Modelling System Availability of Series Configuration with Implicit Temporary Redundancy: Agent-based Simulation Approach

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Abstract. Many critical industrial systems like offshore assets, e.g. floating wind turbines, have a system of series equipment that is configured with short-term redundancy (implicit parallel configuration). Such a configuration is widespread in many industrial applications, where a pump or compressor feeds a storage vessel; if the pump fails, the storage vessel alone can keep the entire system functioning for a short time. The traditional reliability block diagram is challenging and has limitations for such a configuration. This paper presents an agent-based simulation approach that overcomes the reliability block diagram method and assesses the operability, maintainability, and availability of Series-Temporary Redundant systems. The results show that the system availability, using the reliability block diagram method, is about 98.56% compared to the availability of 98.6% using the agent-based simulation approach. The series with a temporary redundant structure improved availability by 0.04%, offering 773 operating hours out of 175200 Hrs. The Series-Temporary redundant structure offers an approximate buffer time of 3.2 days at failure occurrence, which should be sufficient to repair the feeding equipment (pump or compressor).

Keywords: Complex Reliability Block Diagram · Simulation Modelling · Agent-based Modelling · System Availability · Feeding Assets.

1 Introduction

Reliability, availability and maintainability (RAM) analysis are crucial for maintenance engineers to get insights and define appropriate maintenance strategies at the design phase to enhance potential system performance, reduce downtime, and ultimately contribute to competitive advantages [1], [2]. It is particularly vital in complex industries such as petroleum, nuclear and mining, where operational efficiency and failure consequences are critical [2]. Among several reliability analysis methods, reliability block diagram (RBD) models are the most commonly used [3]. Traditional RBDs are static and exhibit several limitations when state dependency, dependent events, non-series-parallel topologies, and load-sharing aspects are involved, which complicate analysis and hinder efficiency in large-scale systems [4] [5].

Several researchers have proposed advances like dynamic reliability block diagrams (DRBD) [3], dynamic Bayesian networks (DBN) [4], Markov models, Petri-Nets models, and state chart models that aim to address some of the limitations of static RBD models. One of the most challenging industrial non-series-parallel topologies is the feeding-storage systems, e.g. pump or compressor feeds a storage vessel; if the pump fails, the storage vessel alone can keep the entire system functioning for a short time. The static RBD does not consider how long the system stays available after the pump fails. To overcome this limitation, the RAM Model needs to consider the dynamic behaviour over time (e.g., tank depletion after pump failure). Markov models, Petri nets and state charts methods are capable of handling the short-term redundancy, however, with different assumptions. For example, the Markov property assumes that future states depend only on the present state, which might not be the case for the feeding-storage system. The system failure might depend on history or be triggered by another state (not necessarily the failure rate of the active one). Moreover, considering the complexity of the feeding-storage system, as it involves three hierarchical levels (system, equipment, component), the agent-based modelling (ABM) with state charts has an advantage over the Petri Nets method. The availability of the system might also depend on the system process (operational parameters) and not only on the failures (i.e.failure rates), where ABM can effectively consider that. Petri Nets method is complicated when several processes and hierarchies are involved (i.e., nesting equipment and states), and diagrams get messy for complex systems [**?**].

Therefore, the purpose of this paper is to estimate the availability of series configuration with implicit temporary redundancy using agent-based modelling with state charts. An industrial feeding-storage system is purposefully selected for this study. The study covers two scenarios. The first scenario represents the current practice of estimating the system availability based on the static RBD method. The second scenario utilises agent-based modelling with state charts. Both scenarios are simulated using a well-known multi-method modelling software called AnyLogic.

In the following section, the reliability and availability theories are explained, and the developed simulation model is presented. In section 3, the results of the two scenarios are illustrated and discussed. Finally, the paper concludes with conclusions, insights, and recommendations for future works.

2 Reliability and Availability Modelling

2.1 Reliability Block Diagram

A Reliability Block Diagram (RBD) is a graphical representation used to model the reliability and availability of complex systems. It illustrates the functional dependencies of system components, where each component is represented as a block, and the arrangement of these blocks determines how system failures propagate. The whole system fails if the system is configured as a Series Configuration, where any component fails. The system reliability can be estimated as:

$$R_{system} = R_1 \cdot R_2 \cdot \ldots \cdot R_n \tag{1}$$

where R_i is the reliability of equipment i.

For example, the feeding-storage system has a series configuration of three main equipment, as illustrated in Figure 1: Feeding, accumulating and distributing equipment.

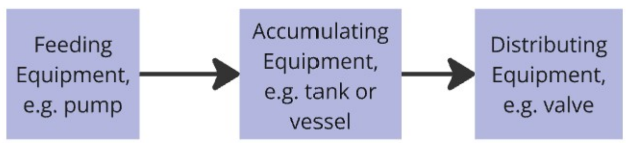

Fig. 1. Reliability block diagram of feeding-storage system.

