of reliability evaluation for a system with more failure and maintenance data available. Benchmark of the results indicates the effectiveness and performance quality of presented method for reliability evaluating of systems.

Keywords: Reliability, Monte Carlo Simulation, Design Phase, Reliability Allocation.

1. INTRODUCTION

Today's competitive world and increasing customer demand for highly reliable products, makes reliability engineering more challenging task. The reliability analysis has grown at a rapid rate as tracked in the literature on the subject. Design for reliability is an important research area, specifically in the early design phase of the product development. Mainly, the reliability analysis takes place at the end of design process, after determination of structure layout. The role of the analysis is to verify whether the reliability of the structure satisfies the demanded reliability. However, at the end of the design process, it is costly, or there is not enough time available to introduce major changes in the structure. Therefore, the results of the analysis have little influence on design. If reliability analysis applied during the conceptual design phase, its impact will be more remarkable on the design process producing high quality items. Results in more reliable and less expensive structure; a structure that is reliable in concept is less expensive than a structure that is not reliable in concept, Even with improvement in a later phase of the design process.
During the recent years, the requirement of modern technology, especially the complex systems used in the industry, leads to a growth in the amount of researches around the reliability base design. Avontuur [1-2], emphasises the importance of reliability analysis in the conceptual design phase. He demonstrates that it is possible to improve a design by applying reliability analysis in the conceptual design phase, reveals how to quantify failure and unavailability in cost, and compare them with investment cost to improve the reliability. Al-kheer [3] developed a reliability-based design approach by integrating the randomness of tillage forces into the design analysis of tillage machines, aiming at achieving reliable machines. The proposed approach was based on the uncertainty analysis of basic random variables and the failure probability of tillage machines. For this purpose, two reliability methods, namely the Monte Carlo simulation technique and the first-order reliability methods were used. Halloran [4] presented a case study for the early design reliability prediction method (EDRPM) to calculate function and component failure rate distributions during the design process such that components and design alternatives can be

selectively eliminated. The output of this method is a set of design alternatives that has a reliability value at or greater than a pre-set reliability goal.

In the most of the recent reliability base design researches, experimental data was used as the main source of the component reliability data; also a part of a system (for example electrical or mechanical part) was studied and hybrid electromechanical systems were not analysed. Furthermore, these studies are not comprehensive to include the various reliability calculations such as: reliability importance, reliability allocation, availability and uncertainty analysis in its results.

In this research, a reliability-based design methodology was developed for electromechanical systems. It overcomes the drawbacks of other reliability evaluation approaches which are not suitable for complex systems with availability of limited failure data for their components. Additionally, this methodology is integrated to include the several reliability estimation. Also two distributions are used to model the components reliability to contain different phases of life-cycle. Reliability evaluation of complex systems in reverse engineering (competitive) design phase, is one of the applications of the presented method.

This paper demonstrates a case study to support the proposed method as an early design reliability tool. In section 2, new method is summarized and illustrates its steps. Section 3 introduces the case study and demonstrates the results. The final section provides a conclusion and future work.

2. STRUCTURE OF THE METHODOLOGY

In this research a methodology is developed for reliability evaluation of electromechanical systems.

The new methods flowchart is shown in figure 1. This flowchart involves eight steps and applies for the case study in the following.

