Modelling Reliability Centered Maintenance Program using Agent-based Simulation: A Case Study

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Abstract. Reliability-centred Maintenance is one of the most common maintenance strategies used in the industry. Although its effectiveness has been shown where comprehensive preventive maintenance campaigns are involved, it is considered a costly and time-consuming maintenance strategy. There is always a need to continuously evaluate the reliability-centred maintenance plan and keep it optimal. Thus, modelling techniques are playing a significant role in modelling and optimising maintenance plans. The purpose of this paper is to model a reliability-centred maintenance plan using an agent-based simulation approach. The method of this study is a combined case study and a simulation modeling method. A drilling asset was purposefully selected for the case, considering three agents: The overall system, main equipment, and auxiliary equipment. The availability of the simulated system is about 95.8%. The actual availability is about 96.16 %, based on the historical failure data, which is used to validate the simulated results. Furthermore, availability based on reliability theory and historical data is also estimated at around 99.3%. It can be concluded that the agent-based simulation model is very effective in mimicking the actual availability compared to the traditional reliability block diagram estimates, which overestimate the availability.

Keywords: Reliability Centered Maintenance · Simulation Modelling· Agent based Modelling· System Availability · Drilling Assets.

1 Introduction

Reliability-Centered Maintenance (RCM) is widely adopted across various industries where high standards of safety and availability are required, such as aviation, petrochemicals, and power generation [1]. It has also emerged to be a desirable maintenance strategy for remote assets as offshore wind farms that suffer from limited accessibility, costly and long time to get corrective maintenance services which lead to high production unavailability [2]. The main goal is to improve the reliability of the equipment and a significant reduction in corrective maintenance operations [3]. RCM has a systematic approach to identifying critical components, analyzing failure modes and effects, and implementing tailored preventive maintenance tasks [4].

Although RCM ensures maximum reliability and reduces corrective maintenance burdens and expenses, many studies [5–9] indicate that RCM can lead to a significant workload in terms of preventive maintenance. RCM plans might face some challenges with noncoherent systems where component interactions complicate maintenance strategies [10]. Several RCM plans managed to keep system availability high in several case studies, a considerable corrective maintenance workload, and excessive preventive workload are observed in these case studies [11–15]. Industrial practices show that RCM and risk-based maintenance programs are emerging to consider more condition-based maintenance tasks [16]. Several studies [17] [18] [10] have also indicated the need to continuously enhance and optimize RCM plans, as they often begin with insufficient reliability data, particularly during the early operational phases of a system. The key step is to establish a feedback loop from operational data to validate assumptions about, e.g. failure modes, failure rates, and mean time to repair that have been implemented during the early operational phases of a system.

Modeling and simulation methods, such as the Reliability Block Diagram (RBD), Monte Carlo [18], Markov Chains [19, 20], System Dynamics [21], Discrete event [22], have been used to enhance Reliability-Centered Maintenance programs. RBDs are extensively used in safety and dependability modeling [23], as they require less input data and are computationally less intensive, allowing a quicker assessment of system reliability [24]. However, agent-based modeling is a promising technique to handle non-series-parallel topologies, hierarchies, process-dependent downtimes and provides a virtual environment to analyse, test, and find optimal maintenance intervals. Limited empirical research has been done to compare different availability modeling methods and evaluate which provides the most realistic estimates. The purpose of this study is to explore the effectiveness of agent based modelling method to model and assess a reliability-centred maintenance program. An industrial system that involves series-parallel topologies and complex hierarchies has been purposefully selected. The availability has been modelled and estimated using two methods: Reliability block diagram and agent-based modelling. The availability estimates from these two methods were compared with the actual availability figures.

The subsequent sections of this paper explain the methodology, present, and discuss the results and findings. The paper concludes with different recommendations on the adaptation of agent-based simulation approaches to model RCM programs and highlights the potential for future research.