2.2 Agent-based Simulation modelling

Agent-Based Modelling and Simulation (ABMS) is a computational method used to simulate complex systems by modeling the behavior and interactions of agents. Unlike traditional modeling approaches, which often rely on aggregate-level assumptions, ABMS focuses on the individual elements of a system and their dynamic interactions over time. Agents in the simulation operate independently, and then interactions among them often occur through point-to-point messaging, interface-based behaviors, or rules of engagement. Agent interactions are governed by internal behavioral logic, often modeled using state charts. A state chart (or state machine) provides a structured way to define how an agent behaves, how it transitions between different conditions (states), and how it interacts with other agents and the environment.

For example, the feeding-storage system can be modelled using a state chart as shown in Figure 2. The system has three main states: (1) working, (2) working while the feeding equipment failed, and (3) the entire system failed. The system should usually be in the working state unless a failure is triggered by either the feeding, accumulating, or distributing equipment. If the accumulating or distributing equipment fails, the entire system will fail and go to a "system failure" state. If the feeding equipment fails, the system will continue to work temporarily until the feeding equipment is fixed and the system is totally recovered or the accumulating equipment is operationally failed. The feeding-storage system is further modelled as shown in Figure 3.

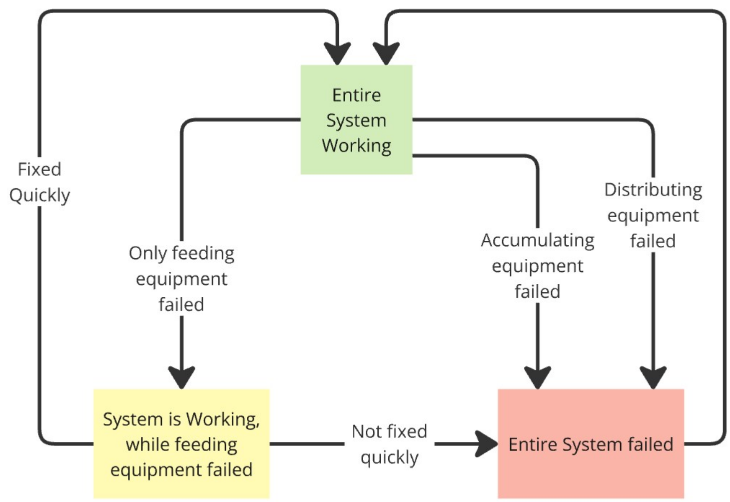

Fig. 2. State machine diagram of feeding-storage system with implicit temporary redundancy.

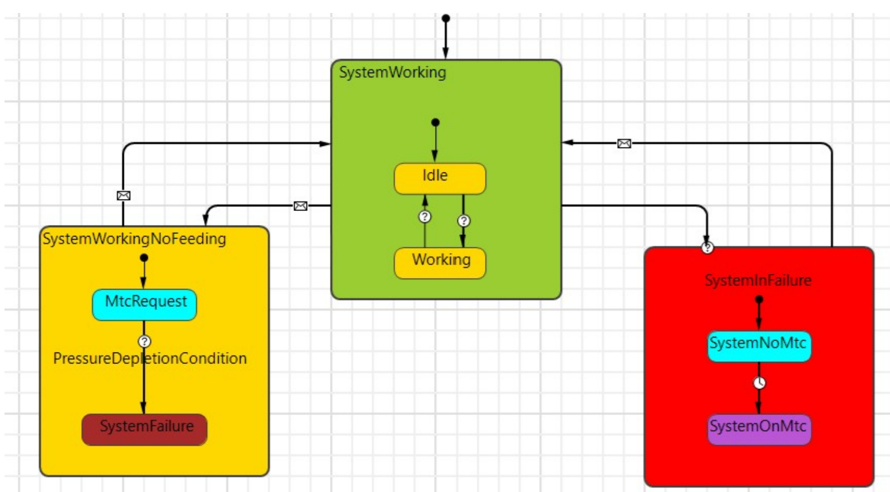

Fig. 3. State chart of the modelled system.

Equipment Modelling After modelling the system behaviour based on three states. The equipment shall also be modelled. The feeding equipment has mainly three main states: working, failures (different failure modes), and repair. The feeding equipment has several failure modes (10 modes are modelled, Figure 4) and each has a specific failure rate and mean repair time, as described in Table 1.

