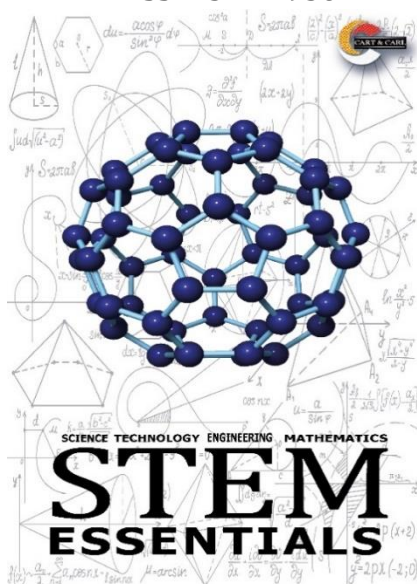




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Simulation-Based Reliability-Centered Maintenance Framework for Instrumentation Loops in Petrochemical Process Units

Abstract

Instrumentation-loop faults can degrade control accuracy and process stability in petrochemical facilities, sometimes without causing an immediate shutdown. This paper presents a simulation-based reliability-centered maintenance (RCM) framework that links fault-response analysis with Failure Mode and Effects Analysis (FMEA) to guide maintenance prioritisation. A representative tank-level control loop was formulated using a mass-balance model and implemented in MATLAB/Simulink as a closed-loop system containing a PID controller, process model, sensor, actuator path and feedback signal. Four conditions were examined: sensor drift, measurement noise, sudden fault injection and increased process delay. Their observed effects were assessed using severity, occurrence and detectability ratings, and Risk Priority Numbers (RPNs) were calculated. Sensor drift produced the highest RPN (336), followed by sudden fault injection (216), increased process delay (175) and measurement noise (140). The response patterns indicated that the faults affect different aspects of performance: drift can produce a stable but biased operating point; noise degrades feedback-signal quality; sudden disturbance creates a pronounced transient deviation; and increased delay slows the response and extends settling. The resulting maintenance logic prioritises calibration and condition monitoring for drift, rapid fault detection for abrupt disturbances, preventive servicing for delayed response, and inspection of wiring, grounding and shielding for noise. The framework offers a transparent way to connect simulated behaviour to maintenance decisions. Because the work used a representative simulated loop and engineering-judgment FMEA ratings rather than field failure records, the findings should be treated as a decision-support demonstration, not as a measured reliability improvement for a live plant.

Keywords: Failure Mode and Effects Analysis, Instrumentation Loop, MATLAB/Simulink, Petrochemical Process, Reliability-Centered Maintenance, Risk Priority Number, Sensor Drift

Introduction

Petrochemical process units depend on instrumentation and control (I&C) loops to measure and regulate variables such as level, pressure, temperature and flow. A typical loop combines a sensor and transmitter, a controller, a final control element and the process being controlled. A fault in any of these elements can distort the information used by the controller or weaken the corrective action applied to the process. The consequence may be poor product quality, unstable operation, avoidable maintenance work or, in more serious circumstances, a process-safety event.

Maintenance planning for such systems is challenging because the operational importance of a fault is not always proportional to how visibly it presents. A noisy signal may be obvious to an operator, whereas a drifting sensor can produce a plausible but incorrect measurement. A controller may therefore continue to regulate the process around an erroneous feedback value. Delayed actuation presents a different problem: the measured value may be credible, but the response arrives too late to maintain the desired dynamic performance. Maintenance programmes that rely only on fixed



intervals or repair after failure may not distinguish these risks adequately.

Reliability-centered maintenance provides a structured means of selecting maintenance tasks according to equipment function, failure mode and consequence rather than applying the same intervention to every component (Moubray, 1997; Nowlan & Heap, 1978). Failure Mode and Effects Analysis (FMEA) is often used within this process to identify how equipment may fail and to compare the relative importance of those failures. However, FMEA ratings can become detached from actual system behaviour if they are assigned without considering how faults influence the process.

This study addresses that practical issue by connecting MATLAB/Simulink fault simulations to an FMEA-based maintenance prioritisation process. A tank-level control loop is used as a representative instrumentation loop. The paper examines four fault conditions, ranks them using severity, occurrence and detectability, and translates the results into maintenance actions. The contribution is the integration of dynamic response observation and risk-based maintenance selection in a single, reproducible workflow. The study does not claim to establish plant-wide failure rates or validate the framework against live plant records; rather, it demonstrates how simulation can support the reasoning behind maintenance decisions.