2 Materials and Methods

2.1 Conceptual Modelling

The conceptual model was developed by defining three primary agents: The overall system, the main equipment and the Auxiliary equipment. Different interactions were designed to simulate the dynamic response to various conditions, including operational procedures, failure occurrences, and corrective and preventive maintenance actions. The conceptual model, developed and based on the results of the system analysis, was considered the core framework for the simulation model. The system level model contains the overall system's operational states, where the equipment level contains more detailed states related to failure modes and schedule maintenance.

Figures 1 and 2 show the conceptual model designed for the system level and equipment level, respectively.

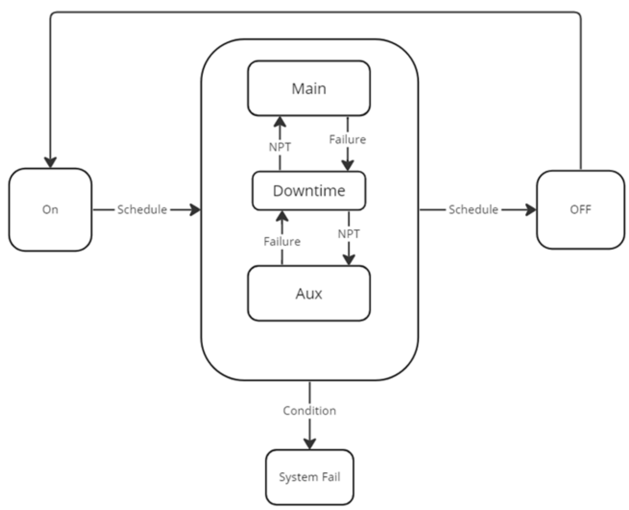

Fig. 1. System-level conceptual model

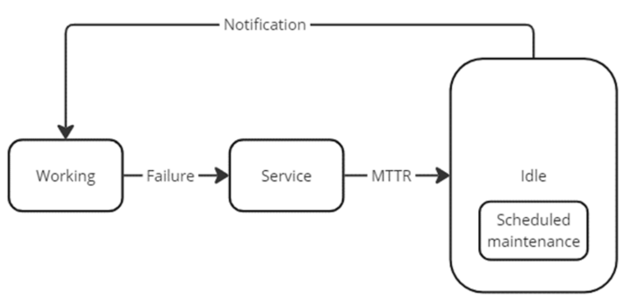

Fig. 2. Equipment-level conceptual model

2.2 Extracting failure rates and time to repair

Following the results of the system analysis, a statistical reliability analysis of the drilling asset was then performed in Python. The results of the reliability analysis then helped determine the reliability characteristics of the selected subunit. Using Pythons library, different Probability Distribution Functions (PDF) were fitted and using Kolmogorov-Smirnov (KS) test, Alaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and Sum of Squared Errors (SSE) the best fitted PDFs and different parameters like Mean Time to Failure (MTTF) were estimated. Statistical measures were selected and used for their ability to evaluate goodness of fit (KS test), balance between accuracy and complexity of the model (AIC, BIC), and minimise prediction error (SSE). The selected distributions and the estimated reliability parameters served as inputs in calibrating the simulation model parameters and ultimately leading to a more realistic assumption regarding failure behaviour.

Figure 3 illustrates various distributions fitted to the empirical data. The Lognormal distribution closely follows the observed data points, reinforcing its selection as the best-fitting model. Using the lognormal distribution, the behavior of the failure mode FTI can be effectively captured.

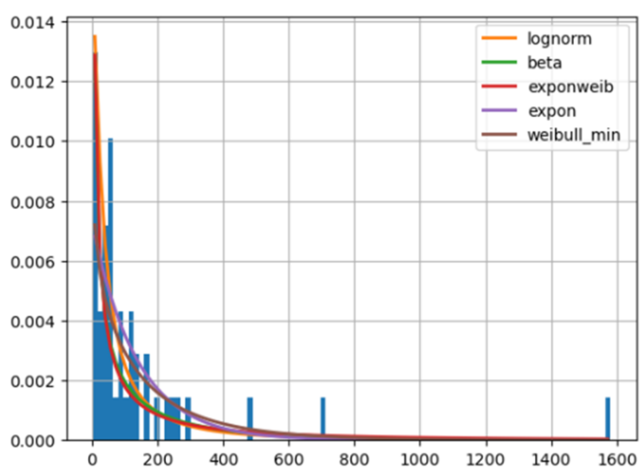

Fig. 3. Probability distributions fitted to empirical data of failure mode FTI for the Main Asset.