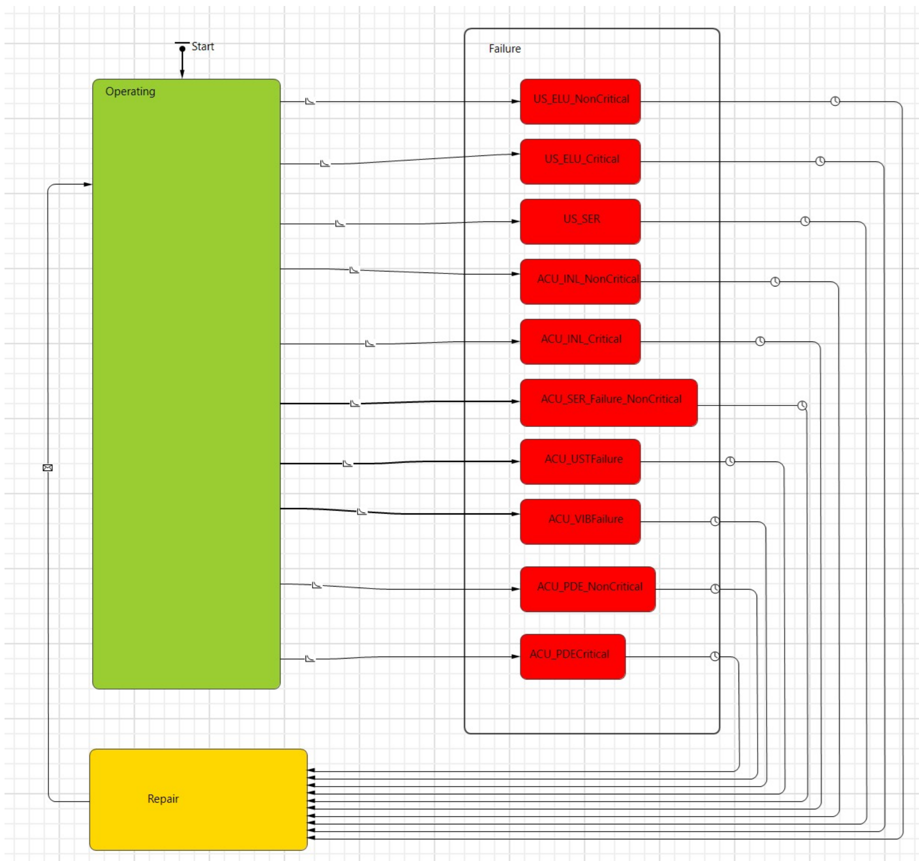

Fig. 4. State chart of the feeding equipment.

The distributing equipment has also modelled as separate agent as it has specific failure modes (4 modes are modelled, Figure 5) and each has a specific failure rate and mean repair time, as described in Table 2.

Table 1. Failure rates and mean repair times for the feeding equipment.

Failure mode	Description	Failure rate per year	MTTR in Hrs
US ELU Non-Critical	External Leakage -Utility Medium	4.681	10
US ELU Crtitical	External Leakage - Utility Medium	0.87	10
US SER	Minor In Service Problems	32.17	10
ACU-INL-Non-critical	Air Compressor Unit- Internal Leakage	7.82	10
ACU-INL-Critical	Air Compressor Unit -Internal Leakage	3.48	10
ACU-SER-Failure-Non-critical	Air Compressor Unit - Minor In Service Problems - Non-critical	33.91	10
ACU-UST-Failure	Air Compressor Unit- Spurious Stop - Non-critical	37.38	10
ACU-VIB-Failure	Air Compressor Unit - Vibration - Critical	1.74	10
ACU-PDE-Non-critical	Air Compressor Unit- Parameter Deviation - Non-critical	9.56	10
ACU-PDE-Critical	Air Compressor Unit- Parameter Deviation - Critical	0.87	10