Materials and Methods

Research Design and System Boundary

The study used a model-based engineering approach. A tank-level control loop was selected as a representative system because liquid level is a common controlled variable in process vessels and because its dynamics can be described through a material balance. The model boundary included the setpoint, PID controller, process representation, sensor/feedback path, actuator path and a transport-delay element. The model was developed in MATLAB/Simulink. The analysis compared normal operation with four fault scenarios: sensor drift, measurement noise, sudden fault injection and increased process delay.

Mathematical Representation

The tank process was represented using the liquid mass-balance principle. For a tank with constant cross-sectional area A , the dynamic relationship is expressed as:

$$A \frac{dh(t)}{dt} = q_{in}(t) - q_{out}(t)$$

where $h(t)$ is liquid level, $q_{in}(t)$ is inlet volumetric flow and $q_{out}(t)$ is outlet volumetric flow. The equation states that the rate of change in stored liquid is determined by the difference between inlet and outlet flow. The controller compares the reference level with the measured feedback signal and adjusts the control action to reduce the error. The model included a PID controller and feedback path, while the sensor and delay elements were modified to represent the fault cases. The model parameters and block settings followed the dissertation's simulation configuration; no plant-specific failure-rate dataset was used to estimate statistical reliability.

Fault Scenarios

Four scenarios were applied separately so that their effects could be distinguished. In the sensor-drift case, the sensor gain was changed from the nominal value of 1.0 to 1.2, introducing a biased measurement. For measurement noise, a band-limited white-noise block was configured with noise power of 0.05. Sudden fault injection was represented by a fault magnitude of 5 introduced at 50 s. For increased delay, the transport-delay setting was increased from 1 s under the comparison condition to 5 s. Simulation stop time was 100 s. These are model settings, not measurements of the frequency or magnitude of faults in an operating petrochemical plant.

Model Checking and Interpretation

The mathematical relationships, controller, feedback connections and fault blocks were checked against the intended Simulink architecture. The model was then run under normal conditions and under each fault condition. Response traces were interpreted in terms of measurement accuracy, signal fluctuation, transient disturbance, response speed and settling behaviour. The validation was behavioural and theoretical: no direct comparison with field measurements or hardware-in-the-loop tests was conducted.

FMEA and Maintenance Selection

Each failure mode was rated for severity (S), occurrence (O) and detectability (D) using the study's engineering-judgment scales. The Risk Priority Number was calculated as:

$$\text{RPN} = S \times O \times D$$

The study adopted the following decision bands: RPN $\geq$ 250, very high priority; 150–249, high priority; 100–149, moderate priority; and below 100, low priority. RPN was used as a screening and ranking aid. Since the scores depend on rating judgments, they should not be interpreted as probabilities or as a substitute for a detailed safety assessment. The final stage mapped each ranked failure mode to a maintenance response consistent with its observed behaviour.

Results

Behaviour Under Normal Operation

Under the normal model condition, the process output approached the desired operating level and the feedback signal remained comparatively stable. The response provided a baseline for assessing the effect of the injected faults. This behaviour indicates that the configured closed-loop model could represent the expected qualitative response of a tank-level controller, although it does not by itself establish that the model reproduces a particular plant installation.

Sensor Drift

With sensor drift introduced, the feedback measurement became biased relative to the process state. The controller therefore acted on inaccurate information, and the process settled at an incorrect operating point despite appearing relatively stable. This result is important from a maintenance perspective: stability alone is not evidence of measurement integrity. A control loop can appear calm while maintaining the process at a value different from the intended setpoint.

Measurement Noise

The noise case produced continuous fluctuations in the feedback signal. The controller responded to these variations, leading to repeated adjustments and reduced smoothness of the measurement signal. The overall process remained comparatively stable in the simulation, but the signal quality was degraded. In a real installation, the appropriate response would depend on whether the noise originates in the sensor, wiring, grounding, shielding, signal conditioning or communication path.

Sudden Fault Injection

The sudden fault introduced an abrupt deviation after the configured activation time. The system experienced a

transient disturbance before moving back toward relative stability. Of the simulated cases, this fault produced the most pronounced immediate disturbance. The result supports the need for effective alarms, fault detection and a clear response procedure for abrupt abnormal signals; it does not establish the probability of such an event occurring in a plant.