In addition, in this study, the mean repair time (MTTR) was also estimated by analyzing historical maintenance data using the same statistical methods as for MTTF. This ensured the dynamic nature of this parameter. Ultimately, using these parameters, the reliability and availability of the system were calculated from these estimated parameters to ensure realistic conditions in the simulation.

2.3 Simulation Modelling

The simulation model was then implemented using AnyLogic software, chosen due to its flexibility and capability to effectively model the complex and dynamic interactions in multi-agent simulation models. Utilising agent-based modelling allows each asset to be modelled as a separate agent. This is beneficial when trying to model each of the failure modes with other specific asset-specific behaviours.

The first modelled agent is the system-level agent, which combines both the main and auxiliary equipment. The system agent has several states, as shown in Figure 4: working (Operational state), operationally not working (Off state), partially failed (Downtime state) and totally failed (Failed state). The second modelled is the main equipment, as illustrated in Figure 5, which includes several failure modes, repair processes, and preventive maintenance intervals. The main equipment agent has three main states: Working, Service, and Idle. In Figure 5, five failure modes are considered within the "Service" state, and six preventive maintenance intervals are considered within the "Idle" state. Failure rates, repair durations and preventive maintenance intervals were included in the model based on the results of the reliability analysis and the obtained operational instructions. Operational hours were estimated based on a non-intrusive working timeline of the asset. Preventive maintenance intervals ranged from daily to yearly maintenance was then estimated based on the required time to perform the tasks. The required time varied from 20 minutes to 1 day on yearly preventive tasks.