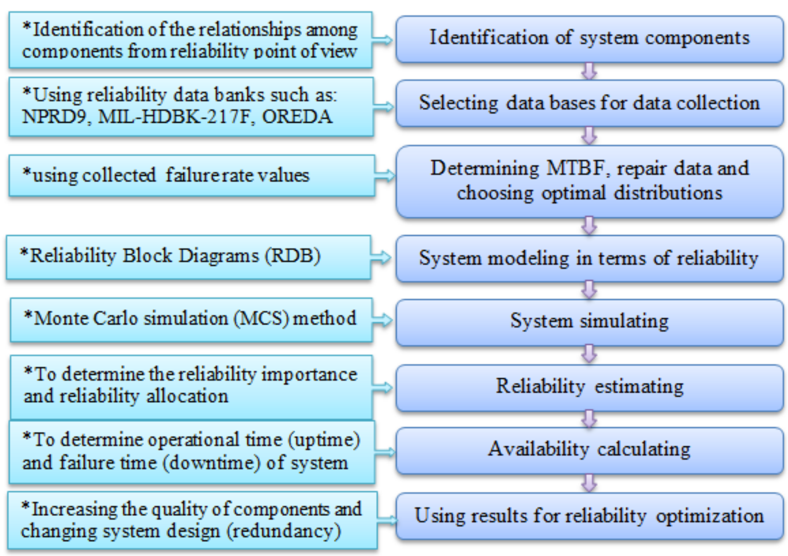


Figure 1: The new methods flowchart as an early design reliability tool

In the first step, subsystems and components of a system are identified and also the their functional relationships are determined. In the next step, the system components maintenance and failure data are collected from some data bases like MIL-HDBK-217F [5], OREDA [6] and NPRD-95 [7]. As mentioned above, this method is applicable in early design phase when there is only limited failure data. This method works well in the lack of suitable methods for reliability evaluation of complex system.. Also, expert judgement is used for specific components failure estimation for which there is no generic failure data. Since, there is a possibility for an error occurrence in data selecting for components failure, uncertainty is evaluated for the obtained results. In this method, Monte Carlo technique is utilized for system simulating. In modelling of the system, Weibull and exponential distributions are used because of their capability for modelling components reliability in different phases of life-cycle (specially Weibull distribution for wear-out phase). In subsequent steps of this method, the estimation is done for reliability and availability value. Also reliability importance and reliability allocation is calculated for reliability optimization. In this research and for the case study, the failure of the selected components (even a simple headlight) leads to system failure and system operation breakdown.

2.1. Reliability data type

There are some reliability data types; including experimental failure data, maintenance data and classified generic reliability data. For a specific system, experimental and maintenance data are collected from its maintenance information during its life cycle. Generic reliability data for a system are collected from similar systems information or classified generic reliability data that are collected from valid data bases. Classified generic reliability data is a suitable source when there is only limited maintenance or experimental failure data for a system. Usually these reliability data are applied in systems design phase.
In this paper, MIL-HDBK-217F, OREDA and NPRD-95 was used as the primary source of component reliability data.

2.2. Monte Carlo Simulation

Monte Carlo analysis is a powerful sampling tool for modeling the reliability of systems. Monte Carlo simulation method uses statistics to mathematically model a real-life process and then estimate the likelihood of possible outcomes. Before performing a Monte Carlo simulation, two category must be determined, one of them is the statistical distribution of the failure and repair processes and other is the logic function of the system, in other word, the relationship of the systems components and sub-systems should be determined [8]. Monte Carlo technique, take samples from cumulative distribution function (CDF) due to its suitability for taking weighted samples from more dense area. Figure 2 [9] illustrates the Monte Carlo simulation.

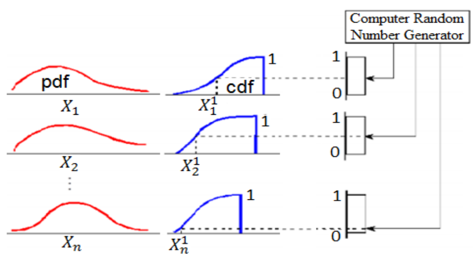


Figure 2: The Monte Carlo computer procedure

3. SIMULATION AND RESULTS FOR A CASE STADY

A Horizontal Drilling Equipment is considered in the reverse engineering stage, as a case study for evaluating the present method. Weibull and exponential distribution are selected in modelling of the system and all results are calculated for this two distributions. As mentioned earlier, RDB is method of choice for reliability modelling of the system. Figure 3 shows this modelling that created from ReliaSoft Blocksim8 software [10]. Each blocks in this model consists of several subsystems and components. After the system simulation, reliability parameters are calculated and analysed.

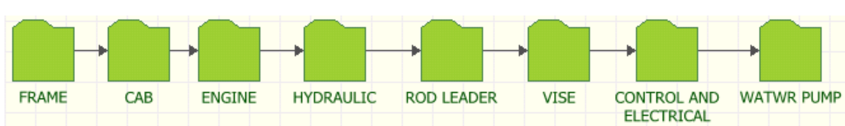
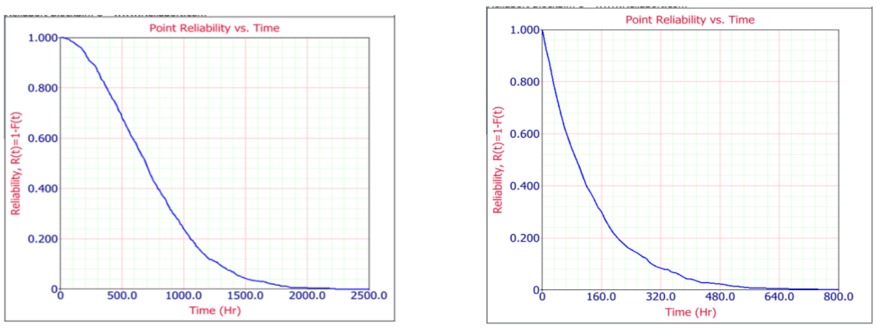