Increased Process Delay

Increasing the transport delay from 1 s to 5 s produced a slower response and longer settling behaviour than the baseline. The feedback remained comparatively smooth, but it represented process changes less promptly. This pattern is consistent with the risk posed by sluggish actuators, valve response problems or delays in the signal path. Maintenance checks should therefore assess dynamic response, not only whether a valve or transmitter passes a static functional check.

FMEA Ranking

Table 1 summarises the FMEA scores reported in the study. Sensor drift had the highest RPN, followed by sudden fault injection, increased process delay and measurement noise. The ranking reflects the combination of the three assigned ratings rather than a direct statistical estimate of risk. Sensor drift ranked first because it was rated severe and relatively difficult to detect, even though its effect could be gradual. Sudden fault injection had the highest severity score but a lower occurrence rating, giving it the second-highest RPN. Noise was rated as more frequent, but its lower severity and easier detectability produced the lowest RPN among the four cases.

Table 1. FMEA scores and maintenance priority

Failure mode	S	O	D	RPN	Priority
Sensor drift	8	6	7	336	Very high
Sudden fault injection	9	4	6	216	High
Increased process delay	7	5	5	175	Moderate–high
Measurement noise	5	7	4	140	Moderate

Discussion

The findings show why instrumentation maintenance benefits from considering the character of a fault as well as its numerical priority. Sensor drift is the clearest example.

Its main effect was not dramatic oscillation or immediate loss of control, but a persistent measurement bias that could cause the controller to maintain the wrong level. A maintenance programme that relies only on visible instability or operator complaints may miss this condition. Calibration history, comparison with independent measurements and monitoring of sustained deviation from expected process behaviour are therefore useful complements to routine checks.

The sudden-fault case presents a different maintenance problem. Its high severity rating reflects the abrupt deviation observed in the model. For this class of event, scheduled calibration alone is not a sufficient response. The maintenance system should also provide rapid detection, alarm handling, diagnostic checks and clear escalation arrangements. Where a loop performs a safety-related function, the design and testing of protective functions must follow the applicable functional-safety requirements; the present simulation should not be treated as a safety validation.

The increased-delay result indicates that static checks may not reveal every important degradation. A valve may move during a test yet respond too slowly under operating conditions. Periodic stroke-time checks, actuator servicing and review of loop trends can help detect this type of deterioration. For measurement noise, attention should be directed toward signal integrity: cable condition, grounding, shielding, terminals and signal-conditioning arrangements. Filtering may reduce visible noise, but it should be assessed carefully because excessive filtering can introduce additional delay and impair control performance.

The integrated workflow provides a practical bridge between simulation and maintenance planning. Simulation helps describe the way a fault affects the loop; FMEA makes the comparative assumptions explicit; and RCM translates the ranking into candidate tasks. This is consistent with the purpose of RCM, which is to preserve required system functions through technically appropriate maintenance rather than to maximise the number of maintenance activities (Moubray, 1997). The workflow can be repeated when plant engineers obtain better failure histories or when the model is extended to additional loops.

There are important limits to the interpretation. The RPN values rely partly on engineering judgment and the study's rating scales. Different teams or operating contexts may assign different values, and RPN multiplication can conceal different combinations of severity, occurrence and

detectability that yield the same product. The ranking should therefore be considered alongside consequence analysis, process criticality and applicable safety requirements. In addition, the simulated tank-level loop is a simplified representation; it cannot reproduce every influence found in a petrochemical unit, including nonlinear valve characteristics, changing process conditions, network effects, sensor ageing, interacting loops or simultaneous faults.

The paper also does not quantify reductions in downtime, maintenance cost or plant risk after implementation. Such benefits remain plausible objectives of the proposed approach, but demonstrating them would require a field trial with baseline and post-implementation data. In particular, operating records should be used to estimate failure frequency, repair duration, recurring failure mechanisms and the effectiveness of the selected maintenance tasks. The framework is best viewed as a structured starting point for this further work.

Maintenance Implications

The RCM actions arising from the ranking are summarised below.

1. Sensor drift (RPN 336): prioritise periodic calibration, inspection of sensing elements and condition monitoring for persistent bias or divergence between process and feedback values. Calibration intervals should ultimately be set using instrument criticality, manufacturer guidance and plant history.
2. Sudden fault injection (RPN 216): establish rapid fault detection and alarm-response procedures; review diagnostic coverage and verify that abnormal signals are escalated promptly. For safety-related loops, use the plant's approved proof-test and functional-safety arrangements.
3. Increased process delay (RPN 175): inspect control valves and actuators, assess valve response and stroke time, service moving parts as appropriate, and investigate communication or control-path delays.
4. Measurement noise (RPN 140): inspect wiring, terminals, grounding and shielding; review signal conditioning and communication quality; and verify that any filtering does not create unacceptable response delay.