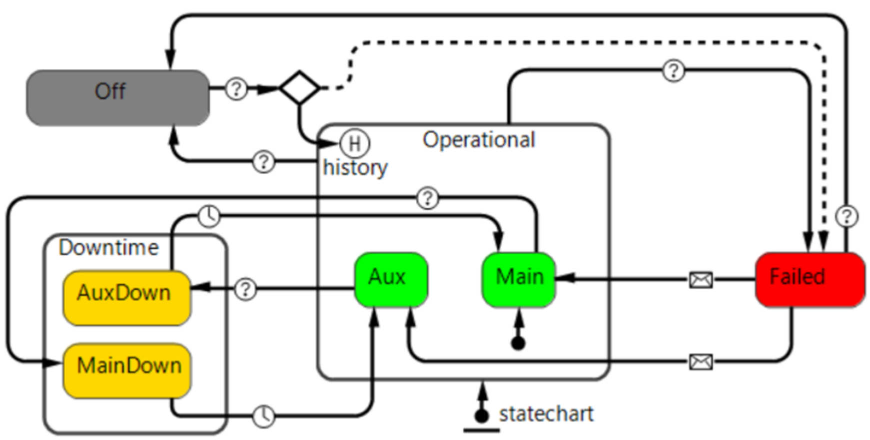

Fig. 4. System level agent state chart

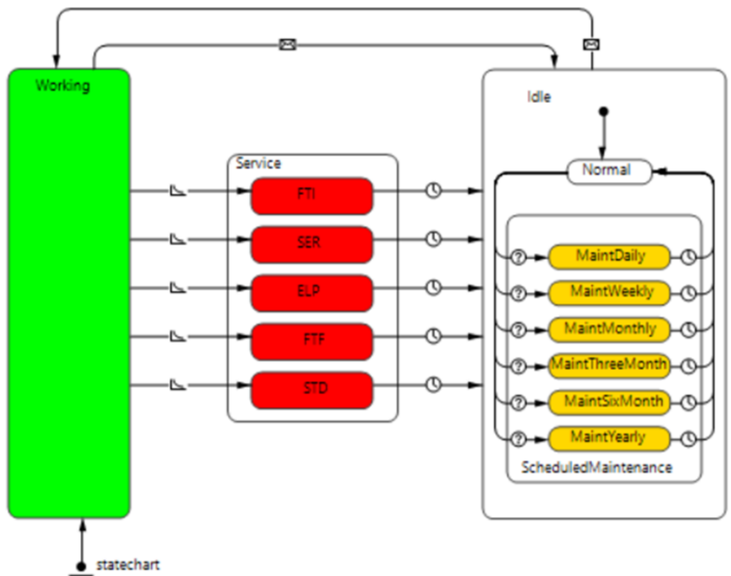

Fig. 5. Main asset agent state chart

2.4 Model Validation

The validation process involved comparing the simulation outputs with the availability and downtime of historical operational and failure data. The metrics used for the validation included historical failure frequency, time to repair, and system availability to ensure the accuracy and validity of the simulation model.

3 Results and Discussion

The results of the simulated availability based on the agent-based modeling approach and the estimated availability based on RBD are summarized in Table 1 and compared against the actual availability figures.

Table 1. Summary of the actual and simulation results

Criteria	**Scenario 1: Actual historical data**	**Scenario 2: Estimated based on Reliability Analysis**	**Scenario 3: Estimated based on Simulation Results**
System Availability	96.16%	99.3%	95.8% ± 1%
Main Equipment Availability	95.2%	97.3%	95.4% ± 1%
Auxiliary Equipment Availability	94.12%	98.4%	93.07% ± 0%

The simulation was performed for five different runs (random seed), and the average values are considered to ensure valid outputs. The results indicate that the system availability based on historical data, the reliability block diagram and simulation was 95.8%, 96.16% and 99.3% . It can be seen that the system availability value based on agent-based simulation approach has better matching to the actual values compared to the figures based on reliability block diagram estimation. The key factor contributing to this divergence is that the simulation analysis managed to capture the transition time when the main or auxiliary equipment switches. This emphasizes how crucial simulation is to accurately model system performance and to portray more realistic characteristics than simple reliability evaluation. This also highlights the importance of having a simulation model to replicate all possible operating scenario of the system. Comparing the historical data with the reliability analysis data highlights the inability of reliability analysis to capture detailed behavior of the system, such as downtime in this model. Additionally, the simulation model provided deep insights related to maintenance activities for each equipment.

The degrading reliability functions of each main and auxiliary assets compared to system reliability is illustrated in Figure 6. System reliability is evidently higher than each of the assets separately. This is due to the fact that the system is designed as a parallel block diagram.

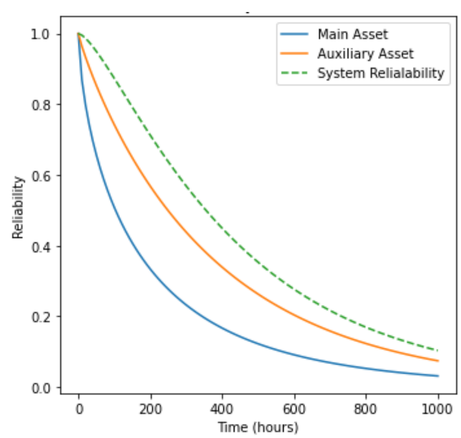

Fig. 6. Reliability function over time for the overall system, Main and Auxiliary Equipment

4 Conclusion

It can be concluded, based on the compared results, that agent-based simulation where multiple agents and states are modelled, provides more realistic availability estimates. In this study, three behaviours were modelled and estimated. First, the transition time when redundant equipment are switching are considered in the overall availability estimates. Second, the preventive maintenance activities that are performed during the idle state of redundant equipment, are considered in the overall availability estimates. Third, several failure modes that has different mean repair times are considered rather than considering a common mean repair time for all failure modes. Considering these three issues made the agent-based simulation approach more realistic and matching the actual availability figures compared to the estimates of the classical reliability block diagram method.

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