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Comparative study of Bayesian network-based root cause analysis methods

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ABSTRACT

Root cause analysis (RCA) is central to biomanufacturing, improving product quality, diagnosing equipment failures and ensuring compliance with stringent safety and regulatory standards. Traditional RCA relies on expert knowledge and manual fault tracing, which becomes impractical as processes scale and complexity increases.

Data-driven RCA methods offer scalable alternatives, exploiting process data to detect faults and infer likely causes. Bayesian networks (BNs) are causality-based methods that explicitly model cause–effect relations and their propagation through process topology, while representing uncertainty via conditional probabilities.

We evaluate a two-stage Fault Detection and Diagnosis–Bayesian Network (FDD-BN) pipeline: first, multivariate or machine-learning FDD methods detect anomalies and nominate symptom variables; second, BNs perform probabilistic inference on candidate root causes. For each stage we compare representative techniques, including classical multivariate monitoring, supervised and unsupervised machine-learning detectors, and a selection of causal-discovery algorithms for BN structure learning from observational data.

Validation uses two industrial benchmarks: the Tennessee Eastman Process (TEP) and an industrial-scale penicillin simulation (IndPenSim), which present contrasting nonlinearity and distributional characteristics. Results indicate that machine-learning FDD methods deliver more consistent detection across both processes. Performance of causal-discovery methods, however, is sensitive to process nonlinearity, non-Gaussian behaviour and violations of algorithmic assumptions; incorporating domain priors improves structure recovery and diagnostic robustness.

The findings inform design choices for scalable, interpretable and auditable RCA systems in biomanufacturing and related process industries, and highlight the value of combining statistical monitoring, machine learning and causal inference under expert-informed

constraints.

KEY WORDS

root cause analysis, data-driven diagnosis; Bayesian network

BIOGRAPHY

Paul Ou is a PhD student at the School of Computing and Information Systems at the University of Melbourne, researching data-driven methods for modelling, optimising and validating digital bioprocess development as part of the ARC Digital Bioprocess Development Hub.

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