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Quantum Approaches for Reliability Estimation: A Systematic Literature Review

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Operational demands in industries, such as the energy sector, highlight the need for reliable equipment in the face of long-term planning and unpredictable factors. This extends to wind turbines, where reliability estimation is crucial for sustained productivity and cost-effective maintenance engineering. However, acquiring reliable data remains challenging due to the costs associated with experimental tests, particularly for emerging technologies with limited field information (Araújo et al., 2023).

Bayesian inference, known for its ability to update knowledge dynamically, is increasingly favored for estimating reliability during developmental stages, using data from various hierarchical system levels (e.g., system, subsystems, and components) (Hafeez and Aziz, 2022). Despite its effectiveness, conventional Bayesian methods face challenges in complex contexts, prompting an exploration of quantum methods (Layden et al., 2023).

Quantum computing, with properties like superposition and entanglement, shows promise in addressing challenges associated with classical methods. Its ability to process multiple solutions simultaneously could accelerate the evaluation of complex Bayesian models, providing an efficient alternative to classical sampling methods (Ohno, 2023). This literature review aims to explore trends and advances in applying quantum methods in Bayesian inference for equipment reliability estimation, guiding future research at the intersection of quantum computing and Bayesian inference in the realm of equipment reliability.

Quantum Bayesian Inference

According to (Fuchs and Schack, 2009), on the quantum spectra, the Bayes rule changes according to $p_{posterior}(\rho) = \frac{p_{prior}(\rho) * tr(\rho E_k)}{\int p_{prior}(\rho) * tr(\rho E_k) d\rho}$. In the new form the quantum version mixes both classical probabilities, p_{prior} and $p_{posterior}$, and quantum probabilities, encoded in the density operator ρ, in which a sequence of measurements E_k is required to estimate ρ. The sequence is usually constructed using a collection of positive operators acting on the Hilbert space such that $\sum_k E_k$ is the identity operator.

The systematic literature review employed diverse methodologies involving three key stages: initial planning, compilation, and curation of articles, and subsequent reporting of findings (Araújo et al., 2023). The Web of Science (WoS) database was chosen for its comprehensive coverage across various databases. Twelve distinct combinations were iteratively generated for search terms, reflecting the intersection of quantum computing, Bayesian inference, and reliability estimation.

During the collection and selection phase, specific criteria, including language and document type, were employed to screen articles. English-written content and document types, including conference papers, were considered due to the emerging nature of Quantum Computing research. The article selection process involved individual readings by two authors, resulting in the identification of 69 relevant articles. Abstract analysis in subsequent steps pointed the selection to 32 articles, with a final analysis identifying 16 papers directly aligned with the research scope. Notably, the relatively limited number of selected papers is acknowledged, considering the unrestricted time range under consideration.

We employed VOSviewer®, an open-source software tool, for a descriptive analysis of articles, generating network maps to illustrate relationships between keywords. This approach offers a comprehensive overview of key aspects covered in the 16 articles of Step 3, revealing keyword co-occurrence (Figure 1). The map's circles, representing keywords in document sources, vary in size based on keyword incidence, showcasing link strength.

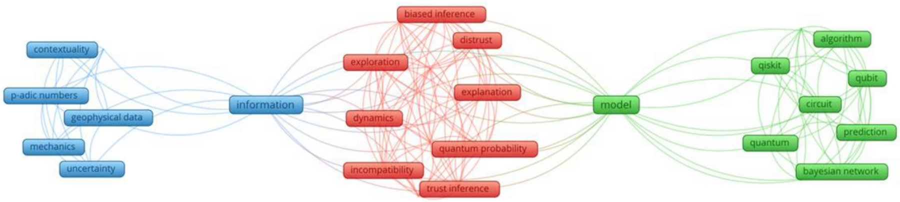

Fig. 1. Articles keywords co-occurrence network visualization.

Among 37 terms appearing in at least two articles, 'quantum Bayesian inference' stands out at the core, closely tied to practical applications like "intelligent hydrocarbon reservoirs" and addressing "extreme events" in power networks leading to "wildfires." Quantum technologies show interest in complex applications and are relevant in the contexts of "information" through a "trust model" and "finance."

The prevalent focus of the considered articles is predominantly theoretical, emphasizing conceptual frameworks over practical applications. Notably, the Quantum Bayesian Inference component, largely experimental, is applied in theoretical problem-solving, particularly in quantum state translation and measurement. However, its practical utilization, especially in parameter estimation for probability distributions, is currently absent in the literature.

A key observation is the prevailing emphasis on estimating the distribution of quantum entities' parameters rather than mapping classical information into the quantum realm. A literature gap identified is the absence of classical-to-quantum mapping, covering the process from encoding a problem with a specific prior distribution to its resolution. While some articles engage in this mapping process, they tend to favor Quantum Bayesian Networks over Quantum Bayesian Inference, potentially due to a lack of research on the latter subject.

Lastly, in the sampling procedure scenario, initial evaluations included quantum sampling concepts like Boson sampling, which may become a common approach in the future. Quantum methods for Markov Chain Monte Carlo are limited and predominantly experimental.

Ensuring equipment reliability is vital for the industry. This study focuses on quantum methods to enhance Bayesian frameworks and sampling techniques. Despite limited applications in the experimental field, the research agenda outlines key directions: (1) classical-to-quantum mapping, investigating methodologies for encoding classical data into the quantum domain; (2) distributions parameter estimation via quantum methods; (3) exploring the applicability of quantum sampling concepts, such as quantum Markov Chain Monte Carlo; (4) practical applications, exploring the real uses of Quantum Bayesian Inference, more specifically equipment reliability and risk assessment; (5) expanding Quantum Bayesian Inference, investigating advantages over classical methods in classical problem-solving contexts.

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References

Araújo, L.M.M., Maior, C.B.S., Lins, I.D., Moura, M.J. Das C., 2023. Technology selection and ranking: Literature review and current applications in oil & gas industry. Geoenergy Science and Engineering 226, 211771.

Fuchs, C.A., Schack, R., 2009. Priors in quantum Bayesian inference. arXiv preprint arXiv:0906.1714.

Hafeez, W., Aziz, N., 2022. Bayesian new group chain sampling plan for Poisson distribution with gamma prior through quality regions. Comput Ind Eng 174, 108826.

Layden, D., Mazzola, G., Mishmash, R. V., Motta, M., Wocjan, P., Kim, J.S., Sheldon, S., 2023. Quantum-enhanced Markov chain Monte Carlo. Nature 619 7969 , 282–287.

Ohno, H., 2023. Quantum Bayesian inference for parameter estimation using quantum generative model. Quantum Inf Process 22 1.