Quantum Computing Applications

Table of contents

1. Introduction

For a long time, quantum computing was considered a technology for solutions in the distant future (fascinating, but out of reach). In the past few years, advances in quantum computer technology and rapidly growing interest in the potential of quantum computing have drastically changed this perception (Figure 1.1). This has led to the development of quantum software and middleware, and quantum computing development tools (Figure 1.2).

Figure 1.1: Enterprises are becoming "quantum ready" (source: Classiq 2025)

Figure 1.2: Quantum computing software and tools vendors (source: Olivier Ezratty 2025)[1]

[1] This overview does not include Chinese quantum computing start-ups.

A wide variety of quantum computing use cases has already been proposed, together with the development of associated application-specific quantum algorithm specifications. There are different kinds of quantum computing use case studies to be distinguished:

- real use case study (retrospective): description of deployment and/or usage of a quantum computing application in a real-world environment;
- intended use case study (prospective): description of a proposed quantum computing application;
- Proof-of-Concept (PoC) use case study: description of an experimental quantum computing application (the experiment has been performed using a real quantum computer and/or an emulator).

  Note
  Quantum emulators are often called "quantum simulators" but this is not the right term. Emulation is a technique that enables one system (the emulator) to behave (almost) exactly like another system (the target). Simulation is the imitation of the operation of a system over time and is based on a model which represents its key characteristics and behaviours.

Quantum computing use cases can either be implemented by solutions based on gate-based NISQ (Box 1.1) and FTQC (Box 1.2) quantum computers (described in [NOREA 2025] Quantum Computing Explained) or by solutions based on quantum annealing (described in [NOREA 2025] Quantum Annealing Explained).

Noisy Intermediate-Scale Quantum (NISQ) computing is a term, coined by the American theoretical physicist John Phillip Preskill in 2012, that applies to current state-of-the-art gate-based quantum computers. The term "noisy" refers to the fact that these quantum computers are very sensitive to perturbances caused by the surrounding environment and may lose their quantum state due to quantum decoherence because they are not sophisticated enough to implement Quantum Error Correction (QEC). The term "intermediate-scale" refers to the not-so-large number of qubits.

Box 1.1: Noisy Intermediate-Scale Quantum (NISQ)

A Fault-Tolerant Quantum Computer (FTQC) is a gate-based quantum computer that is made robust through deployment of QEC and other fault reduction techniques (e.g. reliable qubit control, qubit readout, etc.).

Box 1.2: Fault-Tolerant Quantum Computer (FTQC)

Several of the proposed quantum computing use cases have been implemented as PoCs (Figure 1.3), but only a few of them have currently been deployed and are being used in real-life production environments (Figure 1.4).

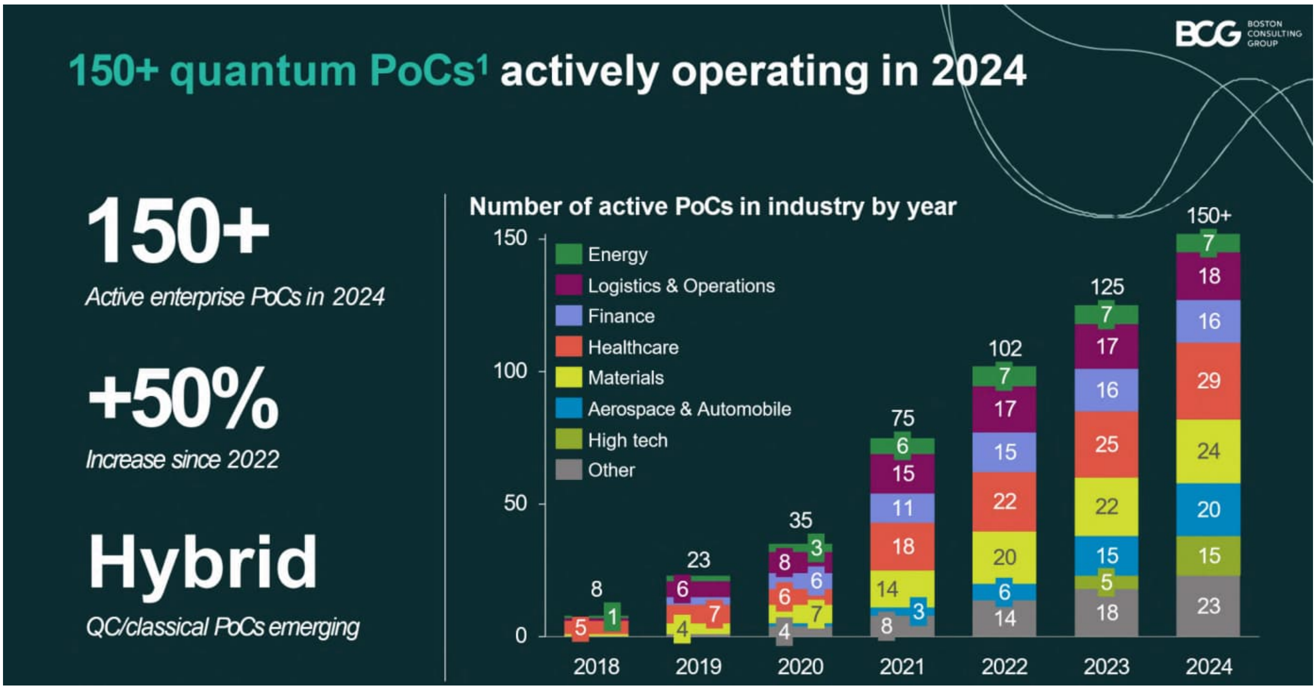


Figure 1.3: Quantum computing PoCs (source: BCG 2025)

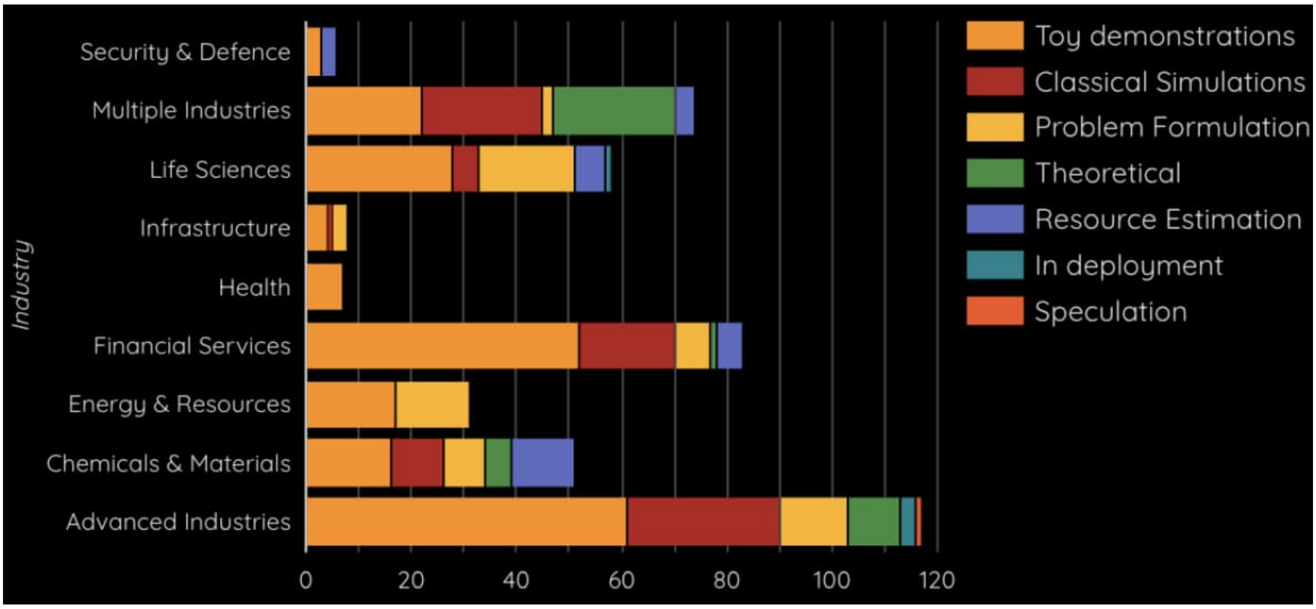


Figure 1.4: Implementation status of quantum computing use cases (source: M. Baczyk 2024)

Many quantum computing use case studies showcase how quantum computing might provide a business advantage for solving a particular (range of) business problem(s). Meanwhile, very few organisations have implemented the proposed solutions. The cause of such discrepancies is that most of these case studies are misleading about the real benefits of the proposed quantum computing solutions. To address this shortcoming, a framework for analysing quantum computing case studies has been developed (Figure 1.5).

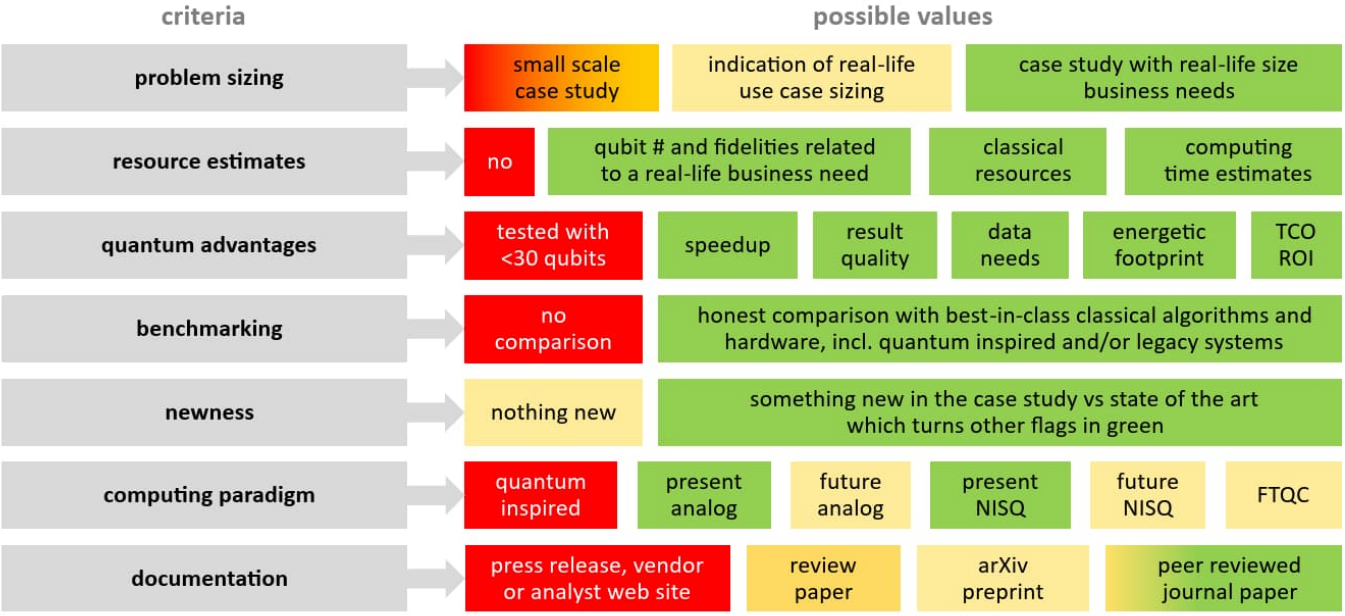


Figure 1.5: Framework for analysing quantum use case studies (source: Olivier Ezratty 2025)

Colour legend

- Red coloured values highlight deficiencies in the proposed quantum computing use case article that are responsible for the aforementioned discrepancies. Example: the article does not specify resource estimates.

- Orange and yellow coloured values indicate possible “showstoppers”. Example: the article does not provide a comparison of the quantum computing solution with available best-in-class classical solutions or the comparison is not fair (e.g. between an exact solution on one side and a heuristic approximate solution on the other side). Also note that there will be no business advantage when the quantum computing solution could be emulated on a classical system or has only been emulated.

- The yellow colour for the “future NISQ” and “FTQC” values indicates that the particular (range of) business problem(s) cannot be solved with currently available gate-based quantum computing hardware as it would require hundreds, thousands or more logical qubits. Such quantum computers will most probably not be available in the short-to-medium term.

- Green coloured values indicate that there could indeed be a real business advantage associated with a proposed quantum computing use case, if there are no red/orange/yellow coloured values for other criteria. Example: the proposed quantum computing solution can be executed on a currently available NISQ quantum computer.

Notes

1. Sustainability not only concerns energy consumption during system operation but also takes into account the environmental impacts of the production of the system hardware and the dismantling/recycling processes.

2. The definition of “quantum advantage” in Figure 1.5 differs from the commonly used definition, i.e. demonstrating that a quantum computer can solve a practical problem that no classical computer can solve in any feasible amount of time.

In 2023, an analysis of a significant number of quantum computing use case studies was performed (Figure 1.6). Most of these studies were found to be deficient with respect to several of the aforementioned evaluation criteria. Furthermore, very few of the proposed quantum computing use cases would bring real quantum speedup. In most cases, classical emulation of the solution turns out to be faster than the quantum version.

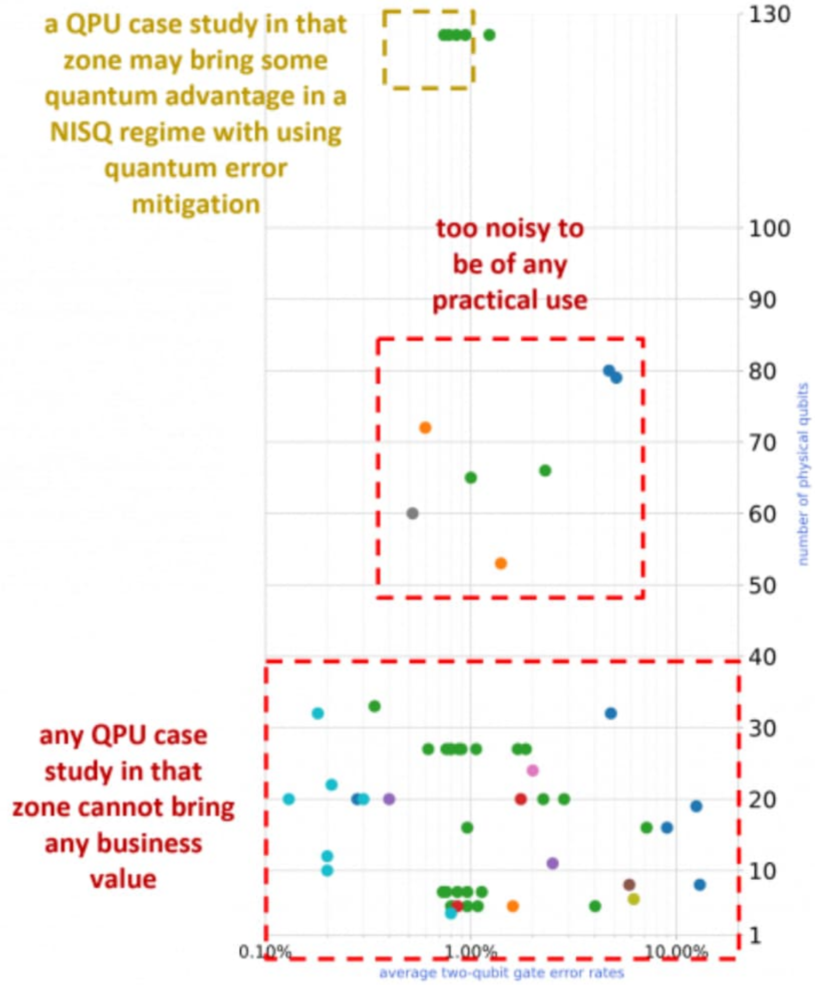


Figure 1.6: Analysis of quantum computing use case articles (source: Olivier Ezratty 2024)

To provide quantum speedup, the quantum algorithm underlying the solution should run efficiently on a quantum computer with quantifiable and reachable resource requirements and the computing time for any conceivable classical solution for the same task should be much longer (based on irrefutable evidence or else based on sufficiently reasonable assumptions[2]). However:

- The proposed quantum computing use cases often require an FTQC quantum computer supporting Quantum Error Correction (QEC). QEC technology is still in its very early stages and the pace of progress is difficult to predict as some difficult hurdles remain to be overcome.

---

[2] It is however extremely difficult to identify the best-in-class classical solution for a given problem.

The advent of FTQC will need substantial advances in both fundamental science and systems engineering; these are not expected to occur in the near future.

- The size of the quantum circuits, in particular the quantum circuit depth (i.e. the number of quantum gate operations, above all two-qubit operations) supported by today's most capable NISQ quantum computers is still very limited due to high error rates. Therefore, Quantum Error Mitigation (QEM) is essential for obtaining meaningful results from NISQ quantum computers. Though a variety of QEM techniques is available, the overhead incurred by sampling (unavoidable for NISQ) increases with quantum circuit size (exponentially in the worst case) and rapidly becomes impractical for large quantum circuits. Another major challenge is that current QEM techniques are mostly based on invariant noise models that are incompatible with the quantum-gate dependent noise that occurs in practice. After years of investigation, we still don't know whether NISQ quantum advantage will ever be attainable. Successful solutions to the identified obstacles have not yet been developed. Until now, efforts to realise quantum advantage in the NISQ era have largely focused on variational quantum algorithms, in particular for solutions that are based on combinatorial optimisation and machine leaning.
- It is sometimes claimed that quantum advantage has been achieved for a simulation or optimisation use case based on analogue quantum computing (e.g. quantum annealing). Though such solutions may be "quantumly easy", it is extremely difficult to pin down the classical computing hardness of performing the same task.

Note that the business advantage of quantum computing for solving a particular (range of) business problem(s) is not restricted to quantum speedup (Figure 1.7).

advantage	definition proposal
space	when the qubit register data space - scaling in 2^N complex numbers with N qubits - exceeds the memory capacity of classical computers.
speed	when a fully-burdened quantum algorithm, including its classical part, runs faster than an equivalent best-in-class entirely classical algorithms running on either the largest supercomputers or a given HPC configuration.
quality	when the quality of the results of a quantum algorithm is better for some respect than the best-in-class classical algorithms. It can relate for example to the error rate of some machine learning classification, to its explainability or to the precision of a chemical simulation to find the ground state energy of a many-body system.
energetic	when a fully-burdened quantum computer and algorithm configuration consumes less energy than the best-in-class classical equivalent. It becomes a sort of energetic supremacy if no classical computing configuration can solve the given problem.
cost	when the total cost of the quantum solution is lower than the total cost of a best-in-class classical solution. There are many ways to calculate this cost. It can be just about hardware and software or also include other incurred costs like people training and cost of software development.

Figure 1.7: Possible quantum computing business advantages (source: Olivier Ezratty 2024)

Be aware that real-life deployment of a quantum computing use case requires more than developing and testing an quantum application algorithm. It typically involves other important tasks such as:

- performing a feasibility study (including verification of quantum computing results[3] and providing convincing proof of quantum business advantage[4]), resulting in a go/no go decision (most of the proposed quantum computing use cases would certainly not pass given the current state of quantum computer technology);
- appropriate setting of algorithm parameters (e.g. the number of samples);
- providing input to the algorithm[5] and processing of algorithm results;
- selection of appropriate quantum computing platform (qubit technology modality, hybrid quantum-classical, on-premises, QCaaS, etc.) and platform configuration choices;
- implementing redundancy, back-up and recovery;
- implementing information security and privacy;
- availability and performance monitoring;
- ongoing maintenance and support;
- documentation.

---

[3] Classic verification is considered the best verification method, but unfortunately it is not a realistic option for certain use cases.

[4] The quantum versus classical comparison must be based on real-life scenarios and not on worst-case scenarios which can be unrealistic and/or unfavourable to classical solutions.

[5] A problem is that even though quantum computers can use a small number of qubits to represent an exponentially larger amount of data compared to classical computers, there is currently no method to rapidly convert a large amount of classical data to a quantum state.

2. Quantum computing use cases

Sections 2.2 through 2.16 provide a brief description of a representative sample of the many quantum computing use cases that have been developed or proposed for different application domains. To avoid misunderstandings regarding these use cases, it is important to know that:

1. The quantum computing use cases described in this chapter have been taken from publicly available literature.

2. Use case studies are not available for all the quantum computing use cases that have been included in this chapter. If available, it has not been verified whether or not these studies satisfy the criteria defined in Chapter 1.[6]

3. The focus is on opportunities offered by quantum computing and not on threats posed to today's cryptography. These threats are described in [NOREA 2025] Post-Quantum Migration.

Readers who are not familiar with (a) particular application domain(s) may skip the corresponding section(s) in this chapter.

Readers who are not familiar with quantum computing methods and techniques may skip section 2.1 and the quantum circuit diagrams and other technical details that have been included in the description of some quantum computing use cases in sections 2.2 through 2.16.

[6] Russ Fein, venture investor with deep interests in quantum computing and author of the Quantum Leap blog: "The evolving quantum computing industry has reached a critical juncture where legitimate scientific progress coexists with significant hype, marketing spin, and even outright fraud. For readers without deep technical backgrounds, distinguishing between genuine breakthroughs and overstated claims has become increasingly challenging."

2.1. “Toolbox” quantum algorithms

Quantum application algorithms are developed by hardware and software quantum computing vendors, (together with) their partners and users, and also by academic researchers. Several of these quantum application algorithms are generic, some of which can be used as such in multiple domains, while others need to be modified to the specific characteristics of the domain. Most quantum application algorithms also need be tailored to fulfil the specific needs of organisation specific use cases.

“Toolbox” quantum algorithms, which are described in [NOREA 2025] Quantum Algorithms and [NOREA 2025] Quantum Annealing Explained, may be used when developing application-specific quantum algorithms. Commonly used “toolbox” quantum algorithms across multiple application domains include:

- Quantum Amplitude Amplification (QAA):

  QAA was invented in 2002 by the Canadian computer scientist Gilles Brassard, the Canadian mathematician and computer scientist Michele Mosca, the Danish computer scientist Peter Høyer and the Canadian mathematician, physicist and computer scientist Alain Tapp. It is used to change the probability distribution modelled by a quantum state by increasing the probability of measurement of so-called marked items. It was used by Lov Grover to improve his algorithm for unstructured search.

- Grover’s Algorithm (GA):

  Grover’s quantum search algorithm, invented in 1996 by the Indian-American computer scientist Lov Kumar Grover, provides at its best a quadratic speedup over classical computer search algorithms. It is therefore generally believed that currently widely used cryptographic hash functions, Message Authentication Codes (MACs) and symmetric cryptographic algorithms are resistant to attacks by means of future powerful quantum computers, provided sufficiently large (underlying) hash values, MAC codes and cryptographic keys are being used.

- Quantum Amplitude Estimation (QAE):

  QAE, invented in 2002 by Gilles Brassard and his colleagues, is used to amplify and select the desired state of a quantum superposition. It is used for solving combinatorial search and optimisation problems.

- Quantum Fourier Transform (QFT):

  QFT, invented in 1994 by the American mathematician and computer scientist Don Coppersmith, is the quantum equivalent of the classical FT algorithm (Box 2.1.1).

The Fourier Transform (FT), named after the French mathematician and physicist Jean-Baptiste Joseph Fourier, is a mathematical decomposition of a time domain signal into elementary single frequency signals with their frequency, amplitude and phase. It is a complex value function of time with, for each frequency, a magnitude (real part) and a phase offset (complex part) of the sinusoid of this elementary frequency.

Box 2.1.1: Fourier Transform (FT)

- Quantum Phase Estimation (QPE):

  QPE, invented in 1995 by the Russian theoretical physicist Alexei Kitaev, is based on QFT and modular exponentiation to find the phase of the eigenvalues (Box 2.1.2) of a unitary matrix or quantum sub-circuit (Box 2.1.3). It is used in many quantum algorithms for solving linear algebra equations (Box 2.1.4).

The Hamiltonian of a system (named after the Irish mathematician and physicist William Rowan Hamilton) is an operator corresponding to the total energy of that system, including both kinetic energy and potential energy. Its spectrum, the system's energy spectrum or its set of energy eigenvalues, is the set of possible outcomes obtainable from a measurement of the system's total energy.

An eigenstate[7] is the measured state of some object possessing quantifiable characteristics such as position, momentum, etc. (the word "eigenstate" is derived from the German word "eigen", meaning "inherent" or "characteristic"). The state being measured and described must be observable (i.e. something such as position or momentum that can be experimentally measured either directly or indirectly) and must have a definite value, called an eigenvalue.

Box 2.1.2: Hamiltonian and eigenstate/eigenvalue of a system

Quantum gates apply a unitary matrix of complex numbers to qubit state vectors (a quantum gate that acts on n qubits is represented by a 2^n x 2^n unitary matrix). The action of the quantum gate on (a) specific qubit(s) is found by multiplying the vector that represents the

[7] In the everyday world, it is natural and intuitive to think of every object being in its own eigenstate; this is just another way of saying that every object appears to have a definite position, a definite momentum, a definite measured value and a definite time of occurrence. However, in quantum mechanics, Heisenberg's uncertainty principle (named after the German theoretical physicist Werner Karl Heisenberg) implies that it is impossible to measure the exact value for the momentum of a particle, given that its position has been determined at a given instant and likewise, it is impossible to determine the exact location of that particle once its momentum has been determined at a particular instant. Therefore, it becomes necessary to formulate clearly the difference between the state of something that is uncertain and the state of something having a definite value. When an object can definitely be "pinned down" in some respect, it is said to possess an eigenstate.

quantum state of the qubit(s)[8] by the unitary matrix that represents the quantum gate; the result is another vector that represents the new quantum state of the qubit(s).

A unitary matrix is an invertible complex square matrix U whose inverse matrix U^{-1} equals its Hermitian adjoint $U^{\dagger}$, i.e. $U^{\dagger} U = U U^{\dagger} = I$, where I is the identity matrix (a square matrix with ones in the top-left to bottom-right diagonal and zeros elsewhere). This follows from $U^{-1} U = U U^{-1} = I$ (the definition of inverse matrix). An important property of unitary matrices (aka unitary operators) is that they preserve norms and thus preserve probability amplitudes.

The Hermitian adjoint $U^{\dagger}$ of a square complex matrix U is obtained by transposing the matrix, i.e. exchanging its rows and columns and then applying complex conjugation to each entry of the transposed matrix, i.e. replacing a + i b by a – i b.