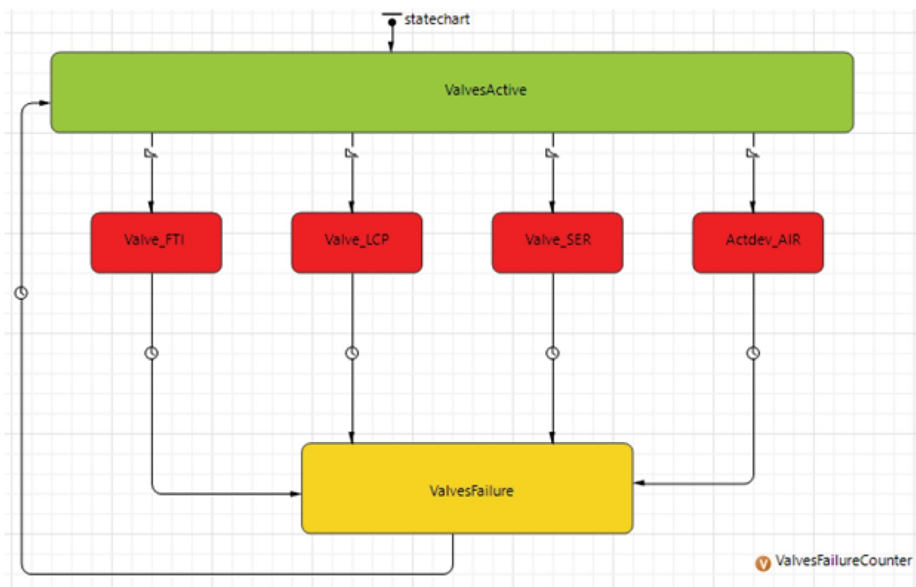

Fig. 5. State chart of the distributing equipment.

Table 2. Failure rates and mean repair times for the distributing equipment.

Failure mode	Description	Failure rate per year	MTTR in Hrs
Valve FTI	Fail to Function as Intended- Critical	1.26	6
Valve LCP	Locked in Closed Position- Critical	0.25	6
Valve SER	Minor In Service Problems- Critical	1.26	6
Valve AIR	Abnormal Instrument Reading- Critical	1.25	6

2.3 Validation Process

The model comprises three components: input, logic, and output. The inputs were chosen on the basis of historical data and expert involvement to ensure their validity. The logic was derived from the case study and was confirmed by experts for precision. The results were partially validated. The results of the simulated scenarios were qualitatively validated by the case study experts, as these scenarios have not yet been implemented and no data have been collected. The considered lifetime for these scenarios is 20 years (175,200 h).

3 Results

The results are summarised in Table 3, where both scenarios are compared. Scenario 1 represents the traditional reliability estimates where the system is modelled as series configuration and the implicit temporary redundancy is not considered. Scenario 2 presents the series configuration with the implicit temporary redundancy. The results obtained show that the system availability, using the reliability block diagram method (scenario 1), is about 98.56% compared to the availability of 98.6% using the agent-based simulation approach (scenario 2). The 0.04% is then considered as the effect of implicit temporary redundancy, where the whole system functions for a short time, even if the feeding equipment fails.

Table 3. Results of modelled scenarios.

Criteria	Scenario 1: Series configuration	Scenario 2: Series Configuration with Implicit Temporary Redundancy
Availability in %	98.56%	98.6%
Availability in hours	172,678	173,451

In Figure 6, the storage equipment managed to keep the system available for almost 25 hours after the feeding equipment failure event. The corrective maintenance service has taken almost 85 hours to reach and fix the feeding equipment. Thus, the system was unavailable for almost 60 hours.

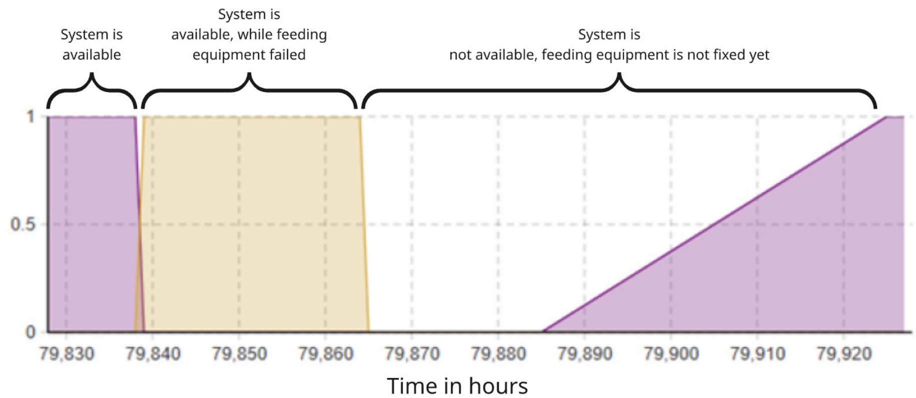

Fig. 6. Snapshot of the system availability timeline during a failure event of the feeding equipment.

During the simulation time horizon, that is, 20 years, the feeding equipment had ten failure events. The storage tank manages to keep the system available on average for 77.3 hours per failure, which provides almost 3.2 days for maintenance service to fix the feeding equipment before the pressure in the storage tank depletes to the 'Failure Pressure' and the system goes completely unavailable.

4 Conclusions

Based on the results, it can be concluded that availability based on the reliability block diagram method provides an overestimate compared to the state chart method. The block based RAM analysis focuses on the structure of components and how they connect to perform a function. While, state based RAM analysis focuses on the dynamic behaviour of components or systems over time—including failure, degradation, repair, standby modes, etc. This principal difference makes state based RAM analysis more effective in accommodating the industrial systems' complexities.

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