Figure 3: horizontal drilling equipment dividing for modelling

3.1. Reliability

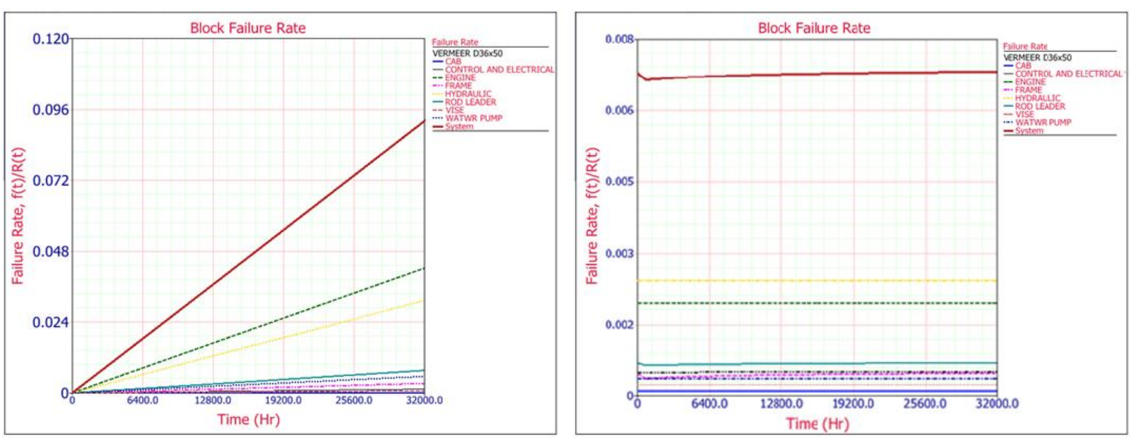
Figure 4 shows the reliability estimation results of drilling equipment for two distribution. Results show that in the lower time the reliability value of system with Exponential distribution is less than system reliability value with Weibull distribution. This is for the value of the Shape parameter (β) that assumes 2 with expert assumption for modelling components reliability in wear-out phase.



(a) **(b)**

Figure 4: Reliability diagrams of drilling equipment with Weibull (a) and Exponential (b) distribution

Failure rate for Weibull distribution in lower time of life-cycle is very small and optimistic but not reasonable. Notwithstanding, values of the failure rate for Exponential distribution in the same life-cycle is reasonable. The results is reverse for Weibull and Exponential distribution in upper life of life-cycle. Therefore with choosing the Exponential distribution for lower time of life-cycle and Weibull distribution for upper time of life-cycle we can consider the system with Bathtub Curve behaviour. Figure 5 shows the failure rate estimation results for drilling equipment and its subsystems in Weibull and Exponential distributions.



(a) **(b)**

Figure 5: Failure Rate diagrams of drilling equipment and its subsystems with Weibull (a) and Exponential (b) distribution

3.2. Reliability Importance

Reliability evaluation of a system depends on its components contribution. In a system with a series structure that has several subsystems, the subsystem with the lowest reliability value, has the highest effect on the system reliability. Therefore, a small variation in the subsystem with the lowest reliability value leads to a great variation in system reliability value. Whereas, variation in other elements doesn't have as much influence as on the system reliability value. The calculation of reliability importance value for a component of a system with ‘n’ element is defined as the following mathematical formulae:

$$IR_i = \frac{\partial R_s}{\partial R_i} \quad (1)$$

In this equation, R_s stands for the reliability of system and R_i is reliability of a component. In this case study, cab subsystem has the maximum reliability value for both Exponential and Weibull distribution. And the minimum is for hydraulic subsystem and motor subsystem for Exponential and Weibull distribution respectively. Therefore, occurrence of failure in hydraulic and motor subsystems is more susceptible. Furthermore, among all components of the system, motor starting has maximum failure rate and reliability importance. So with increase in the quality of component in this subsystems or design change (for example redundancy) reliability of system can be improved.