Box 2.1.3: Unitary matrix applied by quantum gate on qubit(s)

Linear algebra is the branch of mathematics concerning linear equations and their representations in vector spaces and through matrices. Linear algebra is used in most sciences and fields of engineering because it allows modelling many natural phenomena and computing efficiently with such models.

A linear equation is an equation that may be put in the form $a_1x_1 + \ldots + a_nx_n = b$,where $x_1, \ldots, x_n$ are the variables and $a_1, \ldots, a_n$ and b are the coefficients. The coefficients (aka parameters) may be arbitrary expressions, provided they do not contain any of the variables.

Box 2.1.4: Linear algebra equations

- Shor's quantum algorithms:

  Based on QFT/QPE, the American mathematician Peter Williston Shor invented in 1994 the period-finding quantum algorithm and the quantum algorithms for solving the integer factoring and discrete logarithm (dlog) problems, both of which are instances of the period-finding algorithm. Shor's algorithms consist of both a quantum and a classical component. Shor's algorithms quantum algorithms provide an exponential speedup over their classical counterparts. It is therefore generally believed that future powerful quantum computers will be capable of breaking many widely used classical public-key cryptographic schemes, including secret key exchange mechanisms and digital signature mechanisms.

[8] The combined quantum state vector for a set of n qubits is the tensor product of the constituent qubit quantum state vectors, i.e. a vector containing 2^n entries.

- Harrow, Hassidim and Lloyd (HHL):

  HHL was invented in 2009 by the American physicist Aram Wettroth Harrow, the Israeli computer scientist Avinatan Hassidim and the American mathematician and philosopher Seth Lloyd. It calculates the inverse of a large matrix and enables solving of linear equations (Box 2.1.5 and Box 2.1.6).

An Ordinary Differential Equation (ODE) is an equation which involves a single-variable function and its derivatives.

Box 2.1.5: Ordinary Differential Equation (ODE)

A partial derivative of a function of several variables is its derivative with respect to one of those variables, with the others held constant (as opposed to the total derivative, in which all variables are allowed to vary). Partial derivatives are for example used in vector calculus. A Partial Differential Equation (PDE) s an equation which involves a multivariable function and one or more of its partial derivatives. The Schrödinger wave equation (named after the Austrian-Irish theoretical physicist Erwin Rudolf Josef Alexander Schrödinger) is a PDE.

Box 2.1.6: Partial Differential Equation (PDE)

- Quantum Monte Carlo (QMC):

  QMC encompasses a large family of computational methods using some form of stochastic sampling. The diverse flavours of QMC approaches all share the common use of the Monte Carlo (MC) method. This method refers to a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The underlying concept is to use randomness to solve problems that might be deterministic in principle. The name comes from the Monte Carlo Casino in Monaco, where the primary developer of the MC method, the Polish-American mathematician, nuclear physicist and computer scientist Stanisław Ulam (who participated in the Manhattan Project), was inspired by his uncle's gambling habits.

- Quantum Machine Learning (QML):

  QML is a very broad topic and includes several quantum machine learning methods, most of which are quantum variants of classical machine learning methods (Figure 2.1.1).

  Unsupervised QML is a method where, in contrast to supervised QML, quantum algorithms learn patterns exclusively from unlabelled data.

  Many QML methods are based on Quantum Neural Network (QNN) variants, which combine classical Artificial Neural Network (ANN) methods with the advantages of quantum computing, in order to develop more efficient solutions.

QML-based quantum computing use cases often assume the use of some kind of quantum memory (qRAM). However, proposals for the development of qRAM technology have sparked significant controversy and most current qRAM proposals fall short in one aspect or another.

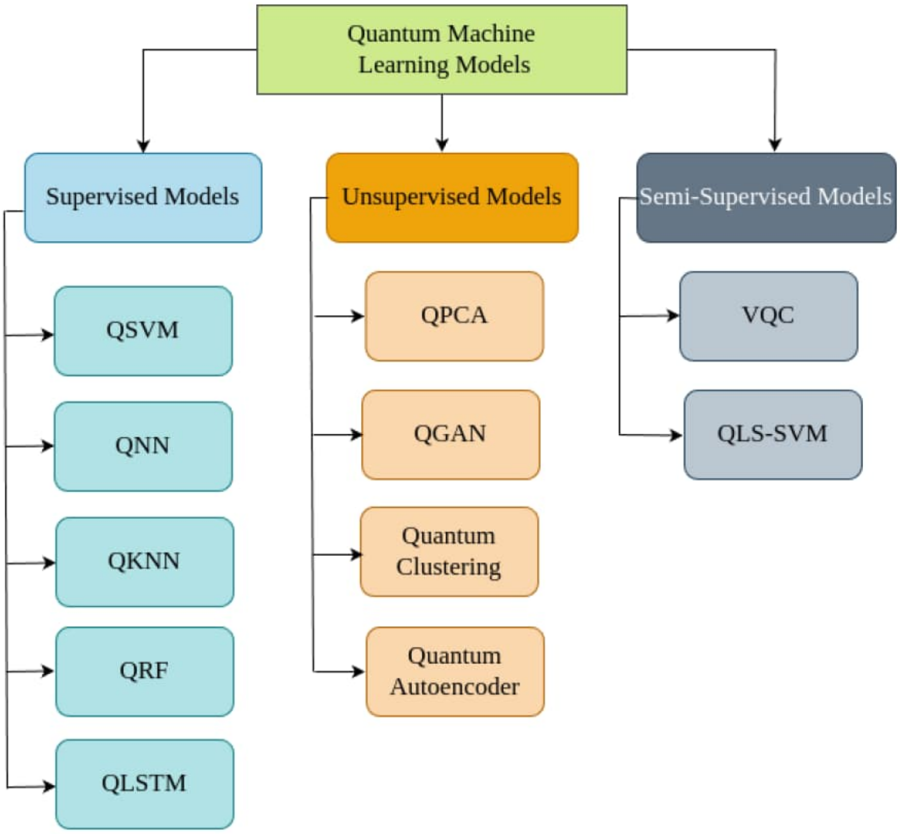


Figure 2.1.1: QML models (source: Ubaid Ullah and Begonya Garcia-Zapirain 2024)

Examples of QML methods include:

- Quantum Reservoir Computing (QRC):

  Reservoir computing is a machine learning method derived from ANN methods that maps input data into higher dimensional computational spaces through the dynamics of a fixed, non-linear system, called a reservoir. After the input data has been fed into the reservoir (which is treated as a black box), a simple readout mechanism is trained to read the state of the reservoir and map it to the desired output. The key benefit of reservoir computing is that neural network training is performed only at the readout stage, as the reservoir dynamics are fixed.

  QRC is an hybrid quantum-classical QML method which encodes the classical input data into quantum states, thus allowing for rich, high-dimensional representations of the data in the reservoir. A classical linear model then reads out the desired output from the reservoir's state, eliminating the need to optimise complex quantum parameters and avoiding the barren plateau problem (Box 2.1.7).

The barren plateau problem is a major challenge for QML, where the objective function's gradient flattens with increasing number of qubits thus creating vast, flat regions in the optimisation landscape that make it extremely difficult to find the global minimum. It is the equivalent of local minima traps in classical machine learning, when a global minimum is searched but difficult to reach due to the vanishing gradient problem.

Box 2.1.7: Barren plateau problem

- Quantum Support Vector Machine (QSVM):

  Support Vector Machine (SVM) is a machine learning method used to classify data into labels by finding the hyperplane that maximises the width that separates the labels in the data. When the data is distributed in such a way that no optimal hyperplane can be found, SVM uses kernel mechanisms to make classification still possible.

  A kernel is a mapping feature that takes data points and maps them into a new domain that makes the dataset easier to classify (e.g. by adding new dimensions to the data). To achieve superior mapping results, QSVM uses quantum kernels based on quantum computing mechanisms that are not available to classical computing (e.g. qubit superpositions and quantum gates that apply rotations to qubit states).

- quantum Principal Component Analysis (qPCA):

  The qPCA quantum algorithm is a quantum-enhanced version of the classical Principal Component Analysis (PCA) algorithm, designed for feature extraction involving quantum-encoded datasets. It identifies principal components as quantum states, leveraging quantum computing to efficiently process high-dimensional data and potentially offer speedups over classical methods. qPCA is crucial for dimensionality reduction in quantum-encoded datasets, preserving essential data structure while reducing the amount of extracted features.

- Quantum Natural Language Processing (QNLP):

  QNLP is the application of quantum computing to Natural Language Processing (NLP). QNLP computes word embeddings as Parameterized Quantum Circuits (PQCs). PQC parameters are optimised using QML methods. QNLP is still in its early stages of development and its application is currently limited to small datasets due to the constraints of current quantum computer hardware.

- Variational Quantum Algorithm (VQA):

According to the variational principle of quantum mechanics, the computed energy of the ground (lowest-energy) state of a quantum system decreases as the approximations to the solution improve, asymptotically approaching the true value from above. This principle has given rise to iterative algorithms for solving these problems, where a crude guess of the solution is the input, and a somewhat improved approximation is the output. This output is then used as the guess for the next iteration, and, with each cycle, the output gets closer and closer to the true solution (but never overshooting).

This approach can be split between a classical and a quantum part, with a quantum computing based iteration step and a classical computing based control step (e.g. based on an objective function, Box 2.1.8) deciding whether to perform another iteration (Figure 2.1.2). The ability to separate the quantum processing among many small, independent steps, with qubit coherence required only over the course of a single step, makes this approaches a clever way to reduce qubit fidelity requirements and still obtain useful results.

An objective function is either a cost function (aka loss function) or a profit function (aka reward function), which an optimisation problem seeks to minimise (cost function) or maximise (profit function).

Box 2.1.8: Objective function

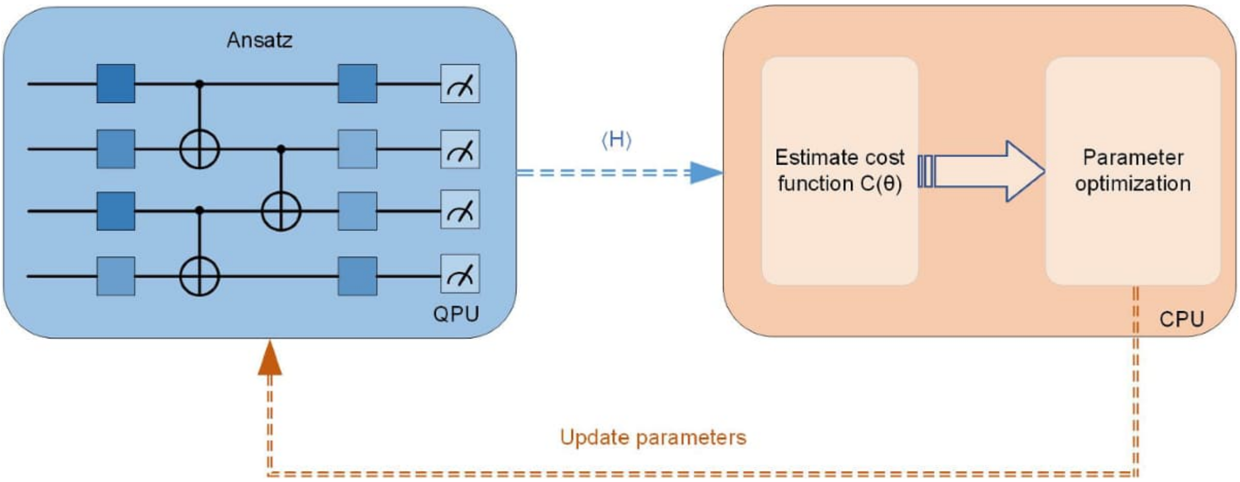


Figure 2.1.2: VQA iterations (source Han Qi et al. 2024)

VQAs require a Parameterized Quantum Circuit (PQC) that takes in a set of parameters that must be optimised. Its initial value is known as the “Ansatz” [9].

Prominent examples of VQA methods include:

- Quantum Approximate Optimization Algorithm (QAOA):

  QAOA (Figure 2.1.3), invented in 2014 by the American physicist Edward Henry Farhi, is used for various optimisation tasks. As its name implies, it provides only approximate results.

[9] “Ansatz” is German for “approach” (“Ansatzpunkt” means “starting point”). There is no one-size-fits-all approach for Ansatz design as the effectiveness of an Ansatz depends on the specific problem to be solved and the capabilities of the quantum hardware.

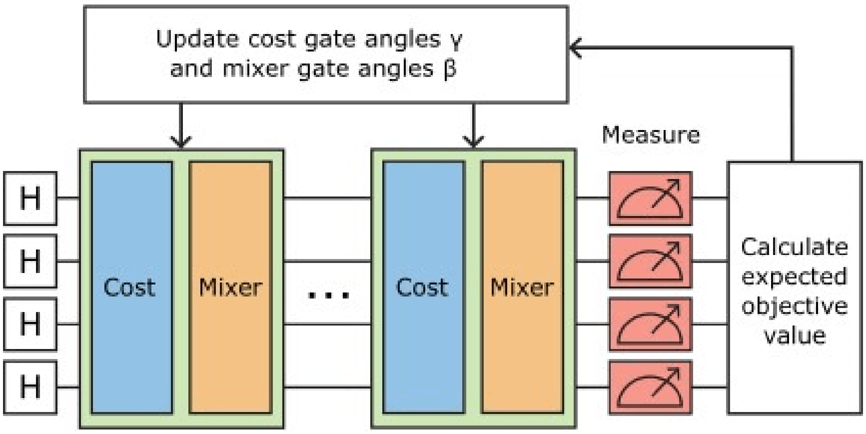


Figure 2.1.3: QAOA quantum algorithm (source: MATLAB 2025)

- Variational Quantum Eigensolver (VQE):

  VQE (Figure 2.1.4), invented in 2013 by the Mexican chemical engineer and computer scientist Alán Aspuru-Gurzik and others, can be viewed as a generalisation of QAOA, providing more flexibility in the choice of quantum circuits and optimisation strategies. VQE was initially developed for quantum chemistry applications but has been adapted to solve arbitrary combinatorial optimisation problems.

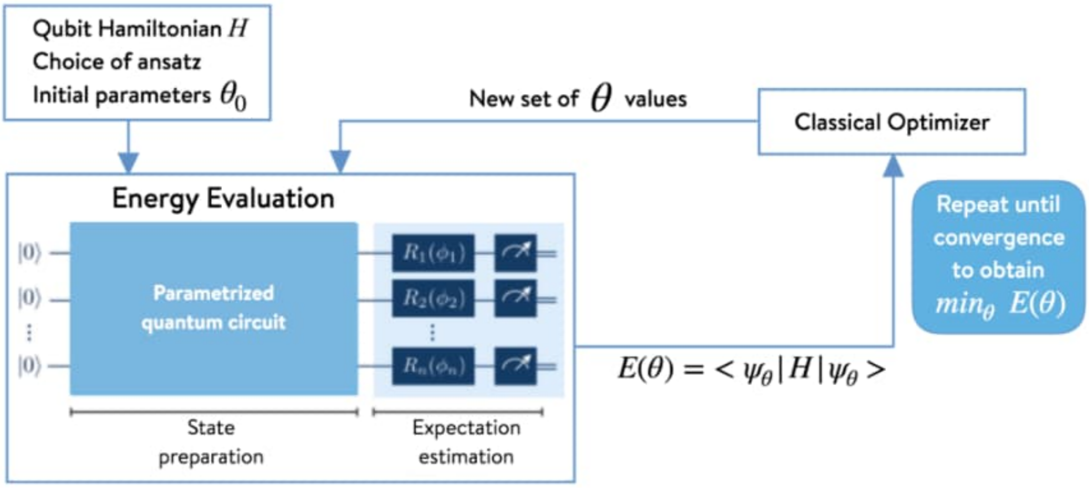


Figure 2.1.4: VQE quantum algorithm (source: Q-munity 2025)

  VQE aims to obtain the lowest eigenvalue of a specific "qubitised" Hamiltonian, using an hybrid variational method.

The variational quantum computing method, which can be further expanded by QML methods, provides quantum simulation solutions for use cases across multiple application domains (Figure 2.1.5).

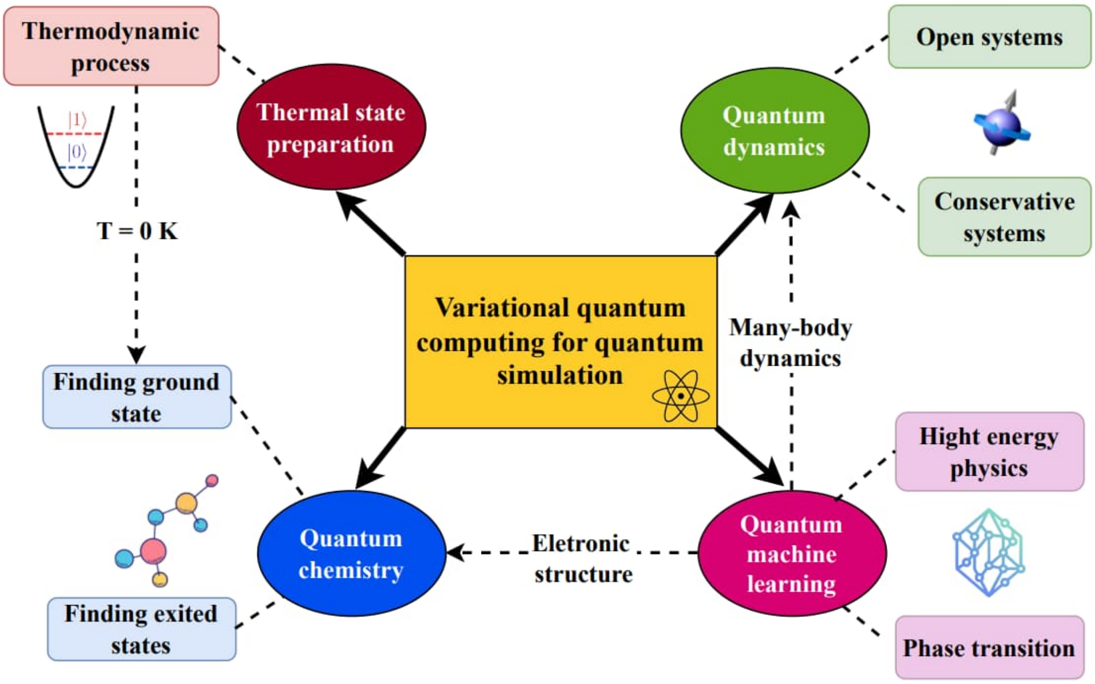


Figure 2.1.5: VQA-based simulations (source: L.Q. Galvão et al. 2025)

- Quadratic Unconstrained Binary Optimization (QUBO):

  The QUBO problem is a mathematical model used to represent complex optimisation problems in a standardised form. The term “binary” refers to the fact that the mathematical form is expressed only in linear terms composed of a constant and a binary variable. The term “quadratic” refers to the maximum power (i.e. two) of the variables in the objective function. The term “unconstrained” refers to the fact that there are no explicit constraints on the binary variables, though the QUBO method allows for penalising potential solutions that violate constraints by embedding these constraints in the objective function. A common way to formulate a QUBO is to express its terms as a matrix.

  The QUBO model is mathematically equivalent to the Ising model (Box 2.1.9) by associating the binary QUBO variables with the Ising spin values.

The Ising model aka Lenz-Ising model, named after the German physicists Wilhelm Lenz and Ernst Ising, is a mathematical model of ferromagnetism in statistical mechanics. The model consists of discrete variables that represent magnetic dipole moments of atomic spins that can be in one of two states (+1 or −1). The spins are arranged in a graph, usually a lattice (where the local structure repeats periodically in all directions), allowing each spin to interact with its neighbours. Neighbouring spins that agree have a lower energy than those that disagree. The system tends to the lowest energy, but heat disturbs this tendency, thus creating the possibility of different structural phases. The model allows the identification of phase transitions as a simplified model of reality.

Box 2.1.9: Ising model

QUBO problems can be solved by quantum annealing or by VQE or QAOA and gate-based quantum computing. One looming question is whether QAOA on gate-based quantum computers is more efficient than QUBO on quantum annealers.

- Binary Quadratic Model (BQM):

  The BQM model (Figure 2.1.6) defines an objective function that is to be optimised with a quadratic component and binary variables. Many combinatorial and optimisation problems such for example QUBO problems and the Ising model can be translated or converted into BQM. BQM problems can be solved by quantum annealing or by QAOA and gate-based quantum computing.

- Discrete Quadratic Model (DQM):

  The DQM model (Figure 2.1.6) defines an objective function that is to be optimised with a quadratic component and discrete variables (taking multiple values). DQM problems can be solved by quantum annealing or by QAOA and gate-based quantum computing.

- Constrained Quadratic Model (CQM):

  The CQM model (Figure 2.1.6) defines an objective function that is to be optimised with a quadratic component, discrete or continuous variables (taking multiple values), and constrains defined on these variables. CQM problems can be solved by quantum annealing or by QAOA and gate-based quantum computing.

Feature	BQM (Binary Quadratic Model)	DQM (Discrete Quadratic Model)	CQM (Constrained Quadratic Model)
Variables	Binary only ({0, 1} or {-1, +1})	Discrete (e.g., {red, green, blue} or {3.2, 67})	Binary, integer, and real (continuous)
Constraints	No native support (constraints must be modeled as "soft" penalties in the objective function)	No native support (constraints must be modeled as "soft" penalties)	Native support for linear and quadratic equality/inequality constraints
Generality	Least general	More general than BQM	Most general; BQM and DQM are subsets of CQM
Typical Use	Unconstrained binary decision problems (e.g., yes/no questions)	Problems where variables need to select from a small set of discrete choices (e.g., job scheduling)	Complex, real-world optimization problems with many variables and explicit constraints (e.g., vehicle routing)

Figure 2.1.6: BQM, DQM and CQM comparison (source: Google AI 2025)

2.2. Financial services

The financial services sector has historically been an early adopter of advanced computing technologies to gain a competitive edge. The use of quantum computing is now being explored.

The field of quantitative finance includes portfolio optimisation (Box 2.2.1), derivative pricing (Box 2.2.2), options pricing (Box 2.2.3), risk management (Box 2.2.4), credit scoring (Box 2.2.5) and algorithmic trading (Box 2.2.6).

> Several portfolio optimisation tasks are performed by financial institutions. One of these is to optimise their returns, spreading the risks, and estimate the Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR), which quantifies the maximum expected loss with a certain degree of confidence over a defined period and for a given confidence interval.

Box 2.2.1: Portfolio optimisation

> Derivatives are financial contracts whose value is derived from an underlying asset, such as stocks, bonds, commodities or market indices. Derivative pricing involves determining the fair value of these contracts based on several factors (current market conditions, price of the underlying asset, time of expiration, interest rates, market volatility, etc.). Derivative pricing covers options, futures, swaps and forwards. It is based on solving linear systems including matrix inversions, linear regressions, matrix powers and Markov chain time discretisation. A Markov chain (aka Markov process), named after the Russian mathematician Andrey Andreyevich Markov, is a stochastic process describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event.

Box 2.2.2: Derivative pricing

> Options pricing is a subset of derivative pricing that deals with valuing options contracts. An option gives the holder the right, but not the obligation, to buy or sell an underlying asset at a predetermined price (strike price) within a specified period (expiration date). Options can be classified into call options (giving the right to buy the underlying asset) and put options (giving the right to sell the underlying asset).

Box 2.2.3: Options pricing

> Risk management assesses and analyses the potential outcomes of an investment or portfolio based on probabilistic models and random sampling.

Box 2.2.4: Risk management

> Credit scoring is used for determining the probability that a client will reimburse his loan.

Box 2.2.5: Credit scoring

> Algorithmic trading (aka algo trading) uses computing algorithms to execute trades in financial markets, allowing for high-speed, automated decision-making and order placement with minimal human intervention.

Box 2.2.6: Algorithmic trading

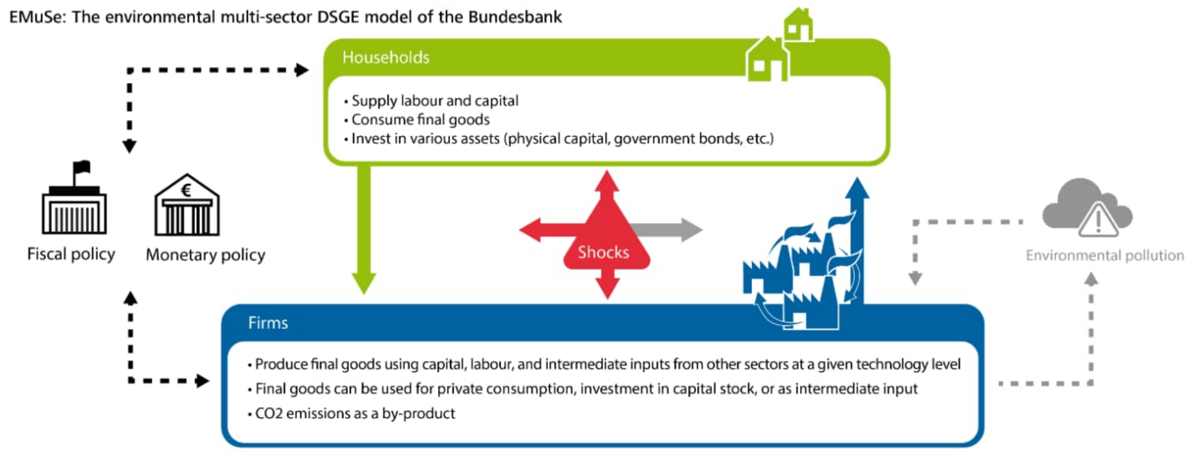
Financial quantum computing applications for the banking and insurance sectors are commonly classified as simulations, optimisations and machine learning tasks (Figure 2.2.1).

problem category	use cases	classical solutions	quantum solutions (NISQ)	quantum solutions (FTQC)
simulation	• derivative pricing. • risk analysis (Basel, Solvency). • financial econometrics. • maximum likelihood estimation. • dynamic stochastic general equilibrium modelling (DSGE). • dynamic economic models.	• Monte Carlo integration. • machine learning. • Black-Scholes model.	• quantum machine learning (variational methods).	• quantum amplitude estimation in quantum Monte Carlo methods. • quantum machine learning (HHL-based methods).
optimization	• portfolio optimization. • trading optimization. • hedging. • optimal arbitrage. • credit scoring. • financial crash prediction.	• discrete/continuous variables. • branch-and-bound for non-convex cases. • interior-point methods for certain convex cases.	• quantum optimization (QAOA or QUBO based) on analog QPUs. • reverse quantum annealing. • VQE methods.	• quantum walks. • Grover and Simon oracle-based searches.
machine learning	• anomaly and fraud detection. • natural language modeling. • risk clustering. • modeling credit spread. • product recommendation.	• regression, classification, clustering, PCA. • deep learning. • unsupervised cluster analysis.	• quantum machine learning (SVM, PCA, …), variational. • quantum deep learning, variational. • quantum cluster analysis (analog).	• quantum SVM, PCA. • quantum deep learning (QCNN, QGAN, QGNN, …)

Figure 2.2.1: Financial services use case overview (source: Dylan Herman et al. 2024)

DSGE (Box 2.2.7) is largely based on the ability to solve linear systems of equations, which could be done with the HHL quantum algorithm on FTQC quantum computers.