These actions should not be adopted as universal maintenance intervals. They are task recommendations derived from the simulated fault patterns and the study's

FMEA scores. A plant implementation should review them with instrument engineers, operations personnel and process-safety specialists, then refine them using actual equipment criticality and maintenance records.

Limitations and Future Work

This study was limited to a single representative tank-level control loop and four separately simulated fault conditions. It did not include hardware-in-the-loop testing, field data validation, multiple simultaneous faults or a full plant-wide reliability model. The occurrence ratings were not calculated from observed plant failure frequencies, and the work did not establish measured changes in availability or maintenance cost.

Future work should validate the model against operating data from a petrochemical facility, using appropriately authorised and anonymised records. Additional scenarios should include actuator saturation, valve stiction, transmitter failure, communication interruption, controller malfunction and interacting faults. The FMEA ratings could be strengthened through a structured expert review and calibrated against historical work orders. A further step would be to compare the proposed maintenance tasks with actual outcomes over a defined monitoring period, using indicators such as repeat-failure rate, time to detect a fault, mean time to repair and loop performance. Extending the model to interconnected pressure, flow, temperature and level loops would also test the framework's usefulness in more complex process units.

Conclusion

This paper has presented a simulation-based framework that connects instrumentation fault behaviour, FMEA ranking and RCM maintenance selection. In the MATLAB/Simulink tank-level loop, sensor drift caused a stable but biased operating point, measurement noise degraded feedback-signal quality, sudden fault injection produced an abrupt transient disturbance, and increased process delay slowed the response. The FMEA produced RPNs of 336 for sensor drift, 216 for sudden fault injection, 175 for increased process delay and 140 for measurement noise. These results placed sensor drift first for maintenance attention, while highlighting that abrupt disturbances also warrant strong detection and response provisions.

The main practical value of the approach is the traceable link between an observed fault signature and a

maintenance action. Calibration and condition monitoring are appropriate candidates for drift; rapid detection is important for sudden disturbances; actuator and valve servicing addresses sluggish response; and signal-path inspection addresses noise. The framework is a decision-support method rather than evidence of a quantified reliability improvement. Field validation and the use of plant-specific failure and maintenance records are necessary before the numerical priorities or maintenance intervals can be generalised to an operating petrochemical facility.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Afolalu, S. A., Ojelabi, R. A., Odi-Owei, S., & Ongbali, S. O. (2018). Failure mode and effect analysis: A literature review. *European Journal of Engineering and Technology Research*, 3(11), 1–7.
- Bauer, M., Horch, A., Xie, L., Jelali, M., & Thornhill, N. F. (2016). The current state of control loop performance monitoring: A survey of application in industry. *Journal of Process Control*, 38, 1–10. <https://doi.org/10.1016/j.jprocont.2015.11.002>
- Braaksma, A. J. J., Klingenberg, W., & Veldman, J. (2013). Failure mode and effect analysis in asset maintenance: A multiple case study in the process industry. *International Journal of Production Research*, 51(4), 1055–1071.
- Geisbush, J., & Ariaratnam, S. T. (2023). Reliability centered maintenance (RCM): Literature review of current industry state of practice. *Journal of Quality in Maintenance Engineering*, 29(2), 313–337. <https://doi.org/10.1108/JQME-02-2021-0018>
- Huang, J., You, J. X., Liu, H. C., & Song, M. S. (2020). Failure mode and effect analysis improvement: A systematic literature review and future research agenda. *Reliability Engineering & System Safety*, 199, 106885. <https://doi.org/10.1016/j.res.2020.106885>
- International Organization for Standardization. (2017). ISO 14224: Petroleum, petrochemical and natural gas

industries—Collection and exchange of reliability and maintenance data for equipment. ISO.

Moubray, J. (1997). RCM II: Reliability-centered maintenance (2nd ed.). Butterworth-Heinemann.

Nowlan, F. S., & Heap, H. F. (1978). Reliability-centered maintenance. United States Department of Defense.

Seborg, D. E., Edgar, T. F., Mellichamp, D. A., & Doyle, F. J. (2017). Process dynamics and control (4th ed.). John Wiley & Sons.