3.3. Reliability Allocation

Reliability allocation is an important step in system design. It allows determination of the reliability of constituent subsystems and components so as to obtain a targeted overall system reliability. Since 1950s [11], several studies have been devoted to this problem and decent number of researches were devoted on this subject. But no general method has been proposed to solve the reliability allocation problem satisfactorily. This situation is due to increasing complexity of current systems and necessity of considering multiple constraints such as cost, weight, and component obstruction among others. An overview is recently published of the methods developed during the past 3 decades for solving various reliability optimization problems [12-13].
Aeronautical Radio Incorporated (ARINC) [14] technique is one of the well-known reliability allocation type that performs based on weighting factors to subsystems of a series structure system. In this method, weighting factors for a subsystem is equal to division of the failure rate of the subsystem to the sum of all subsystems failure rates of system. In this research, ARINC technique is used to achieve the results of reliability allocation. Table 1 shows the results of reliability allocation for subsystems of drilling equipment with Weibull distribution. For this system, 0.95 is considered as a target reliability for 2000 hours (that is equal to 1.25 functioning years for drilling equipment). It should be noted that, these results are obtained for 95% of confidence level.

Table 1: Initial reliability and target reliability for subsystems of drilling equipment with Weibull distribution

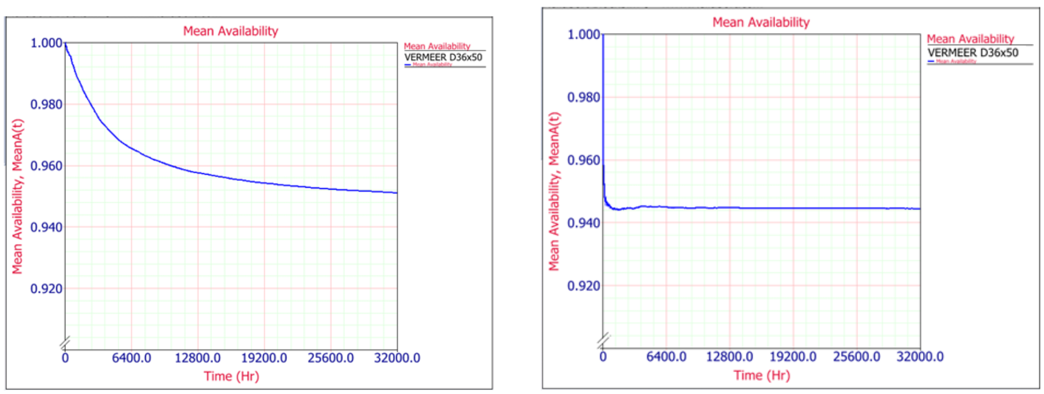
Subsystem	Reliability importance (2000 hours)	Initial reliability (2000 hours)	Weighting factors	Target reliability (2000 hours)
Frame	0.004	0.830	0.032	0.998
Cab	0.003	0.996	0.001	0.999
Engine	0.045	0.071	0.461	0.976
Hydraulic	0.023	0.142	0.341	0.983
Rod Loader	0.005	0.626	0.082	0.996
Vise	0.003	0.995	0.007	0.999
Control & Electrical	0.004	0.923	0.014	0.999
Water Pump	0.005	0.704	0.061	0.997
The whole system	-	0.003	-	0.95

3.4. Availability

Availability is defined as the probability that a repairable system is operating satisfactorily at any random point in life-cycle time. In other words, the probability that a product or system is operational. The availability is formulated as follows that “u” is uptime and “d” is downtime of the system.

$$A = u/(u + d) \quad (2)$$

In a repairable system, because of renewal process in components, the value of system reliability is not a good metrics for decision making about the system. Therefore, in repairable systems analysis, availability measure is used that is a combination of reliability and maintainability parameters [14].
Average availability value for drilling equipment in 32000 hours (that is equal to 20 functioning years for drilling equipment) is about 0.95. Figure 5 shows the average availability diagram for drilling equipment for two distribution. Results show that in a repairable system reliability value is a good parameter only for determining the reliability importance of components. However, the reliability analysis is a beneficial factor for repairable systems.