Dynamic Stochastic General Equilibrium (DSGE) is a macroeconomic modelling framework used by policymakers to analyse economic phenomena, forecast economic conditions, and simulate the effects of policy decisions. These models represent the economy as a system of optimising agents (households and businesses) interacting over time, incorporating random shocks and dynamic relationships to explain and predict economic trends. Example: Deutsche Bundesbank's Environmental Multi-Sector (EMuSe) DSGE model.



Box 2.2.7: DSGE framework (source: AQT 2025)

Quantum annealing PoCs for portfolio optimisation and options pricing are commonly based on QUBO formulations. NISQ PoCs are mainly based on the VQE and QAOA variational quantum algorithms. FTQC PoCs are based on the QAE, HHL, QAOA quantum algorithms and QMC methods.

Risk management is usually based on QMC methods to estimate the range of possible outcomes and their associated probabilities; this use case requires a large number of runs on a powerful FTQC quantum computer.

Production-scale credit scoring will require an FTQC quantum computer with thousands of logical qubits, e.g. to implement the Interpretable Quantum Neural Network for Credit Scoring (IQNN-CS) method (Figure 2.2.2).

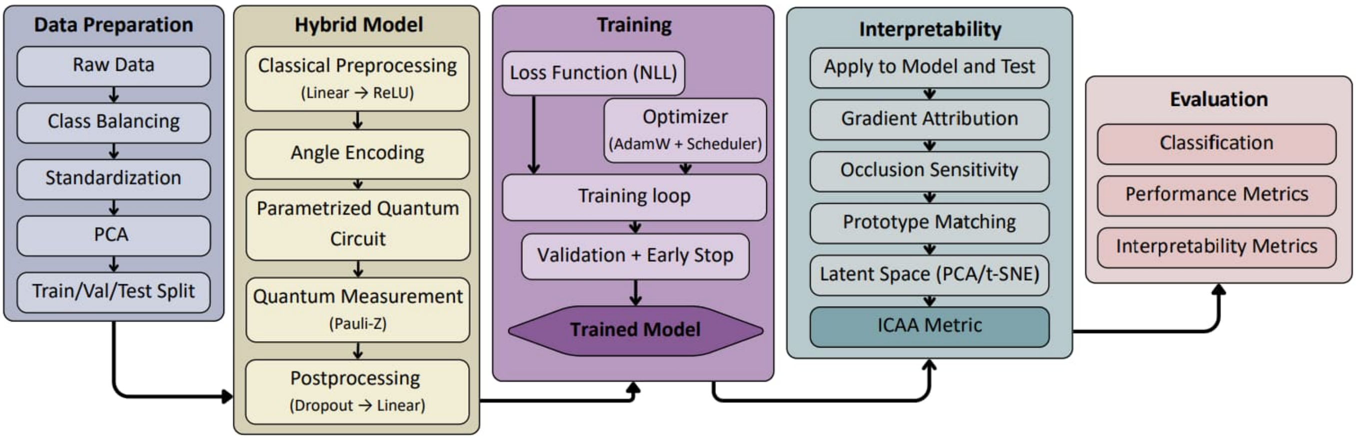


Figure 2.2.2: IQNN-CS method (source: Abdul Samad Khan et al. 2025)

The hybrid quantum-classical IQNN-CS method is based on several underlying classical and quantum computing methods, including:

- the Principal Component Analysis (PCA) machine learning algorithm;
- the Rectified Linear Unit (ReLU) neural network activation function which introduces non-linearity (by outputting the input if it is positive, and outputting zero if it is negative) and also helps preventing the vanishing gradient problem;
- a Parameterized Quantum Circuit (PQC);
- the angle encoding method, to map classical data onto quantum states (using a single feature from the data to set the rotation angle of the PQC's quantum gates);
- the Negative Log-Likelihood (NLL) objective function;
- the AdamW optimizer, an optimisation algorithm used for training neural networks;
- the t-distributed Stochastic Neighbor Embedding (t-SNE) machine learning algorithm;

- the Inter-Class Attribution Alignment (ICAA) metric which quantifies attribution divergence across predicted classes, enabling structured analysis of model reasoning in multiclass tasks.

Credit scoring can possibly also be implemented on a quantum annealer with a large number of qubits, e.g. by means of a QUBO formulation and quantum annealing.

Other financial services quantum use cases include:

- market analysis and prediction, including prediction of financial crashes;
- streamlining the trading settlement process by optimising transaction matching and reducing settlement times to increase the efficiency of trading operations, reduce costs and minimise risks associated with delayed settlements;
- prevention/detection of fraudulent payment transactions using QML methods;
- Anti-Mony Laundering (AML) using unsupervised QML methods;
- robotic advisors for investments, based on QML methods for analysing available information (including real-time market information) to identify (hidden) patterns and trends, in order to enable investors to achieve a diversified portfolio tailored to their financial goals and risk tolerance ("wealth management");
- customer personalisation based on QML methods for analysis of massive amounts of customer data to uncover intricate patterns and relationships, to enable offering of highly personalised financial products and services, thereby enhancing customer satisfaction and loyalty;
- quantum-assisted DLT (Box 2.2.8), including ETFs (Box 2.2.9) to drastically reduce electric power requirements used for "mining", for example based on Proof-of-Quantum work (PoQ) mining using a quantum hash (Figure 2.2.3);

> A Distributed Ledger Technology (DLT) system contains shared, synchronised and replicated data that is geographically spread (distributed) across many sites. Its fundament is "argumentum ad populum", whereby veracity of the data relies on a popular or majority of nodes that forces the system to agree (by means of a a mechanism called "mining" that uses vast amounts of electricity). In contrast to a centralised ledger, a distributed ledger does not require central administration and consequently does not have a single point-of-failure.
>
> The best-known form of DLT is the blockchain, commonly associated with the Bitcoin cryptocurrency. In 2025, Bitcoin's annualised energy consumption was estimated at more than 200 TWh (comparable to that of a country like Thailand), with a carbon footprint exceeding 100 Mt CO_2 (comparable to that of a country like the Czech Republic).

Box 2.2.8: Distributed Ledger Technology (DLT)

An Exchange-Traded Fund (ETF) is a type of investment fund that is also an exchange-traded product, i.e. it is bought and sold on stock exchanges. An ETF divides ownership of itself into shares that are held by shareholders. Shareholders indirectly own the assets of the fund and are entitled to a share of the profits, such as interest or dividends, and would be entitled to any residual value if the fund undergoes liquidation. An ETF generally operates with an arbitrage mechanism designed to keep it trading close to its net asset value.

Box 2.2.9: Exchange-Traded Fund (ETF)

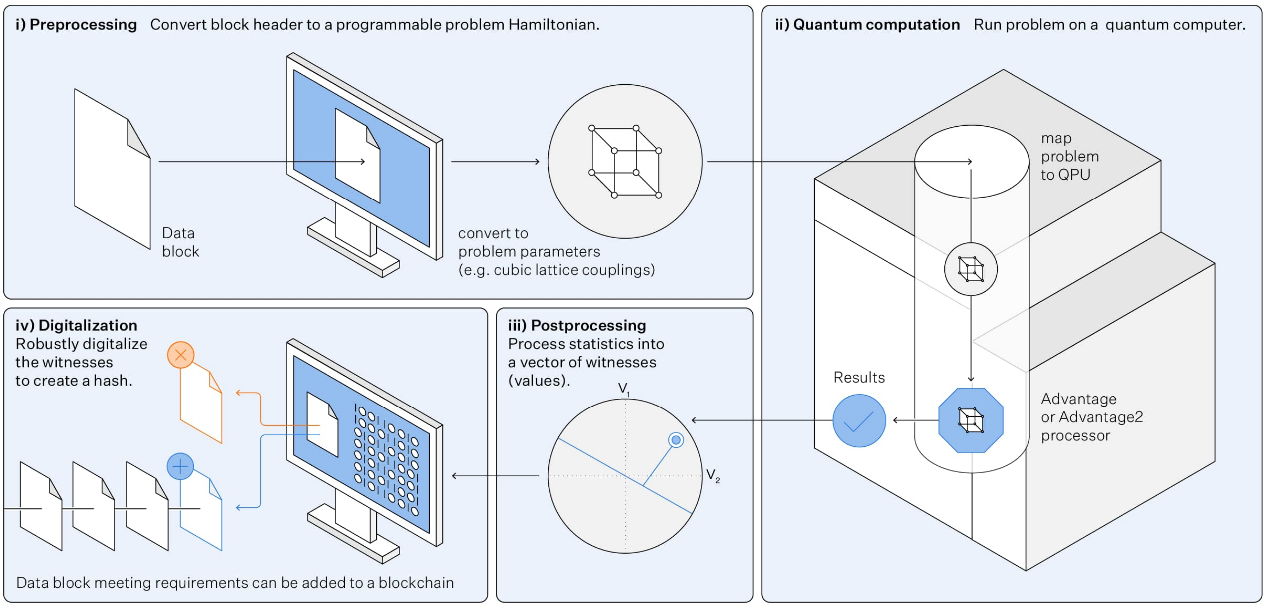


Figure 2.2.3: Quantum hash generation (source: D-Wave 2025)

- development of “quantum money” technologies, based on quantum states that are verifiable but unclonable[10].

QML-based quantum solutions could transform algorithmic trading by processing market data in real-time. This allows for the instantaneous adjustment of algorithmic trading algorithms in response to market fluctuations, thereby capturing profits from transient market inefficiencies.

Proposals based on quantum annealing and gate-based quantum computing have been made for Asset Liability Modelling (ALM) by insurance companies.

NISQ/FTQC QAE- and QFT-based quantum application algorithms could be used to to implement insurance contracts valuation and reinsurance optimisation.

There are many opportunities for the future use of quantum computing by the finance industry, provided that reliable and powerful quantum computers will become available. The time needed to compute solutions and the accuracy of the results often directly translates to the profit and loss

[10] Quantum money was already proposed in 1970 by the American-Israeli research physicist Stephen J. Wiesner. It was first published in 1983 and later influenced the development of Quantum Key Distribution (QKD) protocols.

of the financial business for which the associated problems are being solved. In this way, quantum computing may revolutionise the financial industry.

Most of the existing financial services quantum computing PoC projects have been performed with small data volumes (hundreds of assets), while real-world scenarios are based on high data volumes (thousands if not hundred thousands of assets).

2.3. Life sciences

Quantum computing applications for life sciences include drug discovery (by the pharmaceutical industries), various advanced clinical diagnostics, various healthcare treatment optimisations (e.g. in radiotherapy), and optimisation of healthcare system operations (Figure 2.3.1).

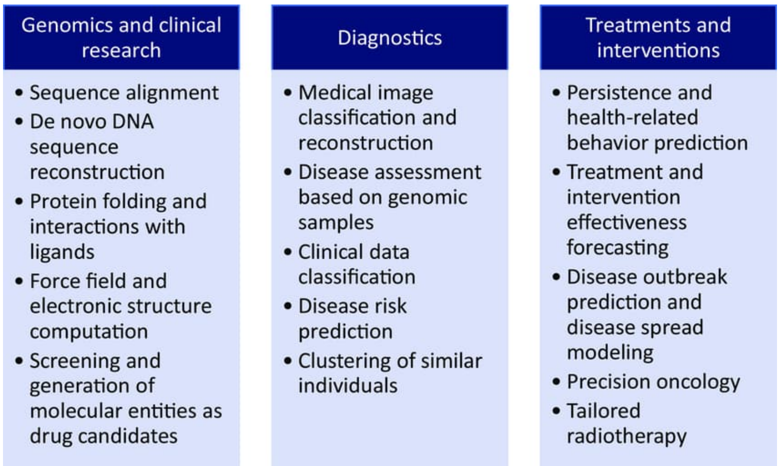


Figure 2.3.1: Quantum computing for life sciences (source: Frederick F. Flöther at al. 2023)

Most quantum application algorithms for life sciences are based on VQE, QPE, QFT and QAOA quantum algorithms and on QML methods, including its QRC variants. There are also proposals for for enabling implementation on quantum annealers using QUBO and BQM formulations. For all these use cases, a very large number of qubits will be required for achieving quantum speedup.

The main goal of drugs design is in-silico drug discovery, i.e. the simulation of living organisms' molecules "in silico", mainly to create or discover new treatments. The drugs design cycle from discovery to market is becoming increasingly lengthy and expensive, particularly during clinical trials (Figure 2.3.2).

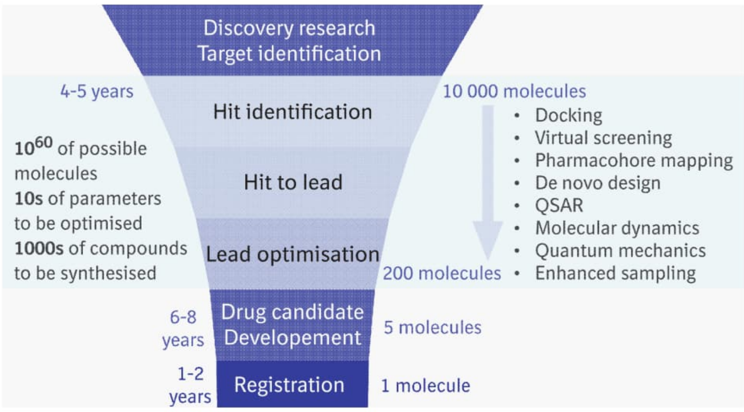


Figure 2.3.2: Drug design timeline (source: Raffaele Santagati et al. 2023)

What is needed for drugs design are molecular simulation tools to create molecules, from the simplest (peptides) to the most complicated (proteins, antibodies, vaccines), to model these molecules in 3D, to analyse interactions between their active sites and targets (e.g. cell surface proteins), to study protein-protein interactions, and to identify contra-indications or detect potential toxicity[11]. Besides news drugs discovery, pharmaceutical companies are also trying to leverage their existing portfolio with drugs re-targeting.

Use of quantum computing for drugs design could significantly shorten the drugs design cycle. Pharmaceutical corporations have been exploring and evaluating the potential of quantum computing for several years, typically starting by conducting pilot projects with quantum annealers and, later on, gate-based quantum computers.

Drugs design (Figure 2.3.3) could leverage quantum computing in areas like molecular docking (used to predict how one molecule will bind to another one and form a stable complex) and genomics. The first potential applications of genomics are DNA sequencing and DNA sequence alignment; RNA folding is currently still a field of research.

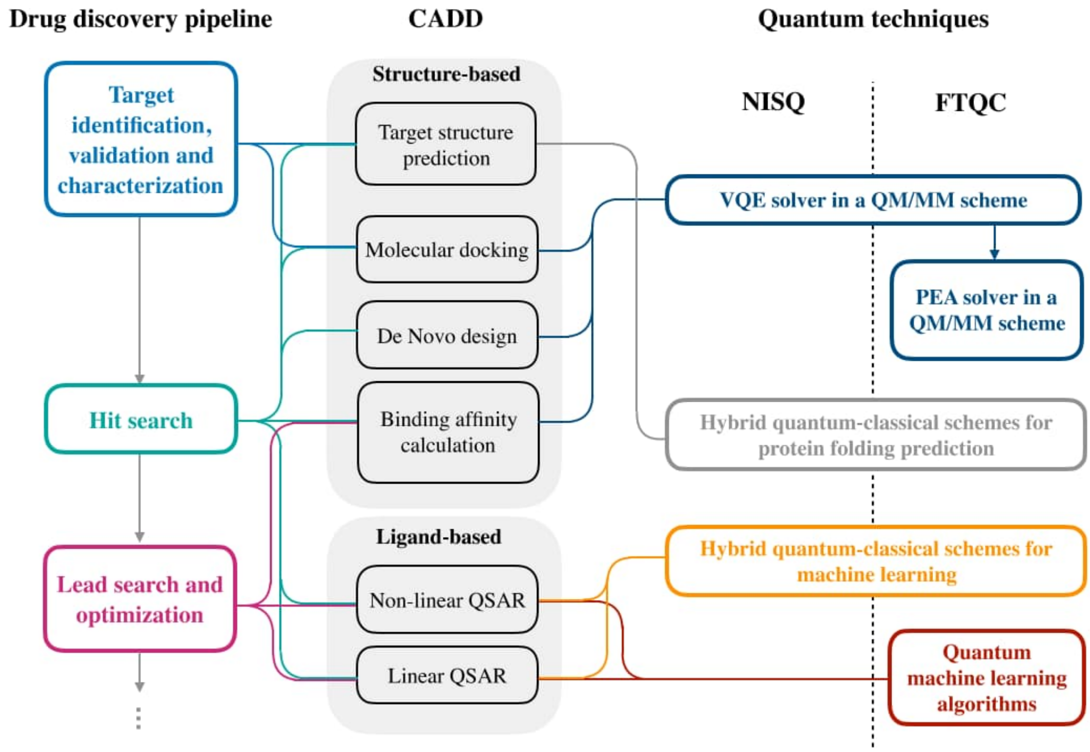
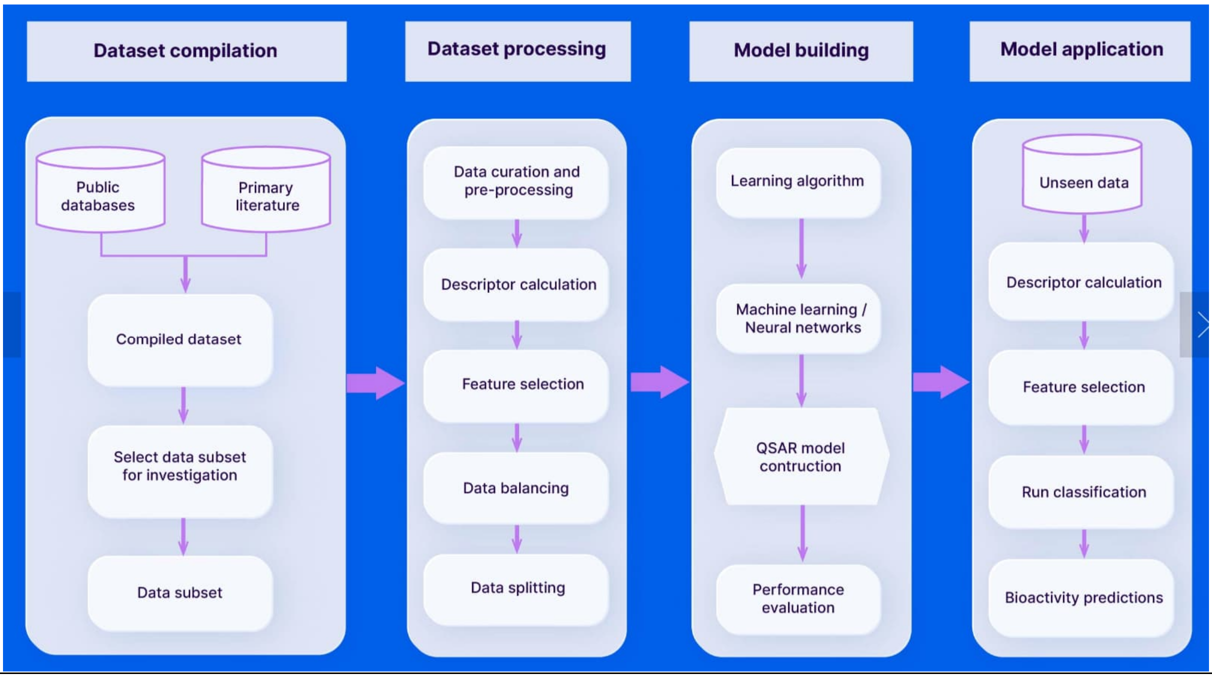


Figure 2.3.3: Drugs design process (source: Y. Cao et al. 2018)

QSAR modelling (Box 2.3.1) is used in drug discovery to obtain insights into the biological interactions of potential drug candidates.

[11] Protein folding and structure prediction are the golden standards of molecular simulation. Quantum computing solutions must compete with AlphaFold, the classical solution from Google DeepMind which can fold large proteins but with some limitations (particularly for entirely de-novo designs). AlphaFold can fold proteins with a number of amino acids way above what NISQ quantum algorithms are currently capable of doing.

Quantitative Structure–Activity Relationship (QSAR) a computational modelling method that creates mathematical models to connect the chemical structure of molecules with their biological or physical properties, like potency, toxicity, or absorption.



Box 2.3.1: QSAR modelling (source: NEOVARSITY 2024)

Oncology, with its diversity of cancers and treatments is currently a critical research field (Figure 2.3.4). An example is the use of the Quantum Multi-order Moment Embedding (QMME) quantum algorithm for the prediction of cancer driver genes (Figure 2.3.5).

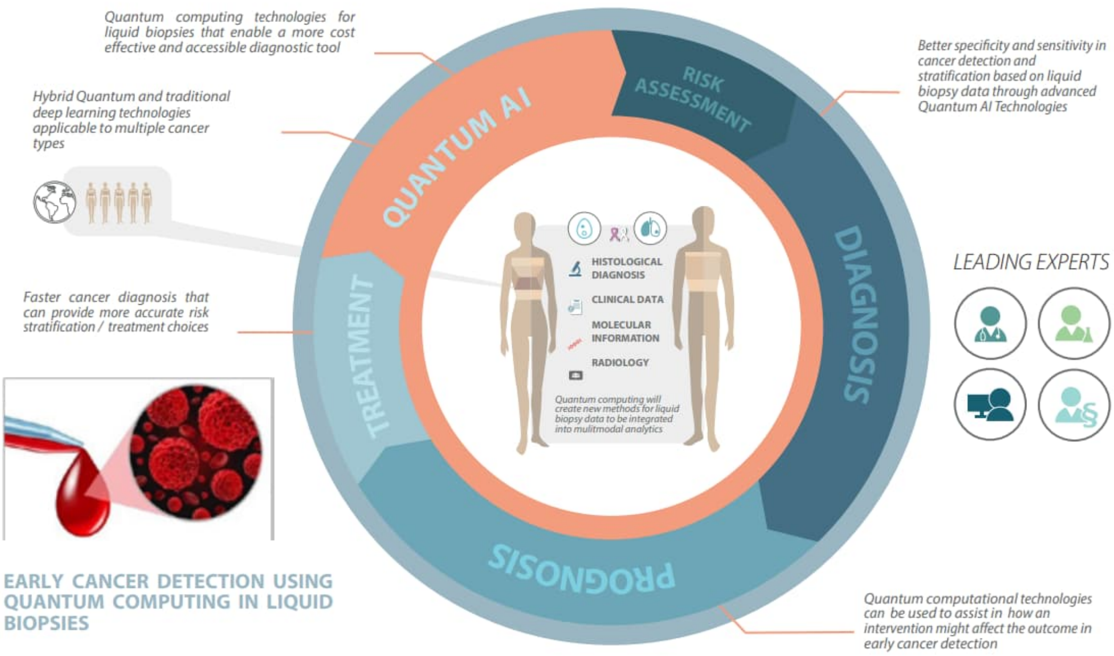


Figure 2.3.4: Oncology quantum computing use cases (source: UKRI 2025)

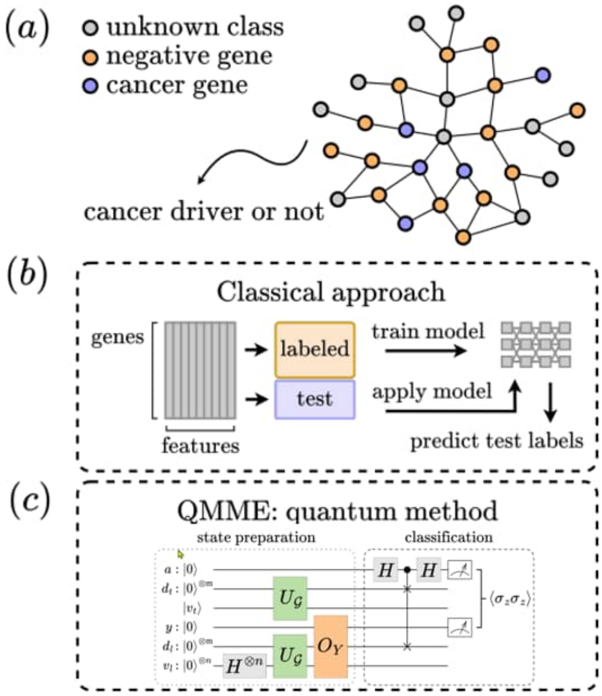


Figure 2.3.5: Cancer driver genes prediction methods (source: P. Marques et al. 2025)

(a) protein-protein interaction network
(b) classical machine learning method
(c) QMME quantum circuit (H = Hadamard gate, U = Unitary operator, O = Oracle)

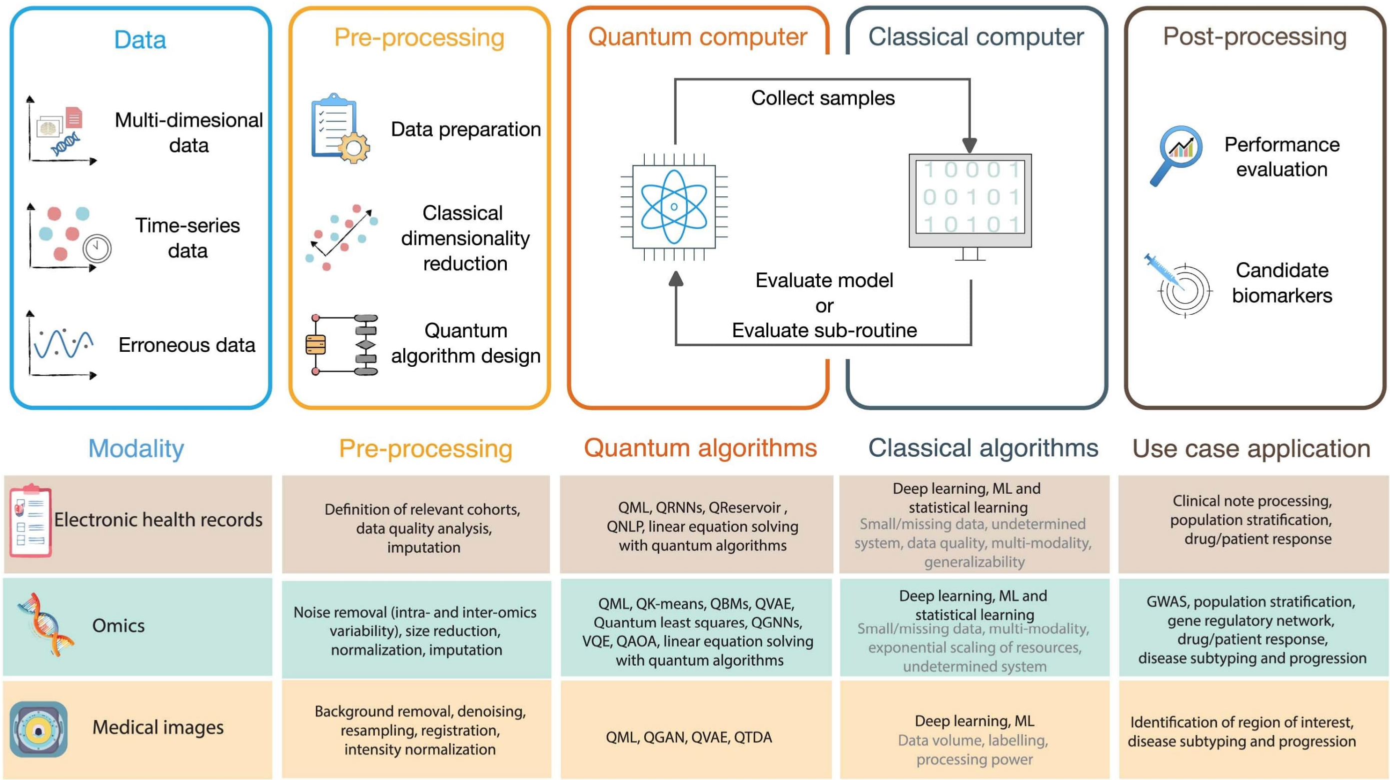


Figure 2.3.6: Hybrid methods for biomarker discovery (source: Frederik F. Flöther et al. 2025)

A key ingredient to facilitate tailored proactive interventions that keep an individual healthy ("precision medicine") is the detection of the early signals ("biomarkers") that the individual's health status is changing. Identification of such biomarkers requires advanced algorithms for analysis of Electronic Health Records (EHRs), omics[12] and medical images. Precision medicine could be enabled by various hybrid quantum-classical computing methods (Figure 2.3.6).

