Quantum Resilience Digital Twin (QRDT)

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Abstract: QRDT develops an advanced Digital Twin platform integrating AI, HPC, and hybrid quantum-classical optimization to model, simulate, and enhance resilience of critical digital infrastructures, supporting decision-making, risk assessment, and scalable deployment across complex, high-impact operational scenarios.

The increasing complexity and interdependence of critical digital infrastructures, including energy systems, telecommunications networks, and cloud environments, require advanced approaches to ensure resilience, security, and operational continuity [1]. Traditional modelling and simulation techniques are often inadequate to capture the dynamic, stochastic, and highly interconnected nature of such systems, particularly under stress conditions, cascading failures, or cyber-physical threats [2].

The Quantum Resilience Digital Twin (QRDT) project addresses these challenges through an integrated technological framework that combines Digital Twin paradigms with Artificial Intelligence (AI), High Performance Computing (HPC), and hybrid classical-quantum computing techniques. The project is positioned within the landscape of deep-tech innovation.

The proposed QRDT platform is designed as a modular, scalable, and interoperable system capable of modelling and simulating the behaviour of critical infrastructures in real-time or near real-time conditions. Digital Twin models enable the virtual representation of infrastructure components and their interactions, allowing the analysis of system dynamics under both nominal and stressed operating conditions. These models are enhanced by AI-driven techniques supporting anomaly detection, predictive analysis, and scenario exploration.

The computational backbone of the platform relies on HPC infrastructures to perform large-scale simulations and high-fidelity analyses. In addition, QRDT introduces a novel layer of hybrid optimization based on the integration of classical and quantum computing approaches. These methods are particularly suited to address complex combinatorial optimization problems related to resilience planning, resource allocation, and response strategies, where traditional approaches may become computationally prohibitive.

A key aspect of the project is the validation of the proposed solution in realistic and operationally relevant scenarios[3],[4]. The platform is validated through the simulation of complex events, including system failures, cyber-attacks, and multi-domain disruptions, with the objective of assessing system resilience and supporting informed decision-making processes. The resulting technological demonstrator will provide evidence of the effectiveness, scalability, and applicability of the proposed approach.

The expected outcomes of QRDT include the development of a fully integrated prototype platform, advanced Digital Twin models for resilience assessment, and a library of hybrid optimization algorithms with comparative performance evaluation against classical methods. The project will also deliver comprehensive technical and architectural documentation to ensure interoperability, reproducibility, and future extensibility, along with a roadmap for industrial development and large-scale deployment.

By integrating heterogeneous computational paradigms into a unified framework, QRDT introduces an innovative approach to the management and optimization of critical infrastructures. The project is expected to significantly enhance resilience and security capabilities, improve decision-making processes for operators and policymakers, and contribute to the advancement of quantum computing applications in real-world contexts. Ultimately, QRDT supports the transition towards more robust, adaptive, and intelligent infrastructure systems, reinforcing the strategic autonomy of the European technological ecosystem.

References

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