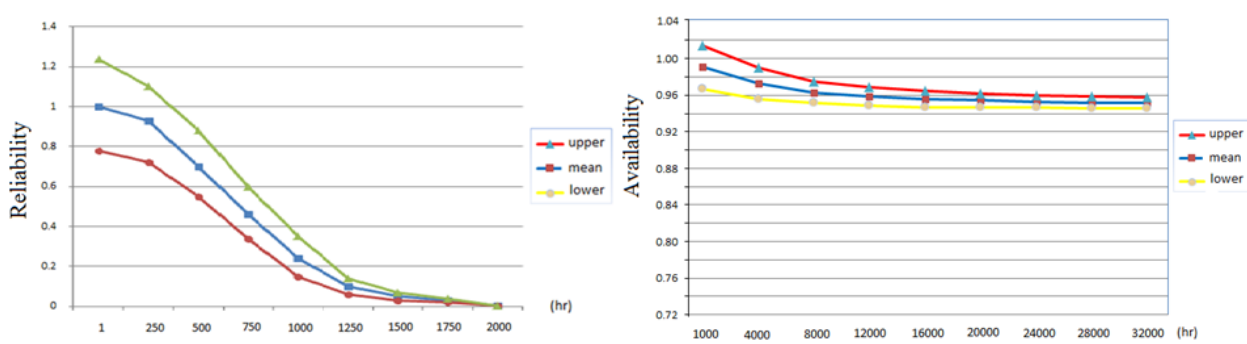


(a) **(b)**

Figure 5: Average availability diagram of drilling equipment with Weibull (a) and Exponential (b) distribution

3.5. Uncertainty

Uncertainty is a measure of the "goodness" of an estimate. Without such a measure, it is impossible to judge how closely the estimated value relates or represents the reality. Uncertainty arises primarily due to lack of reliable information [14]. Engineering systems are often associated with vast amounts of data. This data can be used to estimate the performance of the system, consequences of system failure, and its risks [9,15].
In this research uncertainty analysis is applied for reliability and availability results. Figure 7 illustrates the average, upper bound and lower bound for availability and reliability of drilling equipment with Weibull distribution. This results is obtained for 95% two-sided confidence bound.



(a) **(b)**

Figure 7: Uncertainty result for reliability (a) and average availability (b) of drilling equipment for 95% two-sided confidence bound with Weibull distribution

3.6. Benchmark Test

For validation of presented methodology, a benchmark research has been done with the results of similar projects. The results of a project that is about the reliability evaluation of mining equipment (Dump Tracks) in a copper mine [16], is selected for comparison with the results of current methodology. The reason behind this selection is the existence of similar subsystems and work conditions of Dump Tracks and Drilling Equipment. This project has an advantage for comparison and that is experimental data for Dump Tracks components failures. Table 2 shows the Drilling Equipment and Dump Tracks reliability value in different life-cycle time. Values in table 2 indicates the approximate equal results for both systems.

Table 2: Comparison of Drilling Equipment and Dump Tracks Reliability Value

Time (hours)	Reliability of Drilling Equipment	Reliability of Dump Tracks
0	1	1
50	0.7	0.55
500	0.029	0.0023
1000	0.001	5E-6
3000	5.9E-10	1.75E-17

4. CONCLUSION

In this paper, a reliability-based design methodology for electromechanical systems was developed to overcome the drawbacks of other reliability evaluation approaches which are not suitable for complex systems having limited failure data for their components. This method is applicable in early design phase when there is only limited failure data. So reliability evaluation of complex systems in reverse engineering design phase, is one of the applications of the presented method. The main steps of this approach were presented and applied for a drilling equipment as a case study. Reliability and availability parameters are calculated for this case study. All calculations are computed for Weibull and Exponential distribution. Comparing the various results show that the Exponential distribution is suitable for lower phase of life-cycle and Weibull distribution for upper phase. Reliability importance analysis illustrates that hydraulic and motor subsystems are the critical elements in terms of reliability. In addition, among all components of the system, motor starter has maximum failure rate and reliability importance. So with increase in the quality of components in the subsystems or changing of design (for example redundancy), reliability of system is improved. At the end, a benchmark of the result of this research with similar projects indicates the effectiveness and performance of presented method for reliability evaluation of systems existing in design phase with limited failure data for its component.

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