Quantum computing could potentially improve the efficiency of healthcare systems (hospitals, their emergency departments and insurers). This involves for example optimising resource allocation (e.g. nurse-doctor scheduling), scheduling work hours for medical staff, and performing various data analyses to discover correlations. Currently published use cases are however mostly limited to quantum-inspired solutions.

Many (proposed) healthcare use cases are based on hybrid quantum-classical QML computing methods (Figure 2.3.7).

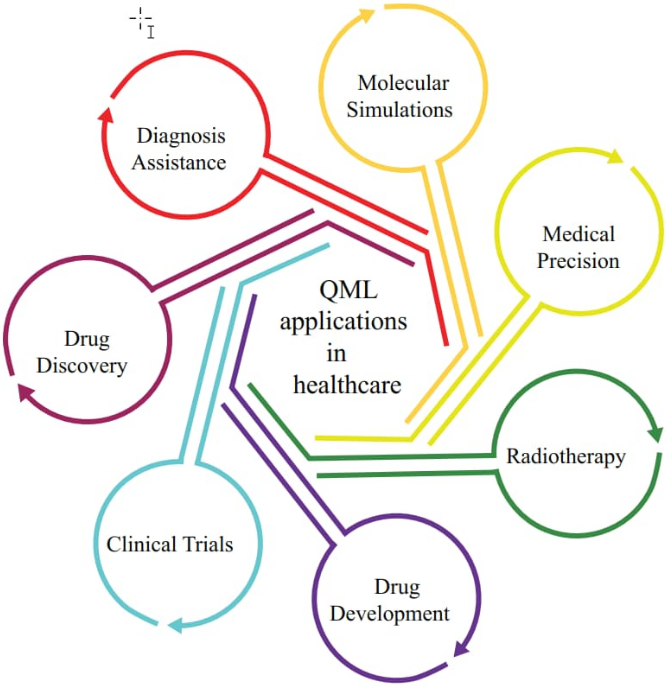


Figure 2.3.7: Healthcare QML models (source: Ubaid Ullah and Begonya Garcia-Zapirain 2024)

Other life sciences quantum computing use cases include (most of them are still at the early stages of research):

- Quantum-assisted vaccine development, by simulating viral and bacterial structures and interactions with the immune system.

[12] "Omics" is a collective term for the study of gen<u>omics</u> (the set of genes and their interactions), lipid<u>omics</u> (the set of lipids, including their pathways and networks), metabol<u>omics</u> (the set of metabolites), prote<u>omics</u> (the set of proteins and their interactions), transcript<u>omics</u> (the set of RNA molecules), etc.

- Creation of digital twins of medicinal compounds using hybrid quantum algorithms, allowing scientists to create and examine molecules digitally, in order to reduce the time needed to screen and choose prospective medication candidates.

- Construction of phylogenetic trees (Box 2.3.2) and analysis of evolutionary relationships based on genetic data.

A phylogenetic tree is a diagram that illustrates the evolutionary relationships and common ancestry between different species, organisms or genes, with branches showing divergence from common ancestors and nodes representing these ancestors or splitting points. It is based on evolutionary history hypotheses and can be used to organise biological diversity and in application fields such as medicine and forensics.

Box 2.3.2: Phylogenetic tree

- Quantum-assisted gene editing methods to predict and mitigate off-target effects, thereby improve the effectiveness and safety of gene therapies.

- Simulation of the behaviour of stem cells and their interactions with various biological environments, aiding in the development of regenerative therapies (“regenerative medicine”).

- Quantum-assisted clinical diagnostics and decision-making (e.g. using QML methods).

- Behavioural health analysis by analysing data from wearable devices, electronic health records and other sources, to understand behavioural health patterns and predict mental health issues, thus enabling early intervention and personalised treatment plans for mental health conditions.

- Tailoring of personalised prevention/treatment plans and prediction of potential drug responses for patients, based on analysis of available data (“personalised medicine”).

- Analysing individual genetic and metabolic data to develop tailored personalised nutrition plans that optimise health outcomes.

- Optimising telemedicine platforms by analysing data from patient interactions, treatment outcomes and healthcare logistics, enabling better accessibility to healthcare services (especially in remote areas).

- Predicting post-surgical complications and also help performing longitudinal biomedical studies that track disease progression, treatment response and the emergence of resistance mechanisms.

- Optimising organ donor-patient matching (e.g. kidney exchange by means of a QUBO formulation for quantum annealing).

- Using QML quantum algorithms for medical image (e.g. radiotherapy images) analysis, which may help train these systems with less data. However, existing quantum algorithms are currently at best just on par with their classical counterparts.

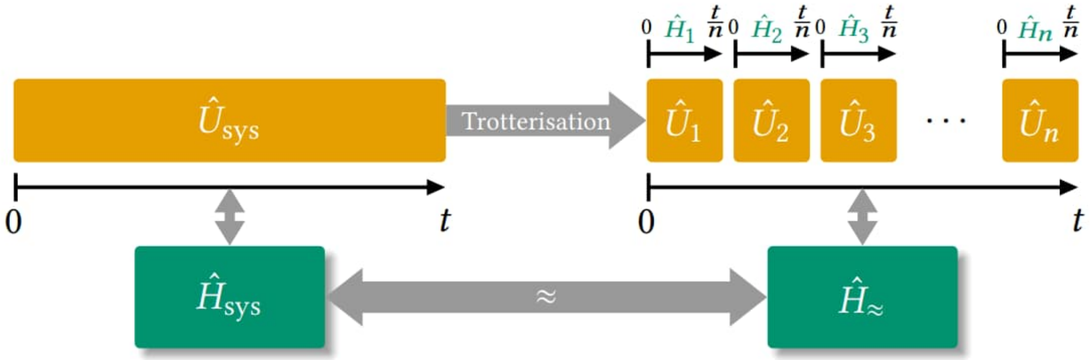
- Optimising lockdown schedules for pandemic outbreaks by means of hybrid quantum-classical methods.

2.4. Science

There is a wealth of quantum use cases that are of interest for this application domain, including:

- Nuclear Physics (NP) and High-Energy Physics (HEP):
    - solving/simulation of Ordinary Differential Equations (ODEs) and Partial Differential Equations (PDEs) using the HHL quantum algorithm;
    - time evolution simulation of quantum systems using trotterisation (Box 2.4.1) and QSVT (Box 2.4.2) methods.

Trotterisation, aka Trotter-Suzuki decomposition, named after the Canadian-American mathematician Hale Freeman Trotter and the Japanese physicist Masuo Suzuki, is a classical computing method that decomposes the unitary time operator of quantum dynamics simulation in small discrete steps. The method lends itself naturally to developing a similar decomposition on quantum computers: the trotterisation quantum algorithm.

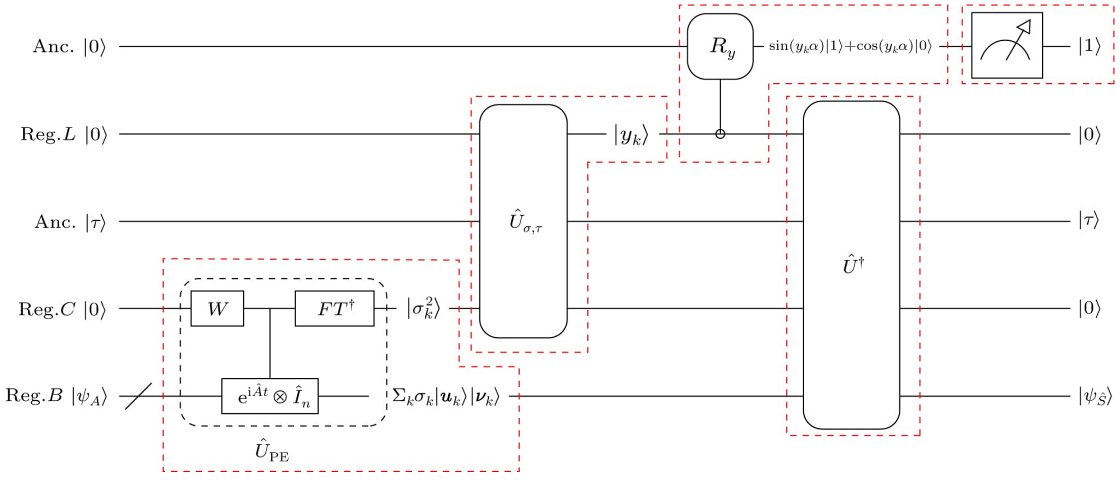


In contrast to continuous unitary time evolution ($\hat{U}_{sys}$), trotterised time evolution consists of a sequence of small unitary time evolution steps ($\hat{U}_1$, $\hat{U}_2$,$\hat{U}_3$, …, $\hat{U}_n$), of which the result $\hat{H}_{\approx}$ is an Hamiltonian that is an approximation of the continuous time evolution Hamiltonian $\hat{H}_{sys}$.

Box 2.4.1: Trotterisation decomposition (source: Maja Franz et al. 2025)

The trotterisation quantum algorithm is currently thought to be unfeasible for long time evolution quantum dynamics simulation of large systems on a NISQ quantum computer because the width and depth of the quantum circuit grows linearly with the time span and the complexity of the quantum circuit grows exponentially with the size of the system to be simulated.

Quantum Singular Value Transformation (QSVT) is a framework for designing quantum algorithms that apply arbitrary polynomial transformations to the singular values of a matrix. It is used for solving linear algebra problems, e.g. based on Grover's search algorithm and quantum linear system solvers based on QPE.



Box 2.4.2: QSVT quantum algorithm (source: Yangyang Ge et al. 2022)

- Astrophysics:
  - simulation of the Big Bang (Box 2.4.3) and of the very early universe;

Big Bang is the scientific explanation that the universe began from an extremely hot, dense state about 13.8 billion years ago and has been expanding and cooling ever since.

Box 2.4.3: Big Bang

  - black hole (Box 2.4.4) simulation;

A black hole is a region in space where an enormous amount of mass has been compressed into a tiny volume thus creating an extremely powerful gravitational pull that nothing, not even light, can escape from. A distinction is made between stellar black holes formed by the collapse of massive dying stars, and supermassive black holes which reside at the centres of galaxies, the formation of which is still unknown.

Box 2.4.4: Black hole

  - gravitational wave (Box 2.4.5) signal analysis;

A gravitational wave is a ripple in the fabric of spacetime caused by the acceleration of massive objects travelling near to the speed of light. Such waves are produced by cataclysmic cosmic events (e.g. black hole formation or neutron star collision) and can be detected by extremely sensitive instruments, e.g. the Laser Interferometer Gravitational-Wave Observatory (LIGO) observatories in the US, Italy and Japan.

A neutron star is a massive star that has exploded (as a supernova), resulting in an extremely dense core composed primarily of neutrons.

A supernova is an extremely powerful and brilliant stellar explosion that marks the final stages of a massive star's life or the catastrophic death of a white dwarf and is crucial for the creation and distribution of heavy chemical elements. A white dwarf is the remnant core of a dead star that has exhausted its nuclear fuel and expelled its outer layers.

Box 2.4.5: Gravitational wave

- analysis of gamma ray bursts (Box 2.4.6);

Gamma rays are the most energetic form of electromagnetic radiation, consisting of high-energy photons (Box 2.4.7). They are often emitted from atomic nuclei undergoing radioactive decay or during cataclysmic cosmic events (e.g. supernova explosions). Gamma rays are highly penetrating and can for example be used in medical imaging, sterilisation and industrial testing.

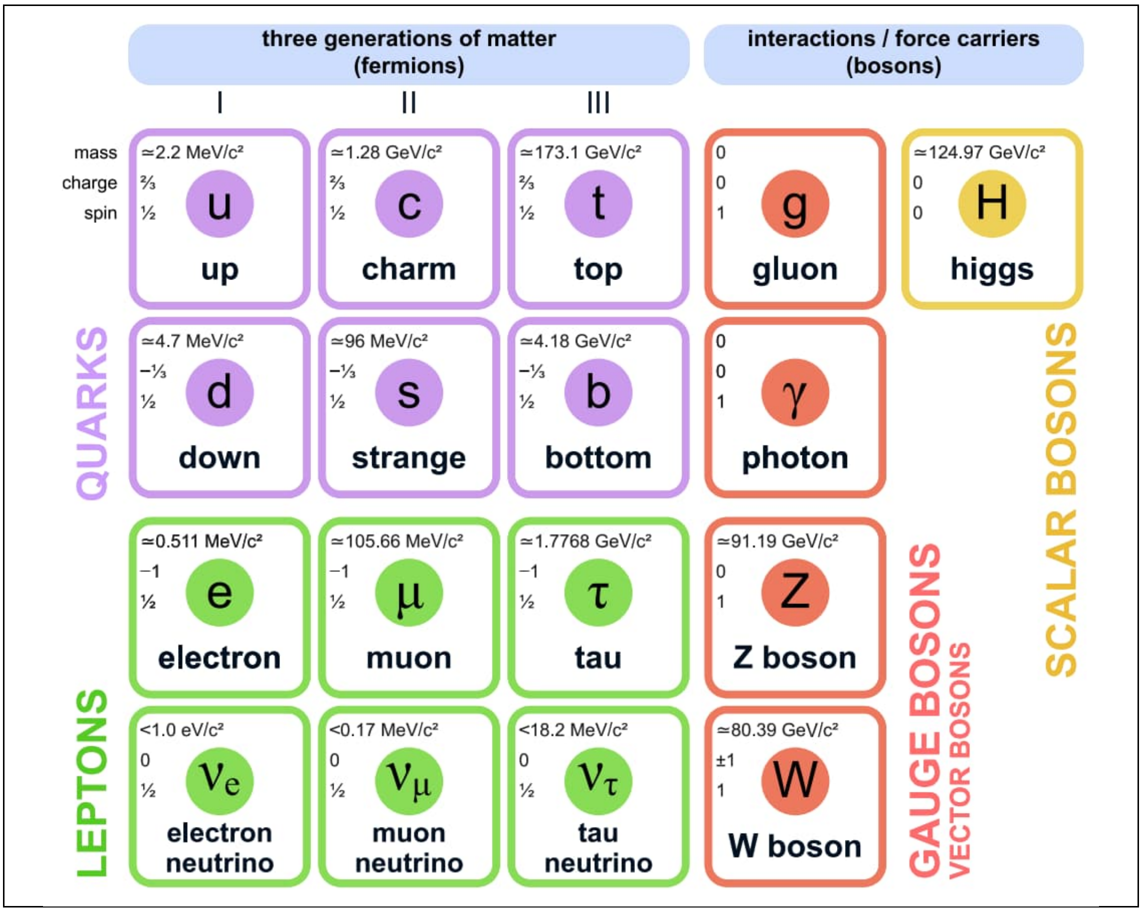
Box 2.4.6: Gamma rays

The Standard Model photon is an elementary subatomic bosonic particle (Box 2.4.8). It is the quantum of the electromagnetic field, including electromagnetic radiation such as light and radio waves, and it is the force carrier for the electromagnetic force. Photons do not have electrical charge, they have zero mass and zero rest energy, and they only exist as moving particles. Photons move at 299,792,458 metres per second in a vacuum, the so-called "speed of light" denoted by c (from the Latin celeritas). The speed of photons in a medium depends upon the medium and is always slower than the speed in vacuum c.

Box 2.4.7: Standard Model photon

Bosons and fermions are subatomic particles. There are two types of bosons: elementary bosons and non-elementary bosons. Elementary bosons, e.g. the photon and the gluon, are elementary subatomic particles. Non-elementary bosons, e.g. stable nuclei of even mass number such as hydrogen-2 and helium-4, are composite subatomic particles made up of smaller constituents. The name boson is in honour of Satyendra Nath Bose, an Indian physicist who developed a quantum theory for these particles (known as Bose-Einstein statistics) together with the Swiss-American theoretical physicist Albert Einstein.

There are also two types of fermions: elementary fermions and non-elementary fermions. Elementary fermions, e.g. the the electron and the muon, are elementary subatomic particles. Non-elementary fermions, e.g. the proton and the neutron, are composite subatomic particles made up of smaller constituents. The name fermion is in honour of the Italian and naturalised American physicist Enrico Fermi.



Box 2.4.8: Standard Model of particle physics (source: Wikipedia 2025)

- detection of dark matter in the form of axions or hidden photons (Box 2.4.9), e.g. by the Dark Energy Spectroscopic Instrument (DESI) fitted on the Mayall Telescope on top of Kitt Peak in the Sonoran Desert near Tucson (Arizona, US).

Axions are hypothetical massive (but very light) particles, while hidden photons are a weakly interacting form of the Standard Model photon. They are both bosonic dark matter and can be searched for by experiments that try to convert them into detectable Standard Model photons.

Box 2.4.9: Axions and hidden photons

- Physics simulations:

These are probably the most amazing potential use cases of quantum computing as they could enable a better understanding of how nature works, how to imitate it and how to produce energy and various materials more efficiently. Example: creating and studying new states of matter, e.g. time crystals (Box 2.4.10) and anyons (Box 2.4.11).

A time crystal is a quantum system composed of of particles whose lowest-energy state is one in which these particles are in repetitive motion.

Box 2.4.10: Time crystal

An anyon is a specific type of (a mathematical construct to study complex interactions in many-body systems) in a 1- or 2-dimensional space. Anyons are neither fermions nor bosons, both of which are particles in a 3-dimensional space. Anyons have statistical properties intermediate between fermions and bosons. A well-known anyon is Microsoft's Majorana[13] topological qubit in which bound states can appear at the interface between insulators and superconductors, called Majorana Zero Modes (MZMs).

Box 2.4.11: Anyon

- Vulcanic monitoring.
- Weather/climate modelling and forecasting:

  The methods for weather/climate modelling and forecasting (Figure 2.4.1) use a wide range of data like temperature, pressure, wind strength, moisture, and other meteorological variables. This also enables more operational use cases, such as for example:

  - tropical cyclone[14] and tornado trajectory forecasting;
  - more accurate weather simulations to predict energy production and improve electrical grid balancing and electricity supply predictions;
  - predict CO_2 emission peaks due to fossil fuel and Liquified Natural Gas (LNG) power plant production;
  - predict water supply and water quality.
- Disaster response (earthquakes, volcanic eruptions, tsunamis, flooding, tropical cyclones, wildfires, etc.):
  - optimisation of placement of in-field sensor equipment;
  - optimisation of disaster response operations.
  - Climate change mitigation: most of the proposed solutions, if not overpromising, are very long term and require very powerful FTQC quantum computers.

[13] In 1937, the Italian theoretical physicist Ettore Majorana predicted the existence of a new class of particles that are their own anti-particles (but they have never been discovered). Majorana was a member of the Italian National Fascist Party. He disappeared under mysterious circumstances after purchasing a ticket to travel by ship from Palermo to Naples to on 25 March 1938. In March 2011, the Italian Rome Attorney's Office started an inquiry into the statement made by a witness about meeting with Majorana in Buenos Aires in the years after World War II. In February 2015, they released a statement declaring that Majorana had been living in Valencia (Venezuela) between 1955 and 1959.

[14] Over the Atlantic and in the East Pacific, a tropical cyclone is commonly called a "hurricane". In the West Pacific, a tropical cyclone is commonly called a "typhoon". In the Indian Ocean and near Australia, a tropical cyclone is just called a “cyclone”.

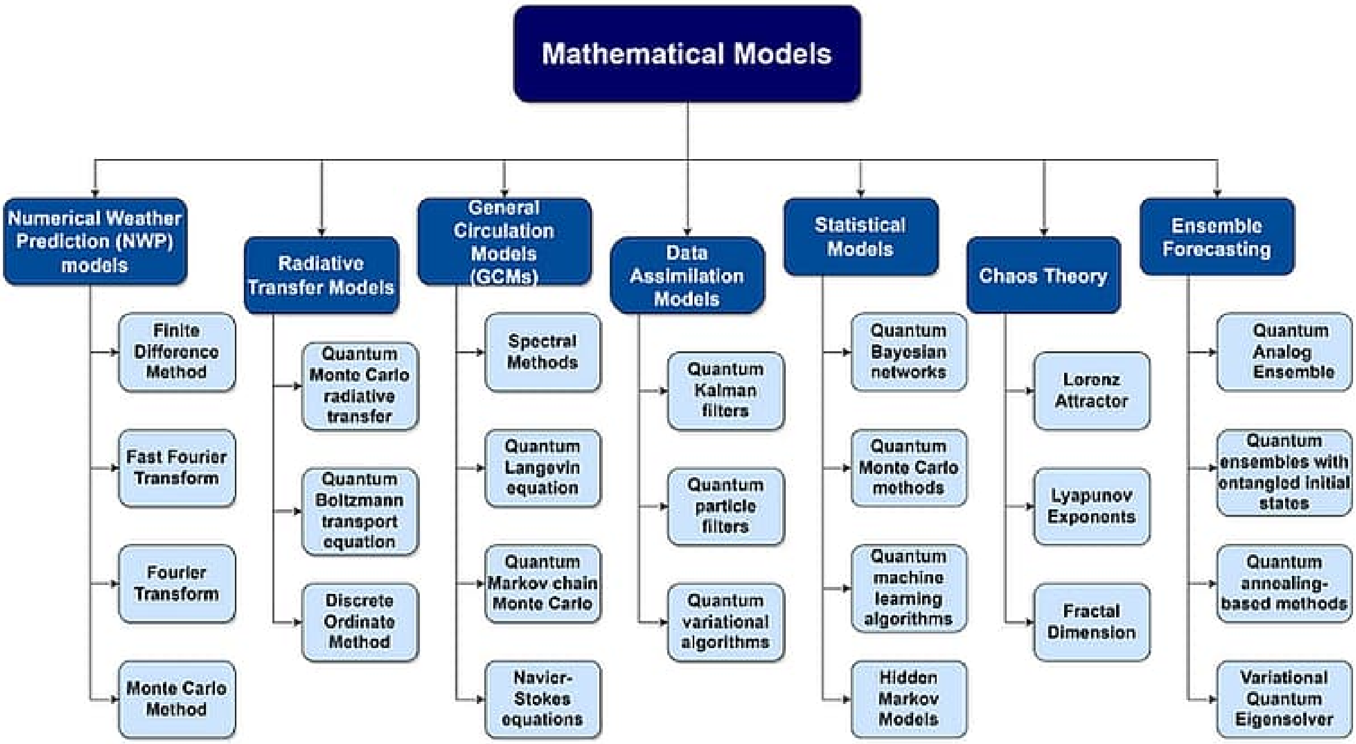


Figure 2.4.1: Weather/climate modelling and forecasting methods (source: Copperpod 2023)

Note

It is important to remark that most weather modelling and related methods typically involve the ingestion of a lot of data which is certainly not where quantum computers excel.

2.5. Chemistry and materials design

Quantum computing could enable development of new and improvement of various chemical engineering and materials design processes. This application field is built on the understanding of Open Quantum Systems (OQSs) which have non-negligible interactions with their environment.

Quantum computing solutions could replace or complement existing classical solutions. They better handle molecule's wave functions spanning large Hilbert spaces (Box 2.5.1) and use reduced density matrices (Box 2.5.2) to estimate energies, electric polarisation, magnetic dipoles and other chemical properties.

Hilbert spaces (named after the German mathematician David Hilbert) allow the methods of linear algebra and calculus to be generalised from finite-dimensional Euclidean spaces[15] to spaces that may be infinite-dimensional. Formally, an Hilbert space is a vector space equipped with an inner product that induces a distance function for which the space is a complete metric space. A quantum state of a single or several quantum objects can be described by a vector in a Hilbert space. e.g. a qubit state is a vector in a 2-dimensional Hilbert space.

Box 2.5.1: Hibert space

A density matrix is a mathematical tool used to describe quantum systems, which consists of a square matrix of complex numbers. A density matrix of a mixed state consolidates both quantum uncertainties (that persists even when the system state is well known) and classical uncertainties (due to a lack of knowledge of individual quantum sources and preparation conditions), while a density matrix of a pure state contains only information pertaining to quantum uncertainties. A pure state describes the state of an isolated quantum system (composed of one or multiple objects) as a linear superposition of its basis states. Quantum decoherence will gradually turn the quantum system into a mixed state. A mixed state is a statistical ensembles of classical probabilistic combinations of pure states. The difference between pure and mixed states lies with the origin of measurement randomness: entirely quantum for pure states and both quantum and classical for mixed states. A pure state can be described with a quantum vector but a mixed state can only be described by a density matrix. A reduced density matrix is a mathematical object that describes the quantum state of a part of a larger composite quantum system. It is created by applying a partial trace to the full density matrix of the composite system, effectively "tracing out" the degrees of freedom of the parts of the system that are not being observed. This allows one to study a subsystem on its own, providing the best possible description of its state, even if the larger system is entangled.

Box 2.5.2: Reduced density matrix

[15] Euclidean space is the fundamental space of geometry, intended to represent physical space. It was invented by the ancient Greek mathematician Euclid.

Most of the quantum algorithms that are developed for chemistry primarily deal with computing the ground and excited state energies of molecules. They may then be used for computing chemical reaction pathways, binding energies and rates of chemical reactions. Examples:

- Understanding and quantifying the nature of chemical bonds between atomic and molecular orbitals (Box 2.5.3) describing the distribution of electron density and energy levels in a molecule.

Atomic orbitals describe the probability of finding an electron in a specific region around a single atom, while molecular orbitals describe the probability of finding an electron in a region that spans two or more atoms in a molecule. Molecular orbitals are formed when atomic orbitals overlap during chemical bonding, creating new orbitals with different energy levels that are delocalised over the molecule.

Box 2.5.3: Atomic and molecular orbitals

- Understanding molecular structure and properties by predicting and explaining the arrangement of atoms in molecules in space, as well as their electronic, vibrational, rotational and spectroscopic properties.

- Determining energy levels and reactivity by determining the energy levels of electrons in atoms and molecules, predicting chemical reactivity, chemical reaction rates and mechanisms.

- Modelling and optimising chemical reactions by learning the thermodynamics and kinetics of chemical reactions, used to study chemical reaction pathways, catalysis, and leading to chemical reaction optimisation techniques.

- Simulating solute-solvent interactions.

- Simulating complex systems such as proteins or biological macromolecules and reactions.

- Simulating out-of-equilibrium phases in quantum matter (mostly for the investigation of superconducting materials behaviour).

Quantum application algorithms used for chemistry are based on PDE, VQE, QMC, quantum walks (Box 2.5.4) and QML methods. Boson sampling with VQE or QAOA is also usable for some quantum chemistry applications. There are also proposals for enabling implementation on quantum annealers.

A random walk (aka drunkard's walk) is a random process that describes a path that consists of a succession of random steps in some mathematical space. Quantum walks are quantum analogues of classical random walks. In contrast to the classical random walk, where the walker occupies definite states and the randomness arises due to stochastic transitions between states, in quantum walks randomness arises through either quantum superposition of states, non-random, reversible unitary evolution of the quantum system or collapse of the quantum wave

function due to quantum state measurements. A quantum algorithm for solving quantum walks was invented in 1993 by Yakir Aharonov (Israeli physicist) et al.

Box 2.5.4: Quantum walk

Quantum chemistry algorithms for both NISQ and FTQC will be highly demanding in the numbers of qubits and quantum gates. Therefore, the related quantum computing processes may need to be distributed over multiple interconnected quantum computers.

A chemistry quantum computing application that currently attracts a lot of attention is about finding ways to produce artificial fertilisers with much less energy. Artificial fertiliser production is nowadays based on the industrial production of ammonia (Box 2.5.5) by means of the Haber-Bosch process (named after the German physicists Fritz Jakob Haber and Carl Bosch), which consumes lots of energy and is is responsible for about 6% of CO_2 global emissions (Figure 2.5.1).

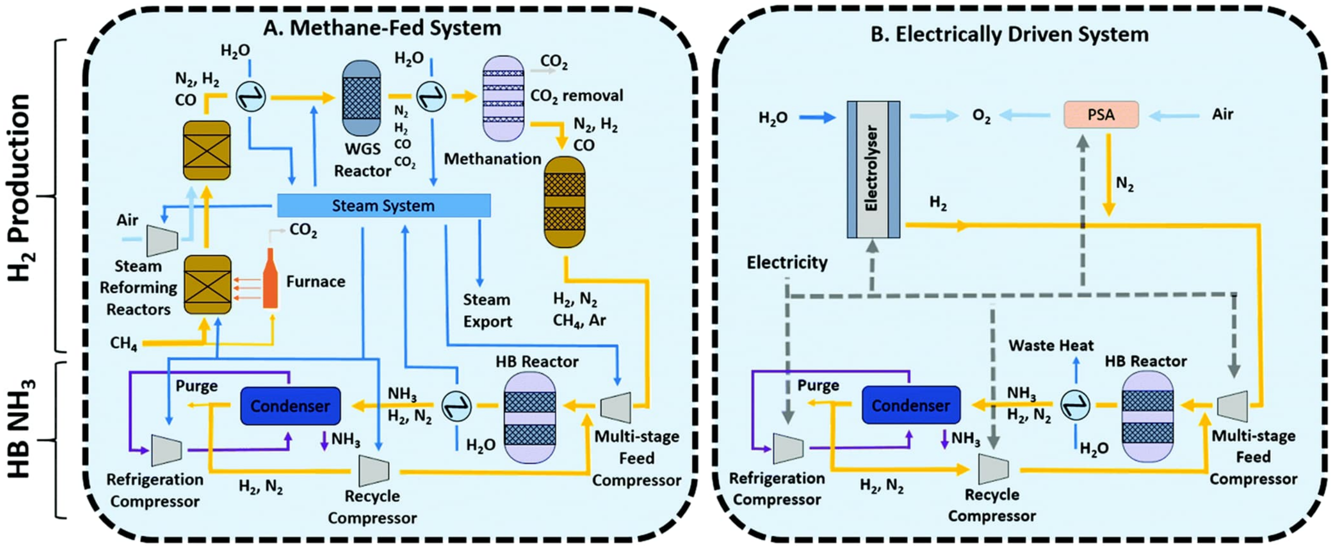


Figure 2.5.1: Haber-Bosch ammonia production process (source: Collin Smith et al. 2019)

Ammonia[16] (NH_3) is a natural fertiliser that contributes to plant growth. It is created using the Ferromolybdenum Cofactor (FeMoCo) chemical complex that operates in bacteria nitrogenase. These ammonia producing bacteria live in soils and water (free bacteria) or in legume root nodules. Legume root nodules are a hundred times more efficient in nitrogen fixation than free bacteria (that's why one plants legumes like peas or beans alternatively with tomatoes in the garden: tomatoes are draining the nitrogen fixed in the soil while legumes are reconstituting the soil nitrogen). The alternative solution is to renew soil with a lot of compost and/or artificial fertilisers. The natural ammonia creating process fixes air nitrogen to produce ammonia at ambient temperature in a very energy-efficient manner. This natural process accounts for about

[16] The word "ammonia" in modern languages comes from the Latin word "ammoniacus". Salt deposits containing ammonium chloride, known as "sal ammoniacus", were extracted near a temple dedicated to the ancient Egyptian god Amun (called Ammon by the Greeks), leading the Romans to name the substance "sal ammoniacus" ("salt of Ammon").

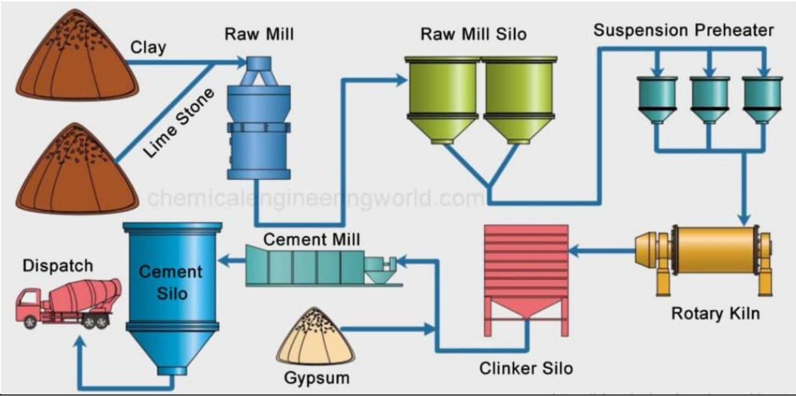
48% of global nitrogen fixation, with 14% happening in soils and 34% in oceans. It also includes natural recycling with dead plants, which happens in compost production and permaculture.

Box 2.5.5: Natural ammonia creation process

Currently, the primary goal seems to be understanding how FeMoCo participates in the nitrogen fixation pathway, the electron transport mechanism in particular, by simulating a few hundred of the involved electron orbitals. It is estimated that only partly simulating FeMoCo would already require more than 2,000 logical qubits and more than 3,000 Toffoli quantum gates[17] (running an optimised version of the QPE quantum algorithm). It is however still unknown whether all of this would be sufficient for creating a more energy-efficient artificial ammonia production process.

Another chemistry quantum computing application that draws a lot of interest is about drastically reducing the amount drastically reducing the amount of CO_2 emissions for cement production (Box 2.5.6).

Cement[18] production nowadays involves extracting limestone and clay from quarries, crushing and grinding these into a fine powder, and then heating this mixture in a rotary kiln at around 1,450 °C to form clinker. The clinker is then cooled and ground with gypsum and other additives, to produce the final cement powder. This production process is extremely energy intensive.



Box 2.5.6: Cement production process (source: Chemical Engineering World 2020)

Quantum computing for material discovery and design applications uses simulation to predict properties of novel compounds before synthesis, potentially accelerating innovation cycles and reducing development costs. Applications include metal alloys, polymers, specialty chemicals and advanced materials with specific performance characteristics tailored to customer requirements. Quantum material simulation leverages quantum computing to model materials that exhibit quantum mechanical properties such as superconductivity, topological states and quantum

[17] Named after the Italian-American physicist Tommaso Toffoli.

[18] The word "cement" comes from the Latin word “caementum”, meaning "rough-cut stone", which describes the mixture of crushed rock and lime that the Romans used to build with. It eventually passed into French as “ciment” before being adopted into English as “cement”.

magnetism. Such materials are particularly challenging to simulate classically and are more naturally modelled as quantum systems.

Methods for the design of new materials commonly are commonly based on Fermi-Hubbard models (Box 2.5.7) of strongly correlated 2D systems like crystals, semiconductors and superconducting materials (high-temperature superconducting materials in particular), which are very difficult to simulate with classical methods. Quantum algorithms could also solve RVE problems (Box 2.5.8) with polylogarithmic complexity.

The Fermi-Hubbard model, named after Enrico Fermi and the British physicist John Hubbard, is used to explain the behaviour of quantum materials. The model describes interacting fermionic particles on a lattice, focusing on two competing processes: hopping (particles moving between sites) and on-site repulsion (repulsion when two particles occupy the same site).

Box 2.5.7: Fermi-Hubbard model

The Representative Volume Element (RVE) is the smallest volume over which a measurement can be made that will yield a value representative of the whole volume. It is used in material sciences to understand and predict the macroscopic properties of heterogeneous materials based on their microscopic structure. It is used for the study of composite materials, polycrystalline materials, porous materials, microstructural analysis, damage and failure analysis and multiscale modelling (from atomic to macroscopic), and for thermal analysis.

Box 2.5.8: Representative Volume Element (RVE)

Much-talked-about materials design quantum computing applications include the creation of new materials for pollution control, waste management and water purification. Another interesting use case is simulating metal corrosion at the atomic level. Other materials design quantum computing applications include:

- development of new solvents for carbon capture and adsorbents or solid sorbents for direct-air carbon capture;

- developing material for carbon capture and storage, e.g. based on MOFs (Box 2.5.9, for example using an hybrid quantum-classical MOF design method based on QNLP (Figure 2.5.2);

A Metal-Organic Framework (MOF) is a crystalline, porous material made of metal ions or metal ion clusters linked by organic molecules. MOFs have exceptionally large surface areas, which allows for efficient interaction and storage of other molecules. MOFs also have tuneable structures, which allows for specific properties and functionalities.

Box 2.5.9: Metal-Organic Framework (MOF)

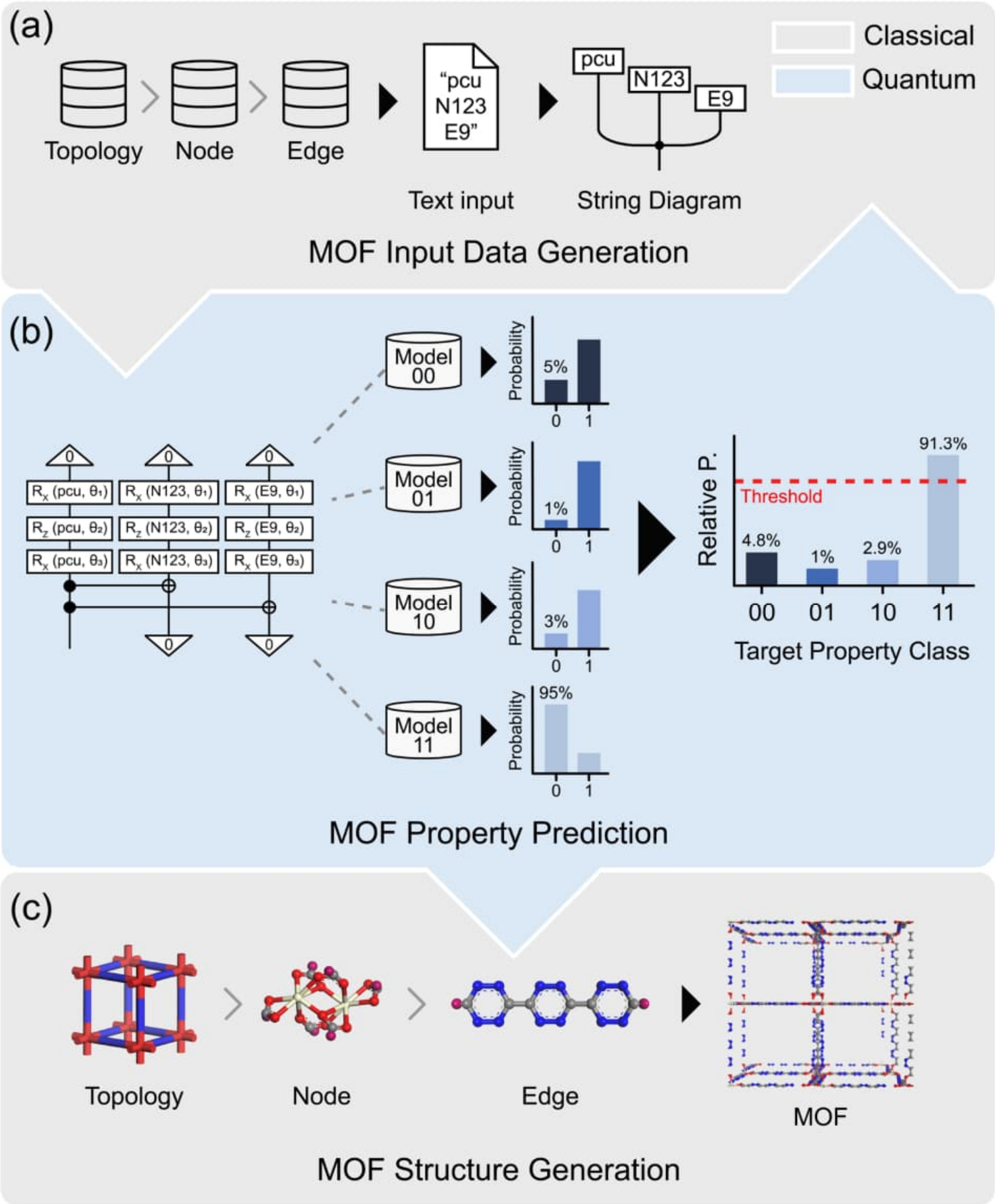


Figure 2.5.2: Hybrid quantum-classical MOF design method (source: KAIST 2025)

(a) MOF input (topology, node and edge) generation process based on random selection rule
(b) property prediction based on relative probability distributions collected from QNLP binary classification models
(c) MOF structure generation based on selected topology, node and edge building blocks

- designing batteries that are more efficient in terms of energy density, charging speed and charging/discharging cycles, e.g. using Quantum Density Functional Theory (Q-DFT) methods (Figure 2.5.3);

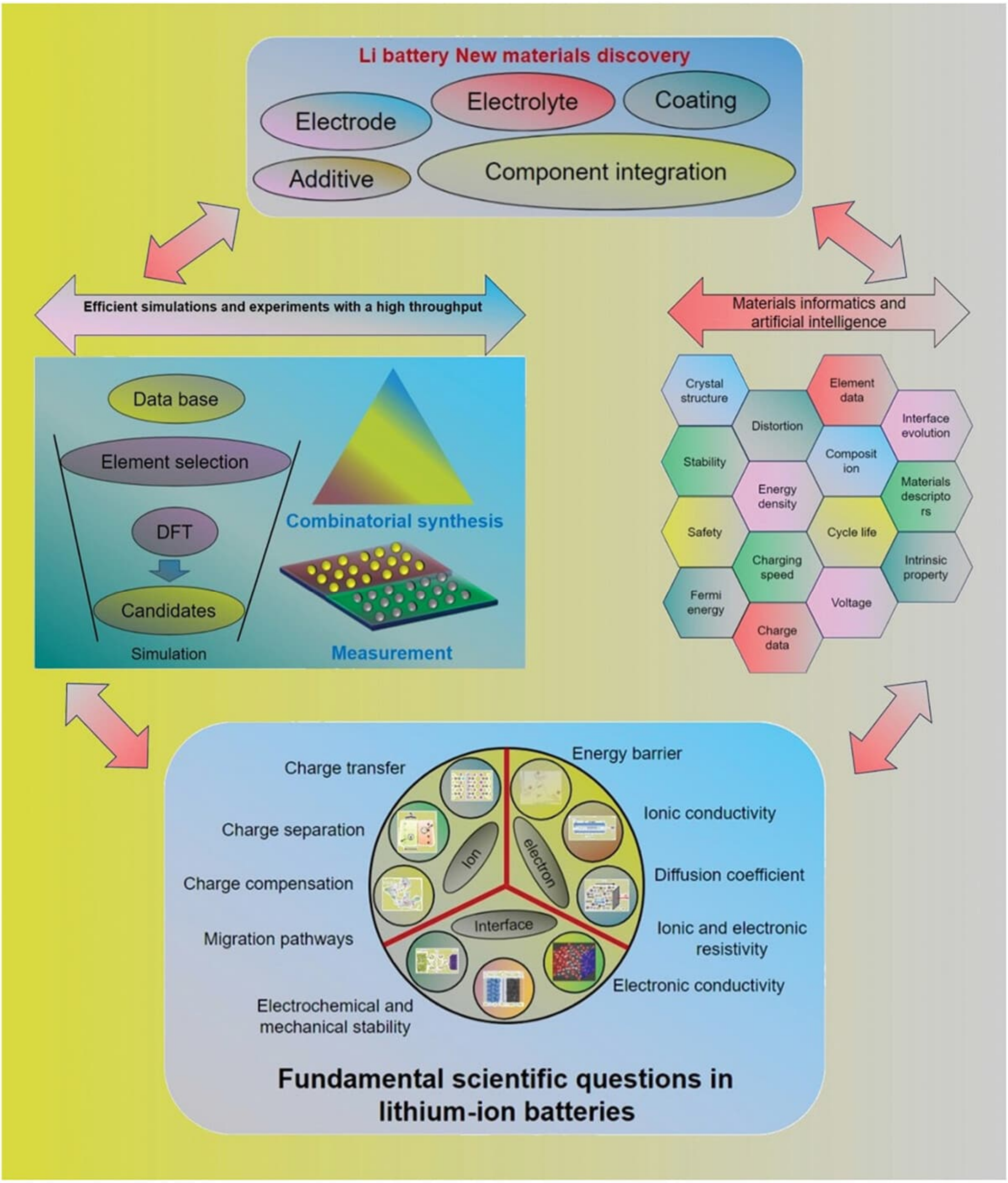


Figure 2.5.3: Exploring novel battery materials (source: Khurram Shahzad et al. 2024)

- designing catalysts that are more efficient, cost-effective, and environmentally friendly (more accurate modelling of reaction mechanisms, transition states and surface interactions), e.g. using the State-Averaged Orbital-Optimized Variational Quantum Eigensolver (SA-OO-VQE) algorithm consisting of iterations of the hybrid quantum–classical State-Averaged Variational Quantum Eigensolver (SA-VQE) sub-algorithm and the classical State-Averaged Orbital-Optimized (SA-OO) sub-algorithm (Figure 2.5.4);

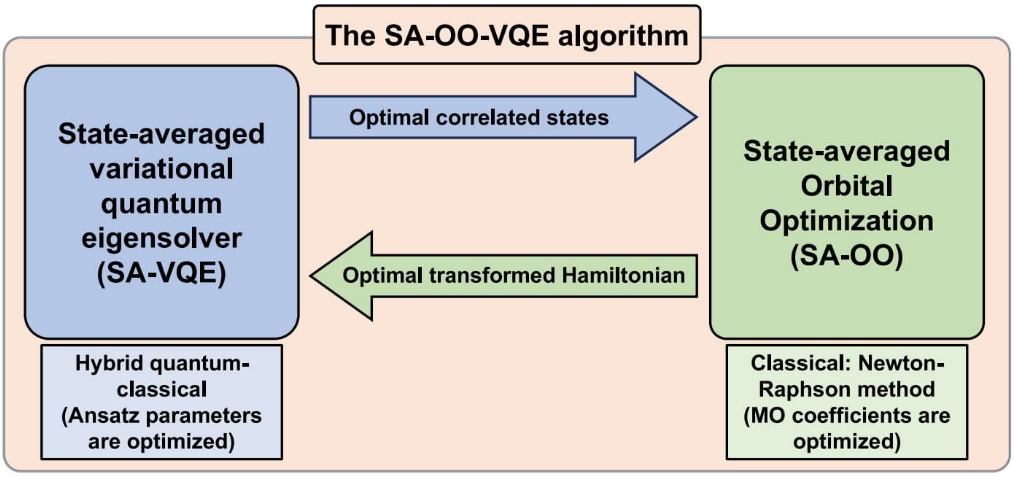


Figure 2.5.4: SA-OO-VQE algorithm (source: Seenivasan Hariharan et al. 2024)

- development of more efficient solar cells;
- development of new materials for replacing materials whose production and recycling are energy intensive (e.g. aluminium and steel);
- development of new and cleaner fuels for replacing coal and LNG;
- development of sustainable hydrogen production techniques, e.g. photocatalysis (Box 2.5.10) for water splitting;

Photocatalysis is a process that uses a catalyst to accelerate a chemical reaction with the help of light energy. A photocatalyst absorbs photons from light sources such as the sun or a UV lamp, creating exited electron-hole pairs which initiate redox reactions, breaking down pollutants, killing microorganisms, or synthesising new compounds.

A redox reaction (aka oxidation-reduction reaction) is a chemical reaction involving the transfer of electrons between two species, where one species loses electrons (is oxidised) and another gains electrons (is reduced). Redox reactions are at the basis of many processes such as photosynthesis, cellular respiration and the functioning of batteries.

Box 2.5.10: Photocatalysis

- creating room-temperature superconducting materials;
- simulation of exotic magnetic materials (i.e. substances with unusual or counter-intuitive magnetic properties).

Quantum application algorithms for materials design are often based on VQE, QAOA and QML methods. There are also proposals for for enabling implementation on quantum annealers.

Several quantum computing hardware and software startups propose development frameworks for quantum simulation of matter and chemical processes and various tools are already available for quantum chemistry computations, e.g. ChemiQ (Origin Quantum, Figure 2.5.5), Inquanto (Quantinuum), MIST (universities of Illinois and Michigan), myQLM-fermion (Eviden), OpenFermion (Google), ORCA (FACCTs), Qamuy (QunaSys), Qiskit Nature (IBM), Qrunch (Qvantify), Quantum Chemistry Library (Microsoft), Quantum Package (open-source) and Qubec (Qu&Co).

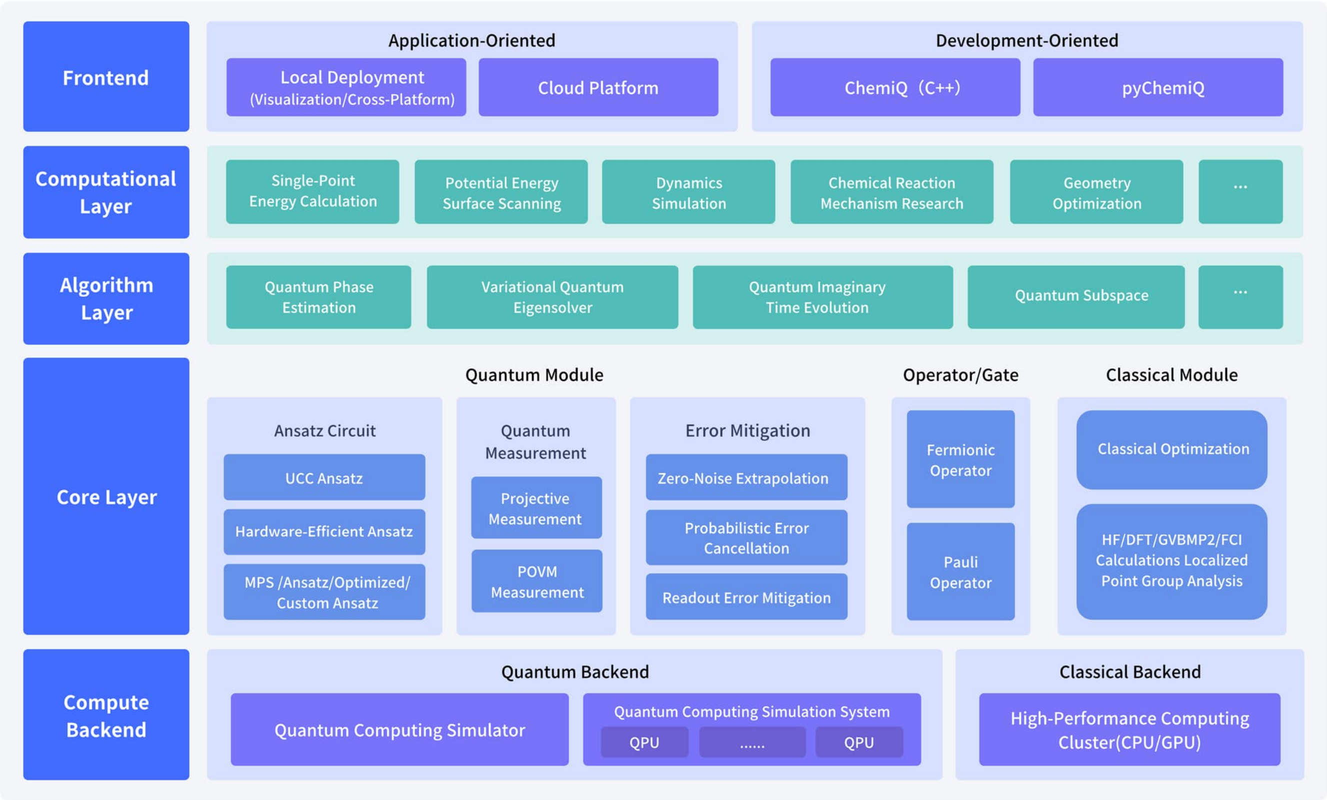


Figure 2.5.5: ChemiQ architecture (source: Origin Quantum 2025)

Quantum computing for chemistry and materials design holds immense promise and the amount of quantum application algorithms that have been developed for this application field is growing at a fast pace. However, proving these algorithms for large-scale problem solving will require reliable and powerful quantum computers.

2.6. Energy, oil and gas

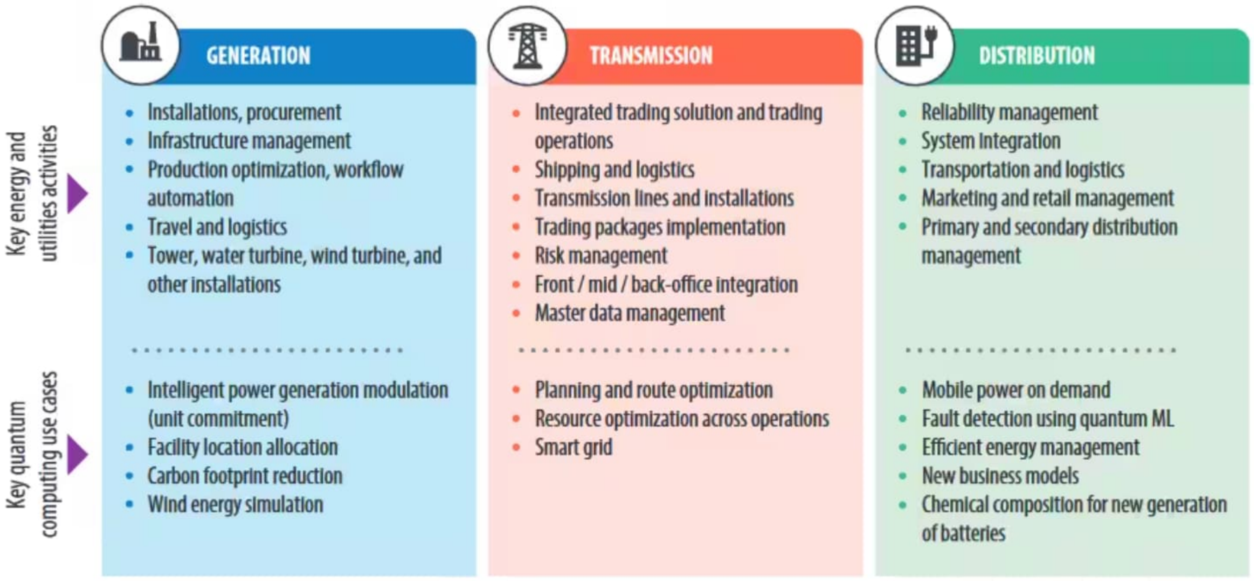


Figure 2.6.1: Energy use cases overview (source: Infosys 2022)

Quantum computing could be used to simulate both fission and fusion nuclear energy reactions with NISQ quantum algorithms (VQE and QML) and FTQC quantum algorithms (QPE and QML) with a large number of qubits.

There are several proposals for quantum application algorithms to optimise (smart) electrical power grids based on QUBO, BQM, DQM or CQM for quantum annealers, based on QML for NISQ quantum computers, and based on HHL, QAOA and QML for FTQC quantum computers. These proposals compete with classical methods, which are often based on MIP methods (Box 2.6.1).

Mixed Integer Programming (MIP) is an optimisation method for solving problems with a mix of continuous and discrete variables. MIP involves defining an objective function along with constraints expressed as mathematical equations that the variables must satisfy. MIP's main distinguishing feature is the inclusion of at least one integer variable, which makes the problem more complex but also more realistic for modelling real-world scenarios. MIP optimisation is used in domains such as finance, logistics and engineering.

Box 2.6.1: Mixed Integer Programming (MIP)

Other energy use cases (Figure 2.6.1) include:

- quantum-enhanced energy demand forecasting (e.g. used for supply-demand balancing);
- quantum-enhanced renewable energy forecasting;
- optimising energy storage and demand response;

- optimising placement of energy facilities, e.g. power plants and renewable energy sites, by analysing multiple factors including geography, resource availability, and available infrastructure (see Figure 2.6.2 for an example[19]);

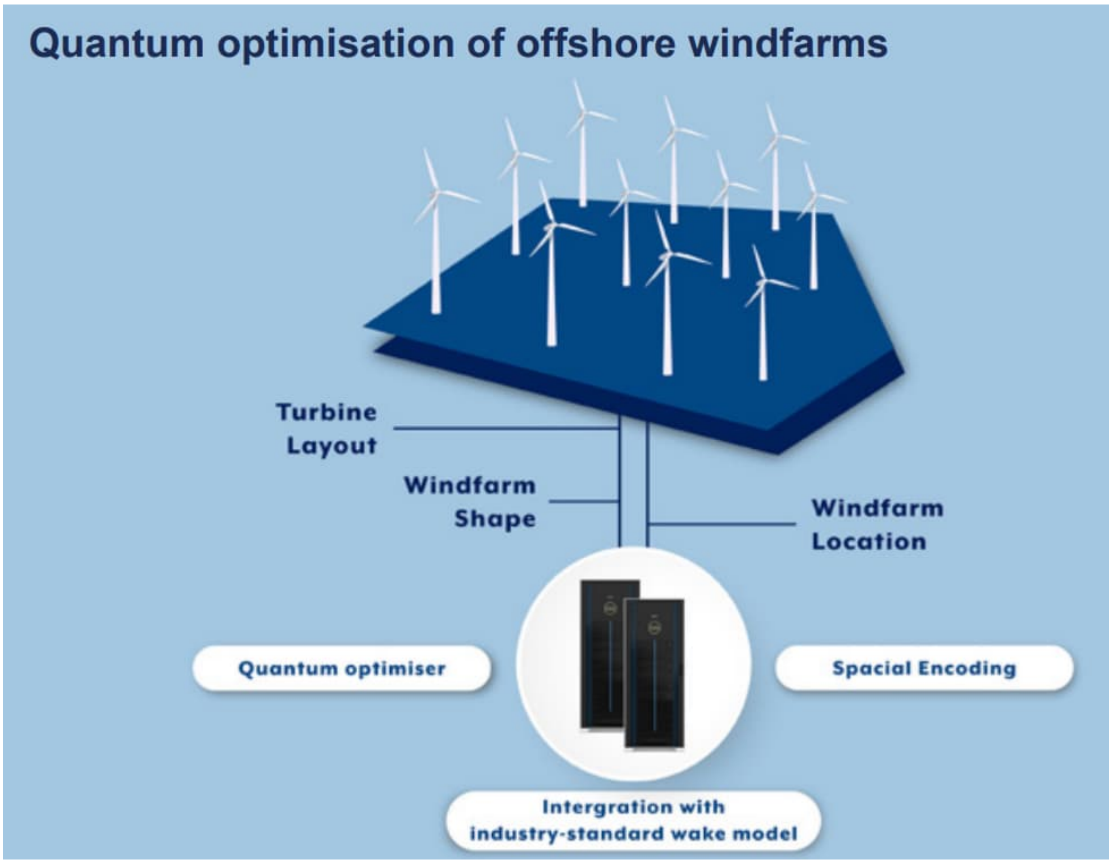


Figure 2.6.2: Optimisation of offshore windfarm placement (source: UKRI 2025)

- optimising scheduling of power generation units to implement to comply with energy demand in a cost-effective and efficient way, e.g. for dispatching of high-renewable power systems (a challenge for classical optimisation techniques because of the inherent stochasticity and intermittency of renewable power generation), using a NISQ quantum computer and Hybrid Quantum-Classical Dispatching (HQCD) quantum algorithm (a variational noise-resilient method based on QRC);

- optimising the fuel load problem in nuclear power plants;

- optimising the maintenance schedule for power generation units;

- improving predictive maintenance for the energy infrastructure by analysing data from sensors and monitoring equipment, to reduce downtime by identifying potential failures before they occur;

[19] Wind turbines create a trail of slower and more turbulent air ("wake") after the wind has passed through them.

- simulation, analysis and optimisation of electrical power grids for both meshed transmission networks and radial distribution networks (Figure 2.6.3), using QAOA (figure 2.6.4);

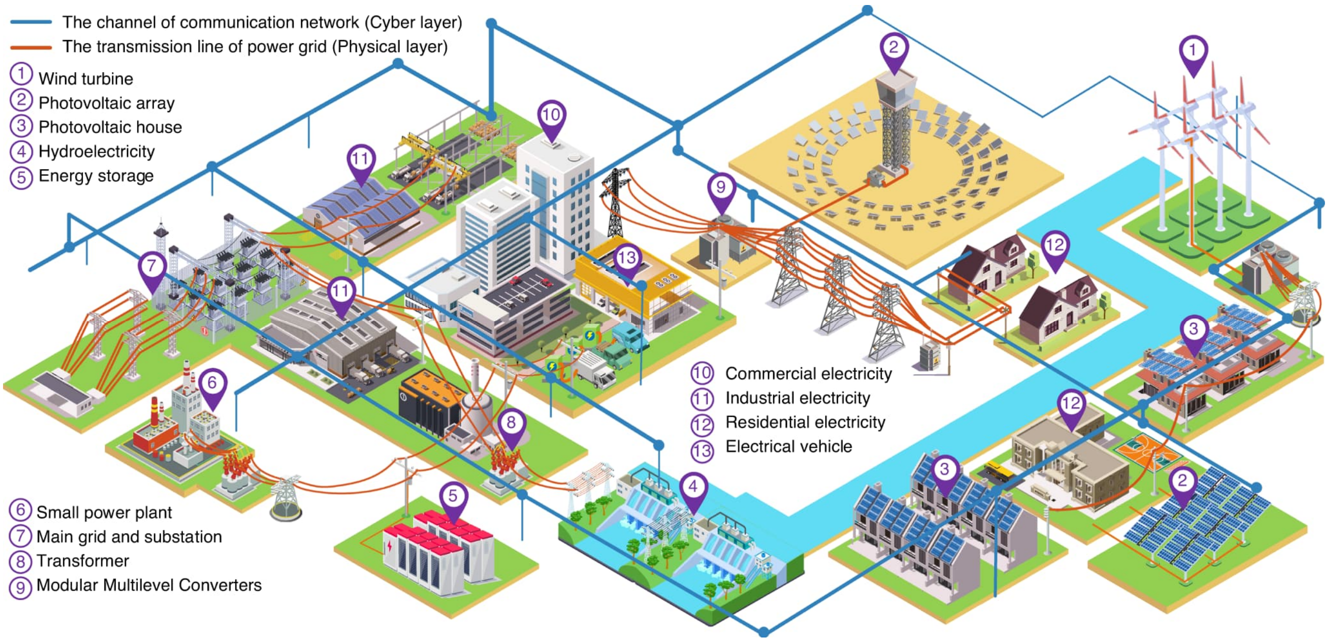


Figure 2.6.3: Cyber-physical power grid (source: Hang Jing et al. 2023)

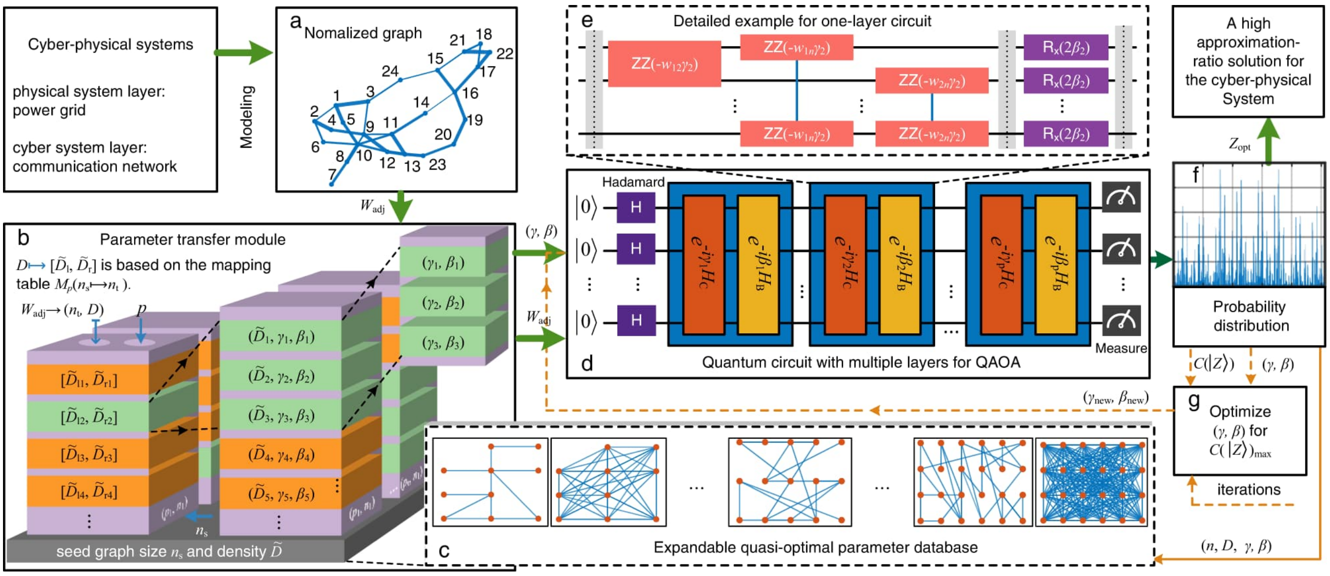


Figure 2.6.4: QAOA method for power grid optimisation (source: Hang Jing et al. 2023)

(a) Cyber-Physical System (CPS) model (normalised weighted graph)
(b) Parameter Transfer Module (PTM) for obtaining the quasi-optimal parameters (γ, β)
(c) expandable quasi-optimal parameter database for storing the mapping tables
(d) quantum circuit with multiple layers, using the transferred parameters (γ, β)
(e) one-layer quantum circuit (example)
(f) probability distribution obtained by measurement
(used for computing the cost function and selecting a high approximation-ratio solution)
(g) optimise the parameters (γ, β) for better performance and extend the database (c)

- optimising the robustness of Distribution System Operator (DSO) electrical power networks in the event of cable outages (known as the "N-1 problem") by rerouting the energy flow through a grid for every potential single-cable outage (Figure 2.6.5), e.g. by QUBO on a quantum annealer or QAOA on a gate-based quantum computer.

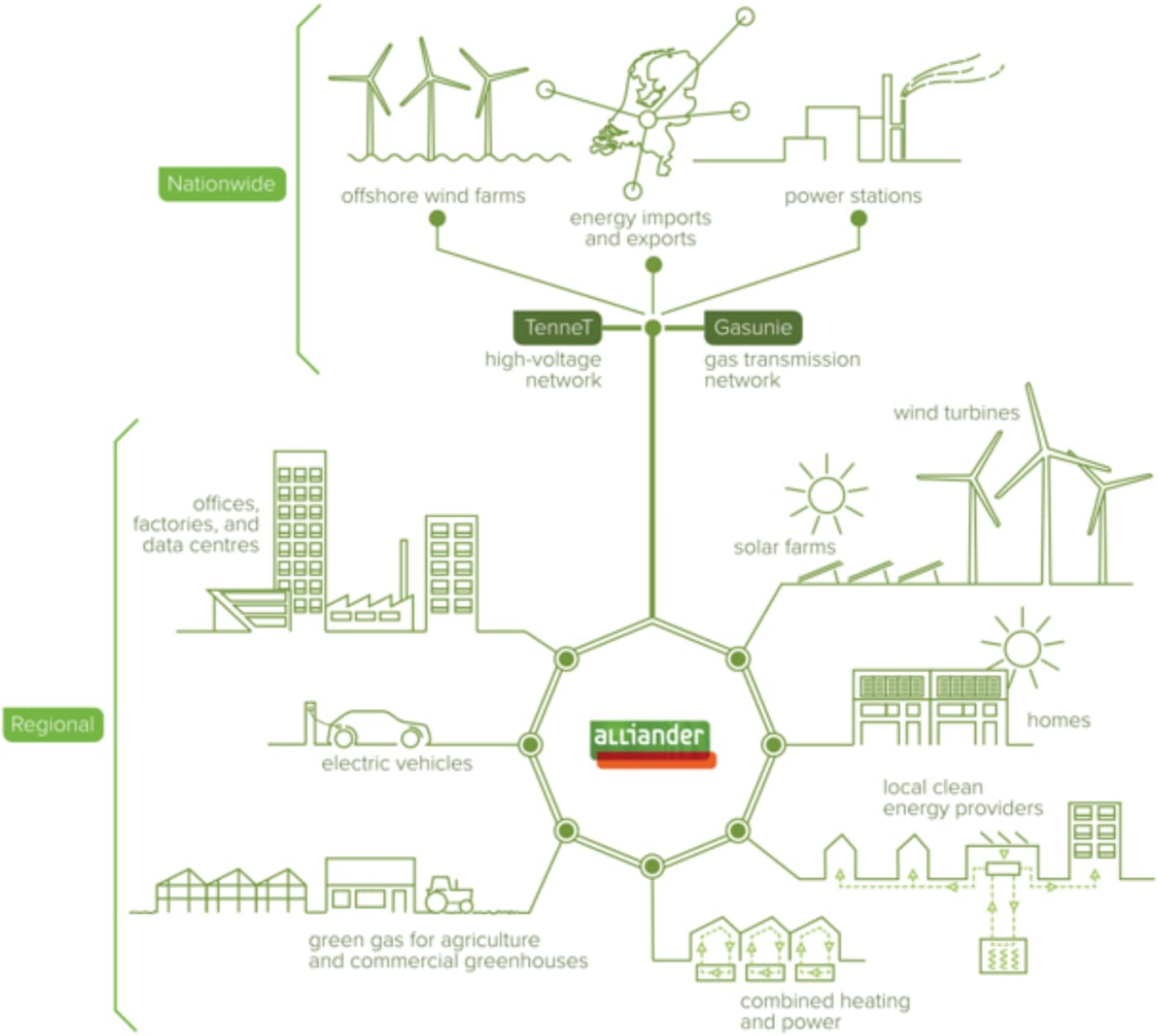
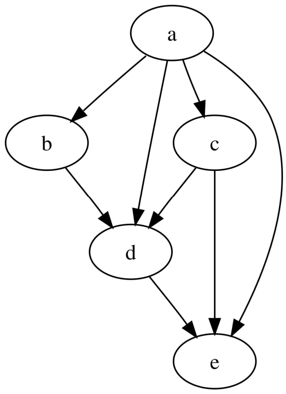


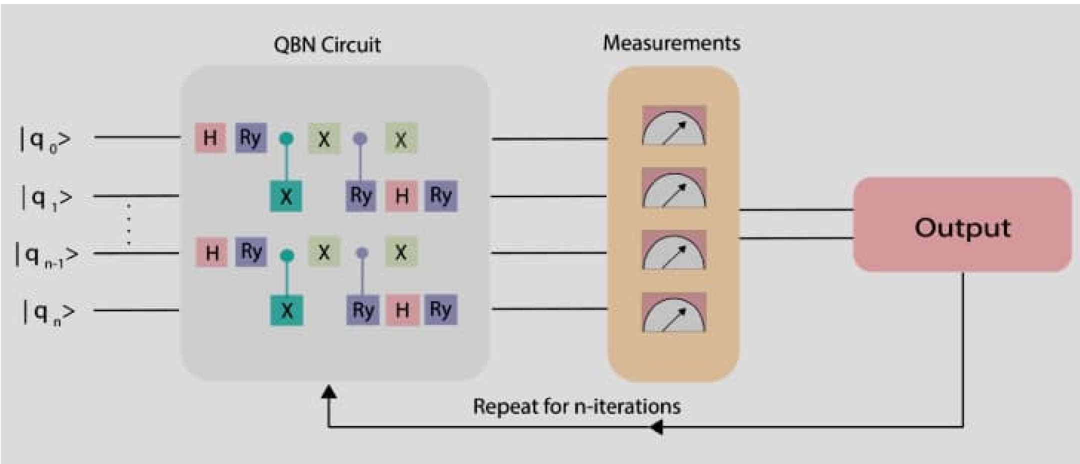
Figure 2.6.5: Electrical power grid as "N-1 problem" solution (source: QAL blog 2024)

Oil and gas use cases include:

- optimising oil exploration by processing data from various sensors (seismic sensors in particular);
- optimising refining, planning, production and transportation processes;
- detecting oil spills by processing satellite imaging data with Quantum Bayesian Networks (QBNs, Box 2.6.2).

A Bayesian Network (BN), named after the British statistician, philosopher and Presbyterian minister Thomas Bayes, is a graphical model using a Directed Acyclic Graph (DAG) to represent relationships and conditional dependencies between random variables. A DAG is a directed graph with no directed cycles, i.e. which is composed of of vertices and edges (arcs), with each edge directed from one vertex to another such that following those directions will never form a closed loop. A Quantum Bayesian Network (QBN) is a quantum computing extension of a traditional BN, replacing classical probability with quantum probability amplitudes to model relationships between variables.





Box 2.6.2: DAG and QBN quantum circuit (sources: Wikipedia / O.W. Siddiqui et al. 2024)

2.7. Transportation and logistics

Automotive quantum application algorithms could be implemented for many use cases, providing improvements over their classical counterparts or even enabling completely new use cases:

- Product design:
  - vehicle fluid dynamics optimisation with CFD methods (Box 2.7.1);

Computational Fluid Dynamics (CFD) uses numerical analysis to analyse and solve problems that involve fluid (liquids and gases) flows. CFD calculations simulate the free-stream flow of the fluid, and the interaction of the fluid with surfaces defined by boundary conditions. It is used to solve problems in multiple application fields, including aerodynamics, fluid flows, heat transfers, combustion analysis and weather simulations. The fundamental basis of almost all CFD problems are the Navier–Stokes equations (Box 2.7.2).

Box 2.7.1: Computational Fluid Dynamics (CFD)

The Navier–Stokes equations, named after the French engineer and physicist Claude-Louis Navier and the Irish physicist and mathematician George Gabriel Stokes, define single-phase fluid flows (i.e. the fluid can be a gas or a liquid, but not both). The solution of the equations yields a vector for every point in the fluid and for any moment in a time interval, whose direction and magnitude are the velocity of the fluid at that point in space and at that moment in time.

Box 2.7.2: Navier–Stokes equations

  - thermodynamic simulations such as Quantum Carnot Cycle (QCC)[20], Quantum Otto Cycle (QOC)[21] and Quantum Stirling Cycle (QSC)[22];
  - quantum-assisted design of new materials for weight reduction, strength improvement, etc.;
  - vehicle crash simulations for crashworthiness assessment using QML methods, replacing currently used resource-hungry Finite Element Analysis (FEA) methods;
  - simulations for autonomous vehicle testing;
  - test vehicle configuration optimisation.

---

[20] Named after the French military engineer and physicist Nicolas Léonard Sadi Carnot.

[21] Named after the German engineer Nicolaus August Otto.

[22] Named after the British engineer and clergyman Robert Stirling.

- Manufacturing:
  - manufacturing process simulation and optimisation, using Operations Research (OR) methods;
  - accuracy improvement of demand forecasting (for end-users and their suppliers);
  - supply-chain optimisation;
  - inventory and warehouse optimisation;
  - resource allocation optimisation;
  - manufacturing robots routing optimisation;
  - energy consumption and CO_2 emission reduction.
- Operations:
  - optimising fleet management and maintenance;
  - optimising staff scheduling;
  - quantum-assisted Automated Guide Vehicle (AGV) path/route planning;
  - AGV safety control, e.g. using Lyapunov-aware Quantum-inspired Reinforcement Learning (LQRL, Figure 2.7.1);

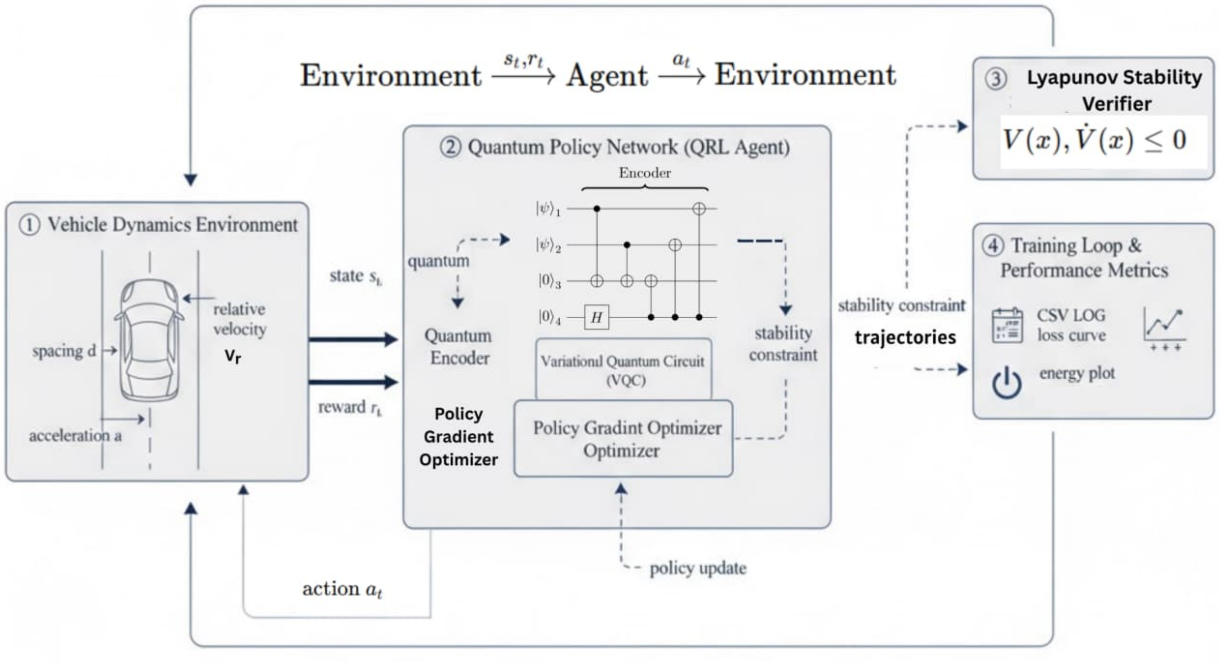


Figure 2.7.1: Overview of LQRL method (source: N. Kraipatthanapong et al. 2025)

- optimising placement of Electric Vehicle (EV) charging stations;

- optimising EV charging to minimise total electric power consumption, e.g. by means of VQE (Figure 2.7.2);

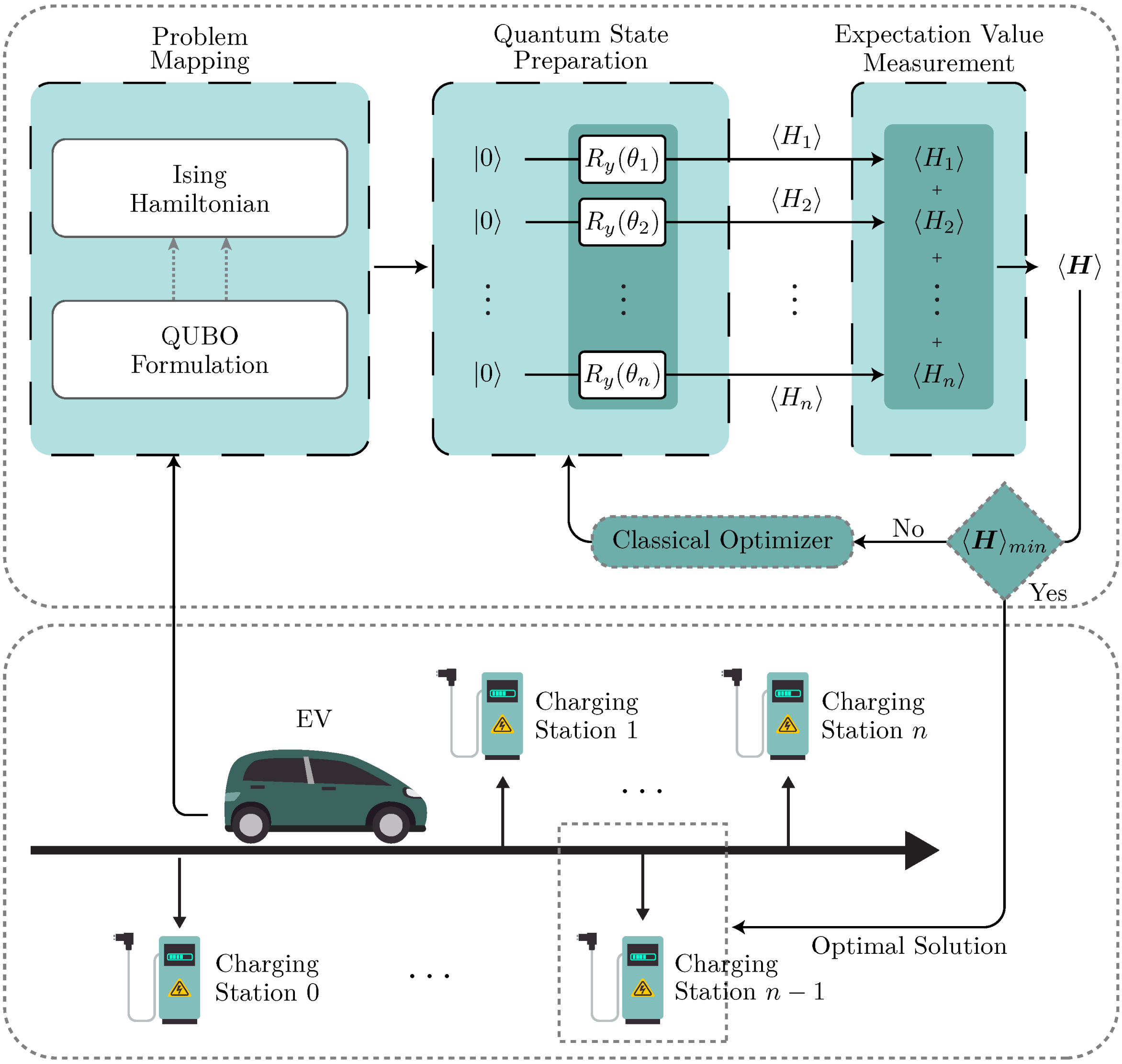


Figure 2.7.2: Overview of EV charging optimisation (source: U. Khalid et al. 2025)

- optimising package loading within transport vehicles;

- car and lorry routing optimisation; example: optimising rubbish collection routing, considering rubbish collection and disposal sites, rubbish types and volumes, collection vehicle types, road restrictions and traffic conditions[23];

[23] The goal is to balance costs (of fleet, fuel and labour), travel times and environmental impacts.

- traffic scheduling optimisation, traffic flow optimisation, and traffic disruption and congestion minimisation, e.g. by means of quantum-assisted cooperative control of traffic signals.

Well-known automotive use cases are the Binary Paint Shop Problem (BPSP) and the Capacitated Vehicle Routing Problem (CVRP), which are complex combinatorial optimisation problems.

Quantum computing solutions for automotive applications (Figure 2.7.3) use QUBO formulations on quantum annealers and Grovers-, QAOA-, Ising-, and QML-based solutions on gate-based quantum computers. Autonomous vehicle quantum computing solutions can be based on QMC running on quantum annealers or gate-based quantum computers. Some of the proposed solutions for automotive applications are based on quantum-inspired methods rather than on quantum computing.

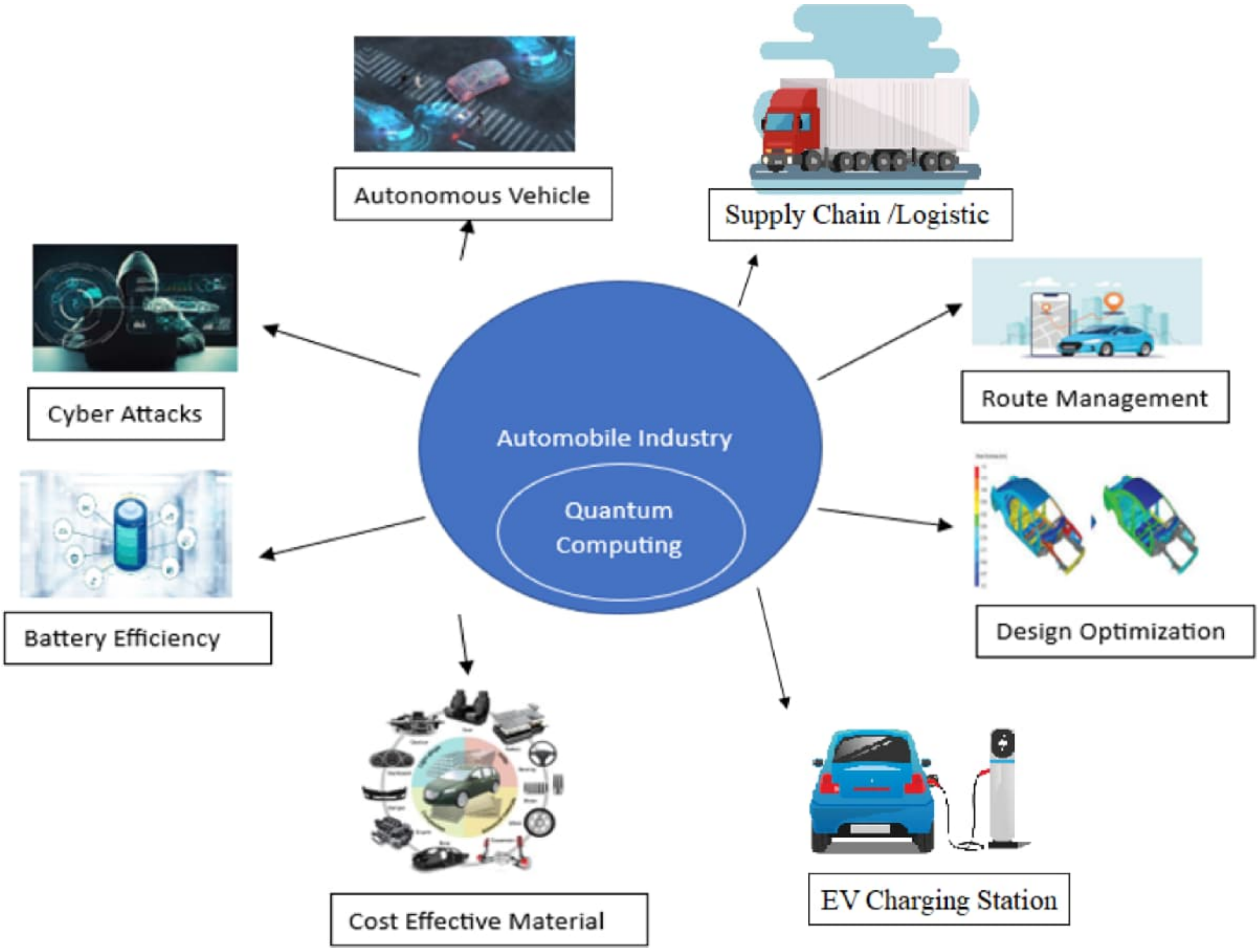


Figure 2.7.3: Automotive industry use cases (source: Muhamed Waqas Arshad 2025)

Major car manufacturers have established strategic partnerships with quantum computer manufactures and quantum software developers (Figure 2.7.4).

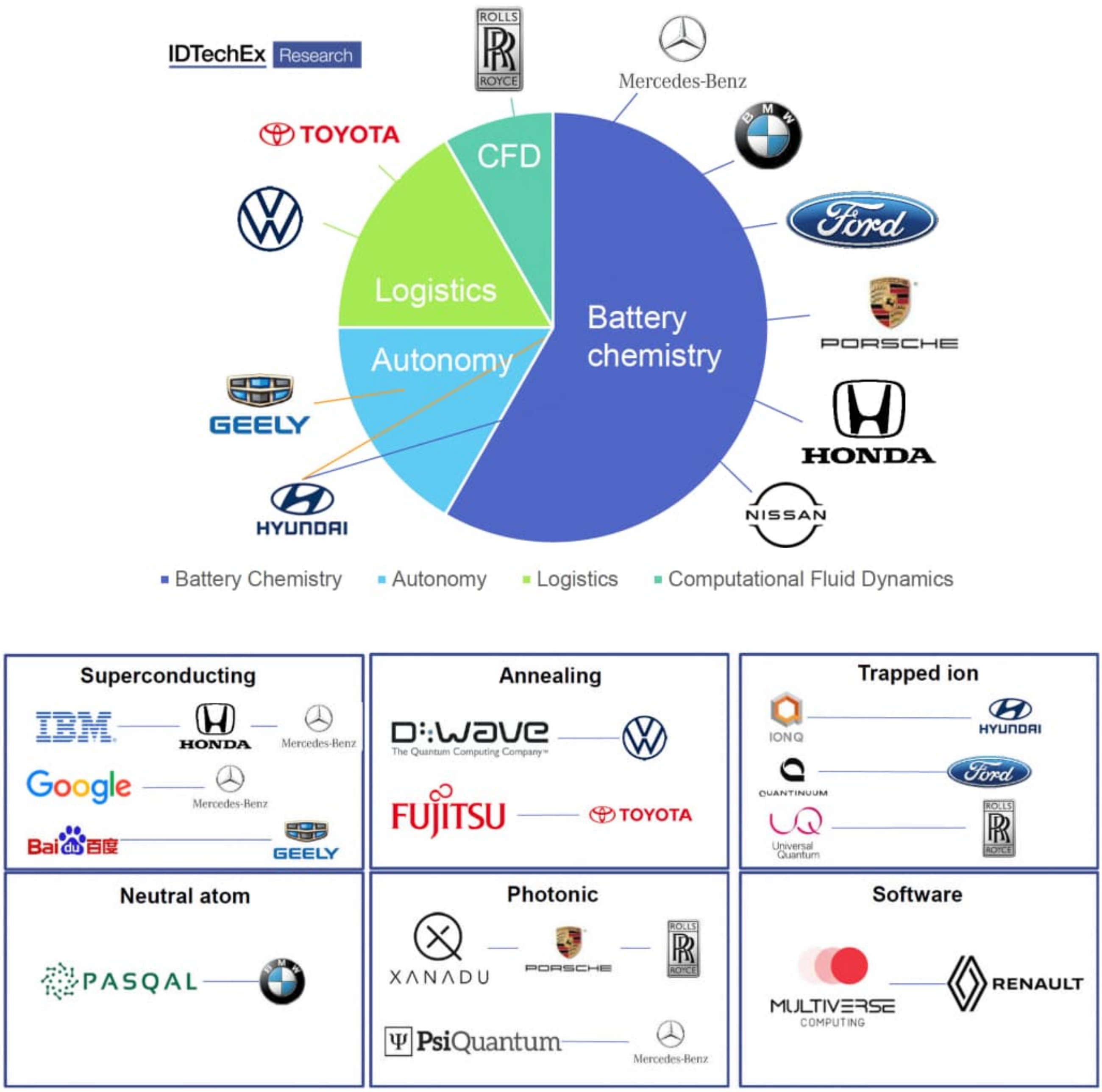


Figure 2.7.4: Car manufacturer quantum partnerships (source: IDTechEx 2024)

The focus of quantum application algorithms for air transportation is on CFD simulations and on optimising aircraft fleet planning (to maximise the capacity to meet demand while optimising the aircraft fill rate). The latter are commonly based on QUBO formulations (quantum annealers) or on QAOA and QML methods (gate-based quantum computers).

Quantum application algorithms could enable optimising airport and aircraft gates management (flight gate assignment problem), to minimise passenger waiting time (a problem that is difficult to solve with classical algorithms). Quantum application algorithms could also be used for flight route optimisation (tail assignment problem), which consists of assigning individual aircraft to a given set of flights and minimising the overall cost.

Other potential use cases for air transportation include:

- modelling of fluid dynamics for aircraft wing and engine design;
- improving flight data analysis;
- quantum-enhanced Air Traffic Management (ATM);
- quantum-assisted Fault Tree Analysis (FTA), used to determine the origin of complex failures, and fault prediction, used to enhance predictive maintenance and reduce unscheduled maintenance events;
- optimising cargo aircraft container loading;
- optimising routing of autonomous flying drones;
- optimising drone delivery packing using a QUBO formulation for the Drone Delivery Packing Problem (DDPP);
- quantum-assisted Unmanned Arial Vehicle (UAV) path/route planning;
- reducing CO_2 emissions in aviation.

Quantum application algorithms for the maritime sector are often based on QUBO formulations (quantum annealers) or on QAOA and QML quantum algorithms (gate-based quantum computers). Some examples:

- optimising fleet-based route planning;
- enhancing the efficiency of port and terminal operations, to reduce wait times and (including reduction of time spent at border control) and increase total throughput;
- optimising container handling by cranes in ports;
- optimising passive sonar tracking.

Use of quantum computing for transportation and logistics use cases is promising (Figure 2.7.5). Various solutions based on quantum annealing and gate-based quantum computing have already been developed and tested. It is currently also the subject of active research for NISQ quantum algorithm development.

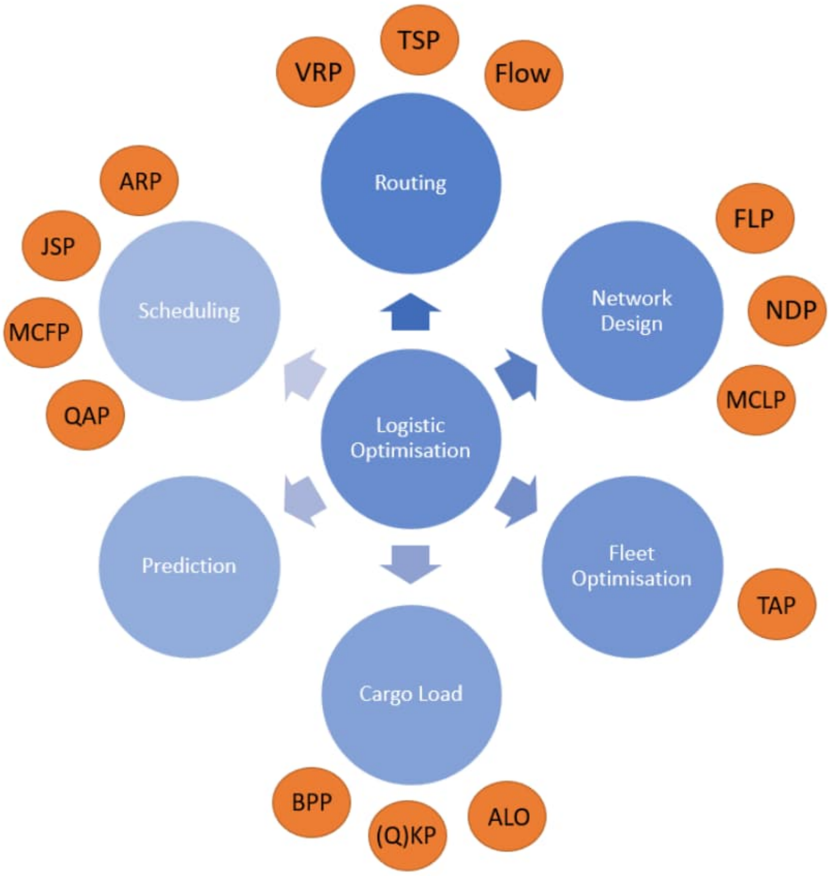


Figure 2.7.5: Quantum computing in transportation and logistics (source: Frank Phillipson 2025)

ALO: Aircraft Loading Optimization
ARP: Aircraft Recovery Problem
BPP: Bin Packing Problem
FLP: Factory Layout Planning
JSP: Job Shop Problem
KP: Knapsack Problem
MCFP: Manufacturing Cell Formation Problem
MCLP: Maximal Covering Location Problem
NDP: New Product Development
QAP Quadratic Assignment Problem
QKP: Quantum Knapsack Problem
TAP: Tail Assignment Problem
TSP: Travelling Salesman Problem
VRP: Vehicle Routing Problem

Note

More sophisticated algorithms have been developed for some of the algorithms shown in Figure 2.7.5, for example:

- Capacitated Vehicle Routing Problem (CVRP), Multi-Depot Capacitated Vehicle Routing Problem (MDCVRP) and Time-Dependent Vehicle Routing Problem with Time Windows (TDVRPTW) for Vehicle Routing Problem (VRP);
- Flexible Job Shop Scheduling Problem (FJSP) and Distributed Flexible Job Shop Scheduling Problem (DFJSP) for Job Shop Problem (JSP);
- Multi-Dimensional Knapsack Problem (MDKP) and Required Multiple Quadratic Knapsack Problem (RMKQP) for Knapsack Problem (KP);

- one-dimensional Bin Packing Problem (1dBPP) and three-dimensional Bin Packing Problem (3dBPP) for Bin Packing Problem (BPP);
- Travelling Salesman Problem with Time Windows (TSPTW) and Open Loop Travelling Salesman Problem (OTSP) for Travelling Salesman Problem (TSP).

An example of a transportation use case that draws a lot of attention is optimising multi-modal transport planning[24].

Different quantum computing methods could be used for transportation applications, including QAOA, VQE and QML.

[24] Multimodal transport refers to transporting cargo from origin to destination by more than one transportation mode. An example is when a container is transported by ship to a seaport, transported by barge to an intermediate port and transferred by a lorry to its final destination.

2.8. Retail

Proposals have been made for several use cases, including:

- Optimising the marketing mix and media plans and maximisation of advertising revenues (promotion optimisation), e.g. by the use of recommender systems (Box 2.8.1) in online sales, opinion analysis, etc.

A recommender system is a computing algorithm that predicts users' preferences for particular items and filters content relating to products and services, accordingly, enabling presentation of personalised suggestions.

Box 2.8.1: Recommender system

The solution could be either quantum-inspired or based on quantum annealing or gate-based quantum computing, e.g. by means of the Variational Quantum Recommendation System (VQRS) quantum algorithm (Figure 2.8.1) or by means of a Discrete-Time Markov Chain (DTMC) quantum algorithm (Figure 2.8.2).

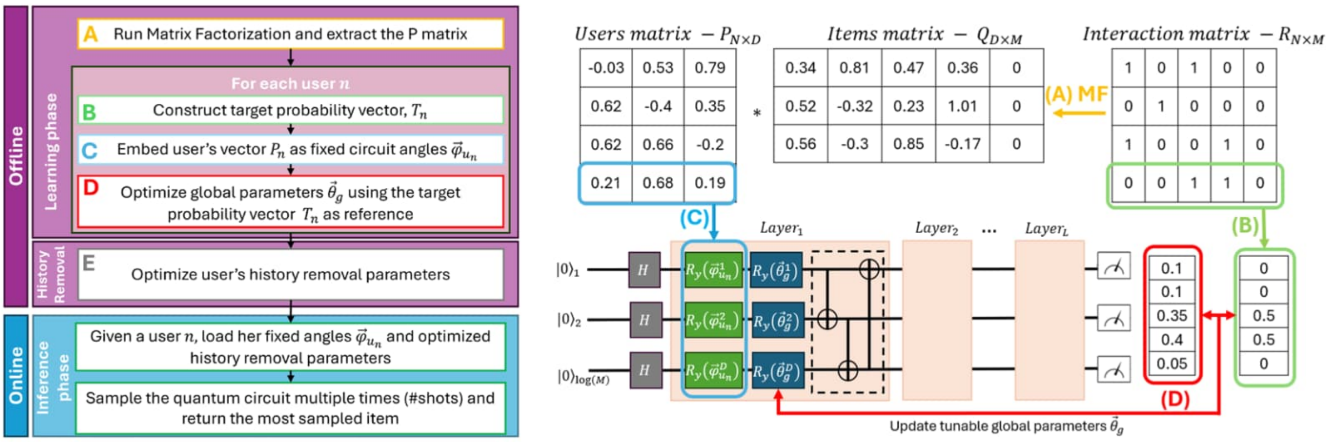


Figure 2.8.1: VQRS quantum algorithm (source: S. Debi and A. Makmal 2025)

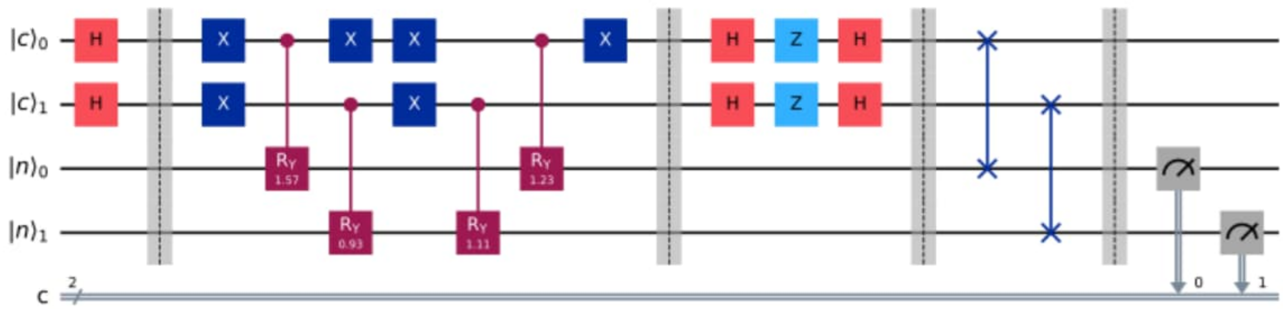


Figure 2.8.2: DTMC quantum circuit (source: Or Peretz et al. 2025)

- Quantum-enhanced real-time market simulation to test and predict market responses to different business strategies in real-time, providing a competitive edge in rapidly changing markets.

- Quantum-enhanced machine learning for market segmentation, enabling more targeted marketing and product development.

- Quantum computing-based customer analytics, e.g. using QNLP based text analytics.

- Quantum-assisted Customer Relationship Management (CRM), to gain deeper insights into customer preferences and behaviour patterns thus enabling more personalised marketing strategies and customer service solutions (presumably enhancing customer satisfaction and loyalty).

- Quantum computing-based price optimisation, taking into account variables like cost of goods sold, competitor pricing, customer sensitivity, regulatory requirements and brand standards.

- Quantum computing-based workforce optimisation, taking into account variables like shift timing, task assignments, staffing levels and cross-training needs.

- Quantum computing-based last mile delivery, taking into account variables like vehicle capacity, traffic, customer time windows, fuel costs, driver regulations and environmental concerns. Example: Quantum for Real Package Delivery (Q4RPD) solution based on quantum annealing CQM hybrid solver (Figure 2.8.3).

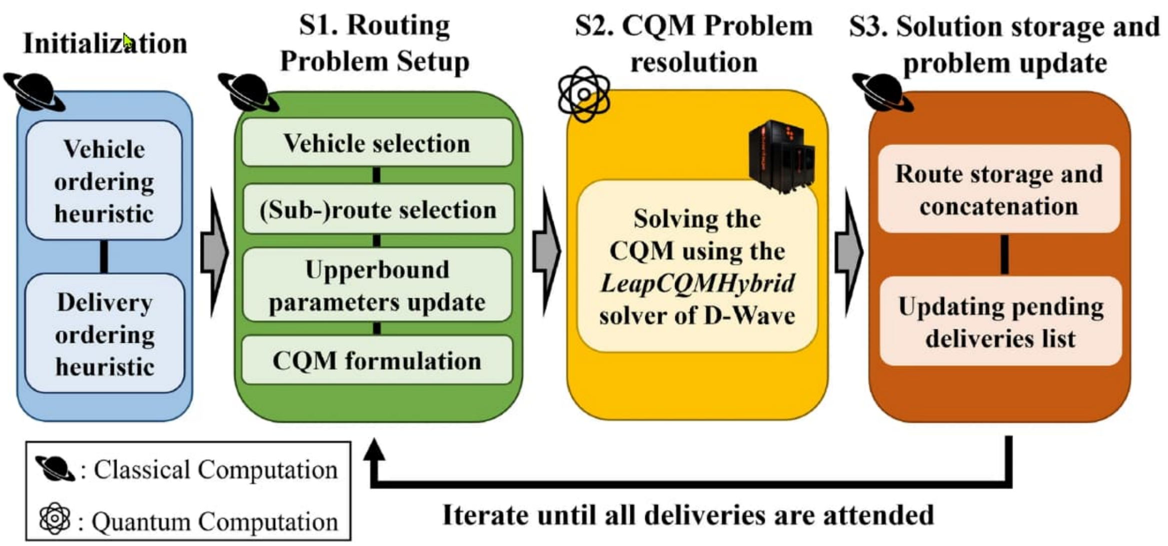


Figure 2.8.3: Q4RPD method (source: Eneko Osaba 2024)

The retail sector could also benefit from generic quantum computing solutions for logistics improvements, e.g. inventory optimisation.

2.9. Telecommunications

Use cases being developed or proposed for telecommunications include (several of them are implemented by a QUBO formulation on a quantum annealer):

- optimising network planning and provisioning;
- optimising network traffic management;
- predictive network analysis using QRC;
- optimising resource allocation for Wide-Area Networks (WANs);
- optimising configurations of paths and wavelengths on landline fibre optics networks and satellite networks;
- optimising placement, power and frequency assignment of overlapping cells in mobile networks;
- optimising placement and configuration of Multiple Input Multiple Output (MIMO) antennas in mobile networks (Figure 2.9.1), e.g. using the CQAO quantum algorithm (Box 2.9.1);

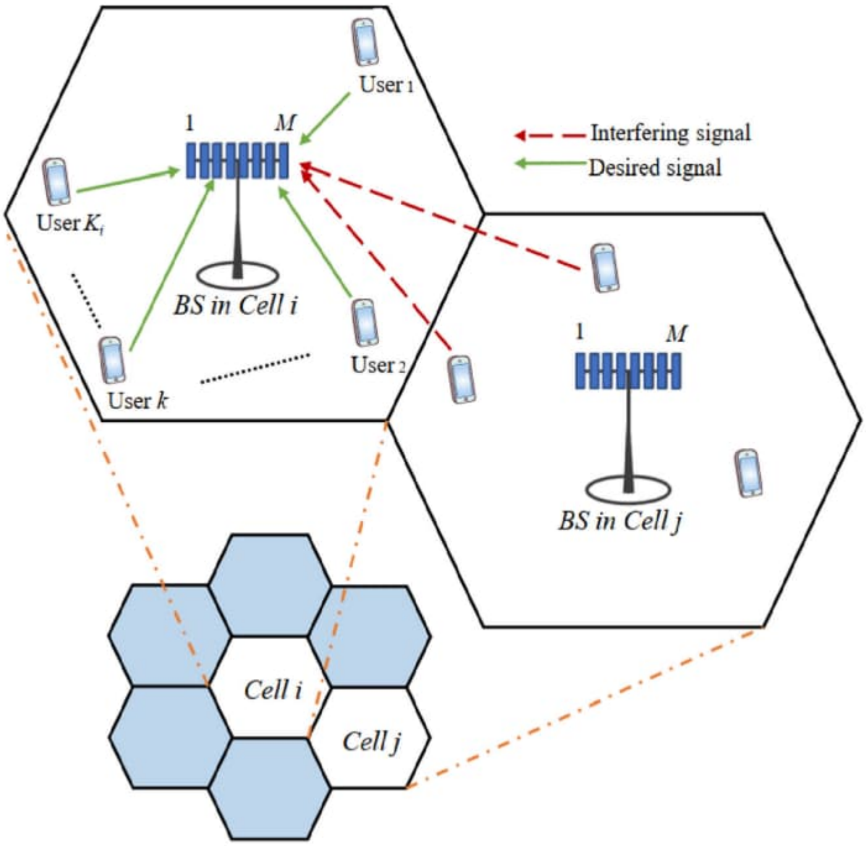


Figure 2.9.1: Uplink multi-cell MIMO system (source: M.R. Almasaoodi et al. 2023)

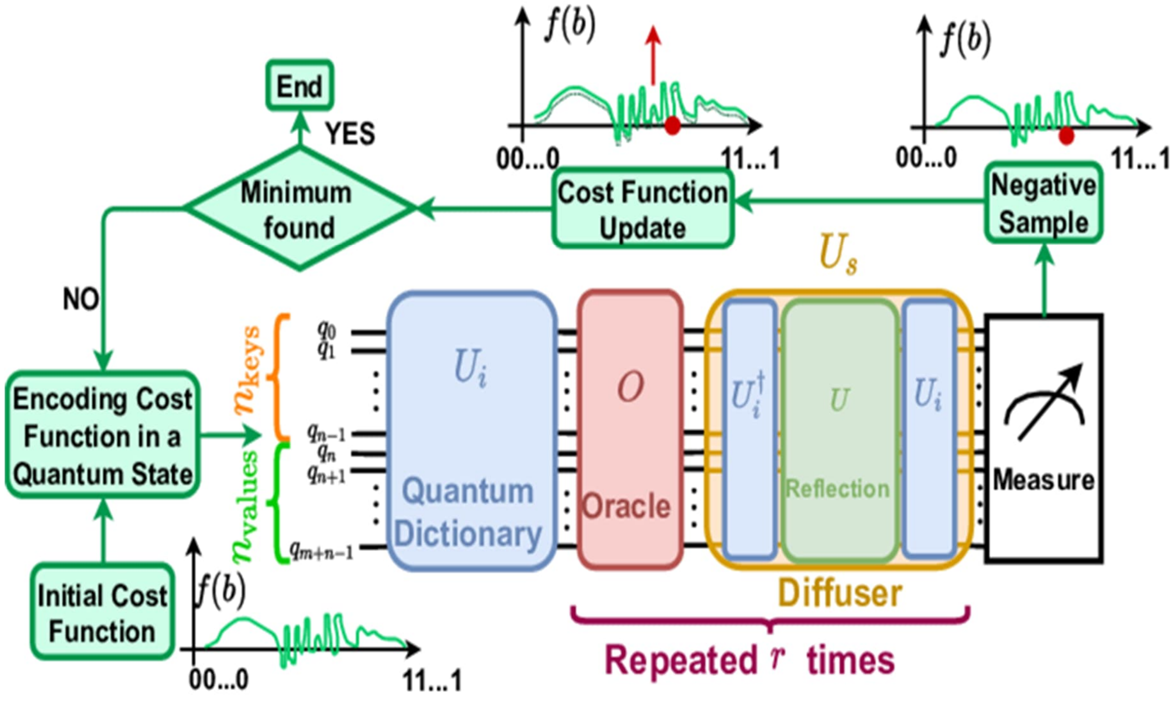
The Constrained Quantum Optimization Algorithm (CQAO) identifies the best extreme value (either the minimum or maximum) of an objective function or an unsorted database. The CQAO method combines two algorithms:

1) Logarithmic Search Algorithm (LSA), which is used to identify a specific searched item within a sorted database;
2) Constrained Quantum Relation Testing (CQRT), which is a quantum function that is is used to adapt the LSA algorithm so that it suitable for an unsorted database and capable of handling constrained cases.

Box 2.9.1: Constrained Quantum Optimization Algorithm (CQAO) algorithm

- optimising tracking of mobile devices across mobile base stations (e.g. using an hybrid solver on a quantum annealer);
- wireless network energy efficiency improvement using index modulation techniques based on the GAS quantum algorithm (Box 2.9.2);

Grover Adaptive Search (GAS) is a quantum algorithm that provides quadratic speedup for solving binary optimisation problems, by iteratively using Grover's search algorithm to narrow down the search for optimal solutions below an adaptive threshold. The algorithm starts with a superposition of all states and repeatedly applies Grover's search, with an oracle that flags states below the current threshold, to amplify the amplitudes of promising solutions. When such a solution is found, the threshold is updated to the new minimum value, narrowing the search space for subsequent iterations.



Box 2.9.2: Grover Adaptive Search (GAS) quantum algorithm (source: D. Volpe et al. 2024)

- minimising the Peak-to-Average Power Ratio (PAPR) for OFDM systems (Box 2.9.3).

Orthogonal Frequency Division Multiplexing (OFDM) divides a high-bandwidth signal into multiple closely spaced parallel narrowband signals. This technique improves spectral efficiency for high data rates and also provides robustness against interference and multipath fading.

Box 2.9.3: Orthogonal Frequency Division Multiplexing (OFDM)

Quantum computing holds the potential for addressing complex optimisation problems for the telecommunications industry. A multitude of quantum application algorithms have already been developed or proposed. However, most of these algorithms will require reliable and powerful quantum computers to provide quantum advantage.

2.10. Industry and manufacturing

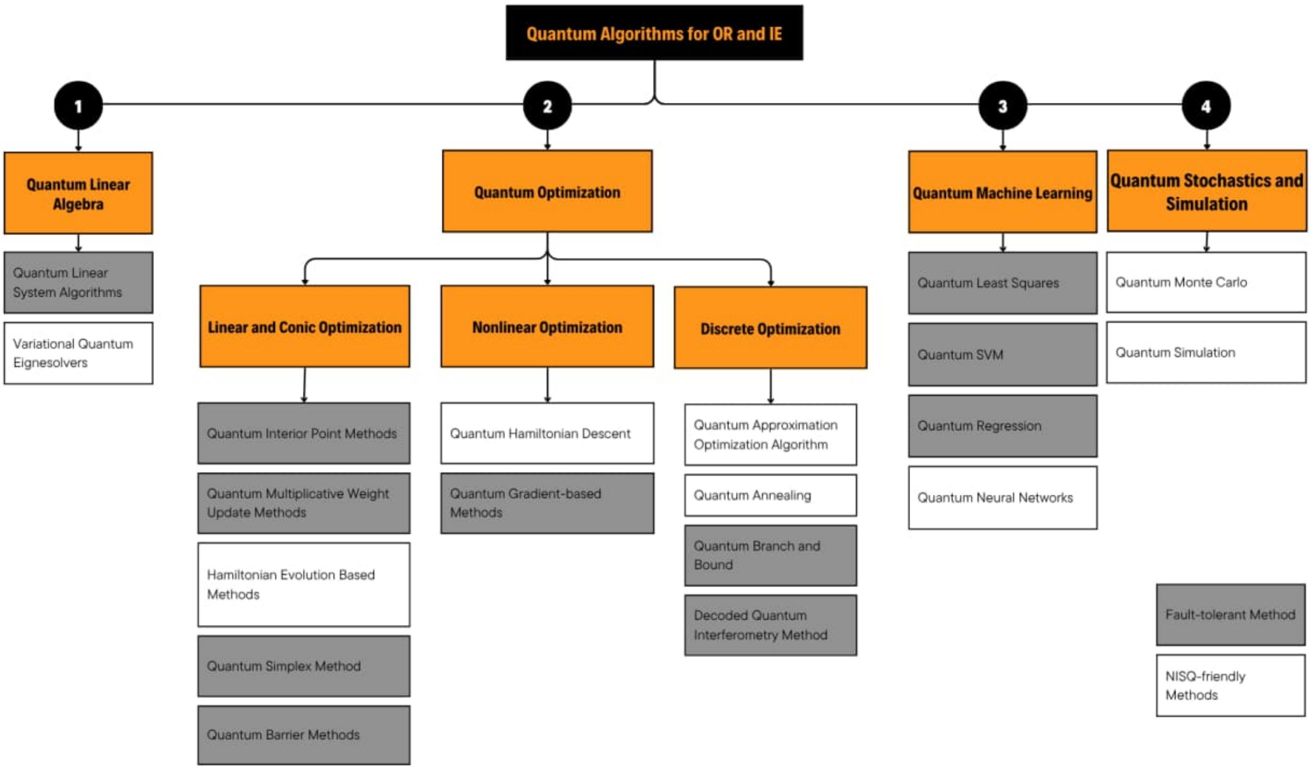


Figure 2.10.1: Quantum algorithms for industrial engineering (source: E.L. Tucker et al. 2025)

Various quantum application algorithms have been developed or have been proposed for industry/manufacturing use cases (Figure 2.10.1). Some use case examples:

- Use cases based on generic solutions for transportation and logistics (supply chain optimisation, warehouse and inventory optimisation and demand forecasting).

- Manufacturing process simulation and optimisation, using Operations Research (OR) methods.

- Optimised electronic circuit design:

  Classical circuit placement (routing) optimisation is a problem problem that is difficult to solve with classical algorithms but could be partly handled by quantum algorithms. This problem could be solved with a QUBO formulation on a quantum annealer or gate-based quantum computer (requires lots of qubits). It could be useful for ASIC and FPGA developers and for Computer-Aided Design (CAD) tools.

- Quantum-enhanced Factory Layout Planning (FLP, Figure 2.10.2):

  The main goal is to to minimise construction costs and operational costs, taking into account scalability requirements and various trade-offs.

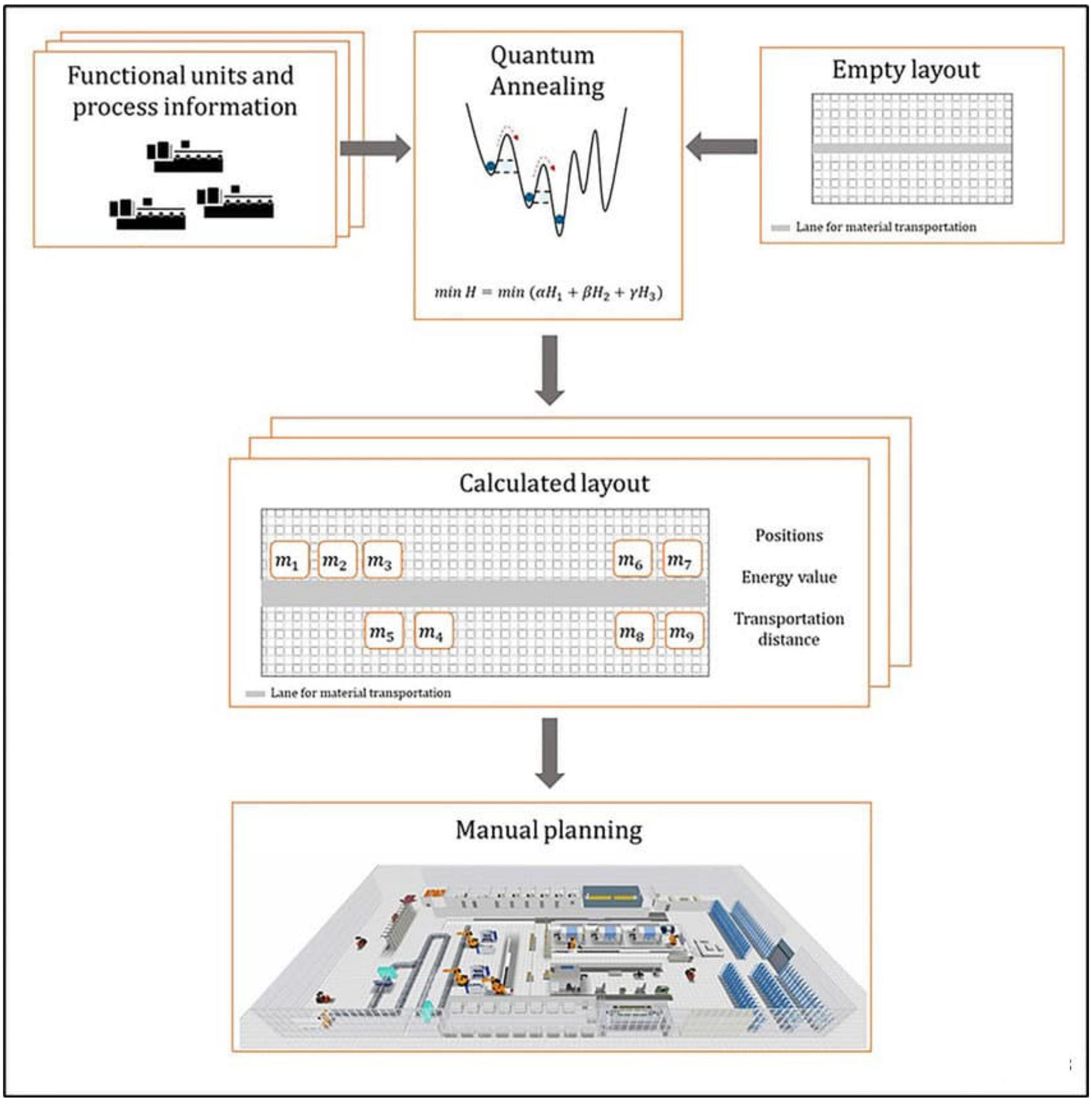


Figure 2.10.2: Quantum annealing based FLP (source: Matthias Klar et al. 2022)

- Improved prototyping and testing:

  The goal is improving the product design and reducing the cost of prototyping (e.g. by reducing the testing effort).

- Job Shop Problem (JSP) aka Job Shop Scheduling Problem (JSSP):

  Each job consists of a sequence of tasks that need to be processed in a specific order. Each task must be performed on a specific machine, and no two tasks for the same job can be processed simultaneously. Several quantum algorithms have been proposed to solve this computational challenging optimisation problem, with a lot of variations depending on the problem constraints. These solutions operate on quantum annealers or on gate-based quantum computers using VQE. They compete with still-improving classical algorithms based on machine learning methods[25].

- Robot localisation:

  Localisation allows mobile robots to create an internal map of their environment, which is essential for tasks such as surveying, manipulation, inspection and delivery. A quantum computing solution for this computational challenging optimisation problem could be implemented using a Grover quantum search oracle to perform a double localisation on a 2D map, one for the horizontal axis and another for the vertical axis (Figure 2.10.3). This solution could be particularly beneficial in environments with high location ambiguity or large search spaces, such as a warehouse with many aisles or complex navigation zones. For the time being, the actual effectiveness of this approach is however severely constrained by the technical capabilities of currently available quantum computers.

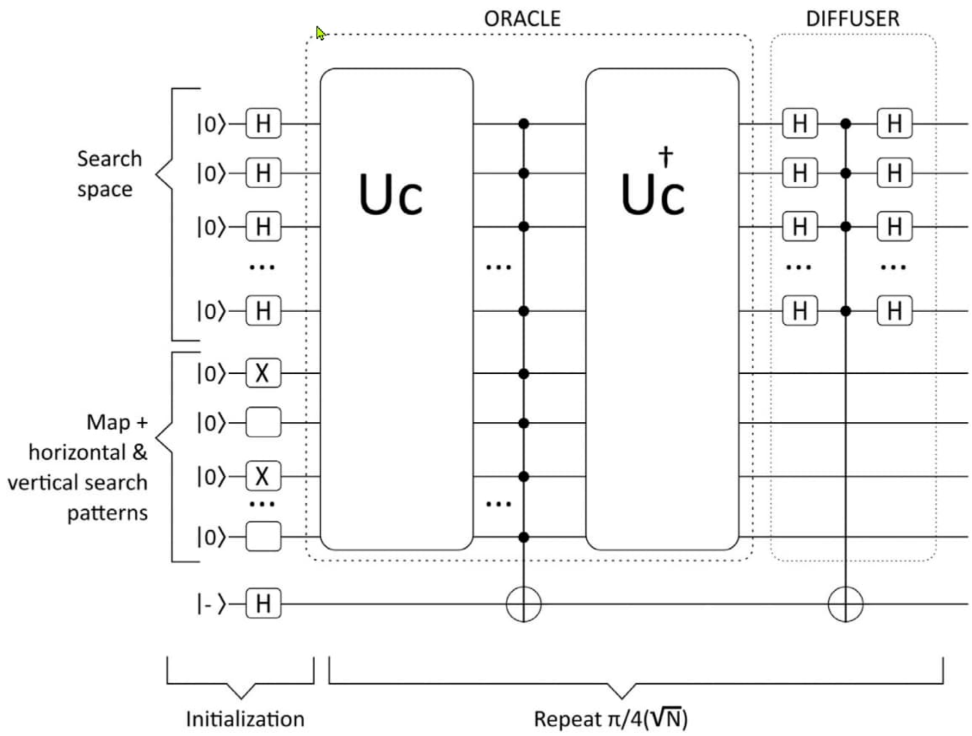


Figure 2.10.3: Quantum algorithm for robot localisation (source: Unai Antero et al. 2025)

- Optimised robot planning:

  The goal is to implement efficient load balancing (within the cycle time of the whole production line) between the robots operating in a manufacturing plant or logistic warehouse, with

[25] In 2024, a team in Germany and the Netherlands determined that quantum speedup would require physical error rates below 10^{-6} and qubit readout times below 10 ns.

optimal sequencing of individual tasks and robot movements and avoiding traffic jams. This is a variation of the JSP and Vehicle Routing Problem (VRP) problems.

- Quantum-enhanced robot inspection of industrial components:

  The goal is to optimise robotic inspection tasks derived from CAD models, which presents a considerable computational challenge that could be addressed by the use of hybrid quantum-classical optimisation methods on quantum annealers or gate-based quantum computers.

- Improved quality control and defect detection (precision manufacturing):

  Quantum application algorithms could assist in quality control by detecting equipment failures before they occur. This can reduce the downtime by allowing for proactive maintenance.

- Quantum-assisted predictive maintenance:

  The goal is to predict the remaining useful life of engines and other manufacturing sensitive components.

2.11. Civil engineering

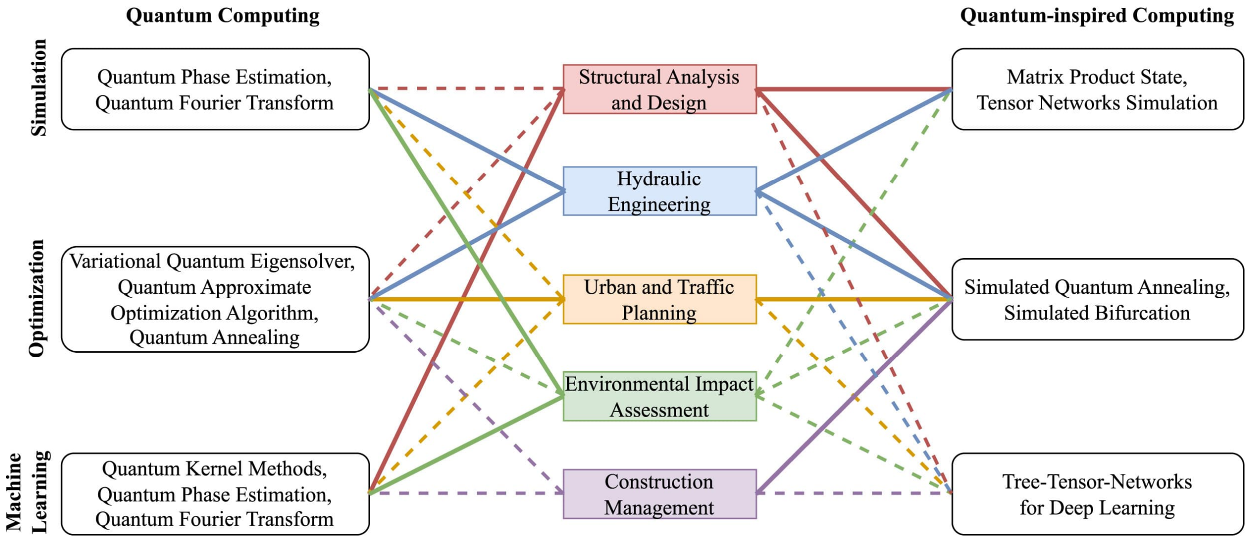


Figure 2.11.1: Quantum computing for civil engineering (source: Joern Ploennigs et al. 2025)

Quantum use cases developed or proposed for civil engineering (Figure 2.11.1) include:

- topology optimisation (engineering methodology for designing light-weight high-strength mechanical structures);
- simulations for structural analyses, e.g. QAOA (Figure 2.11.2) for the Quantum Finite Element Method (Q-FEM, Box 2.11.1);

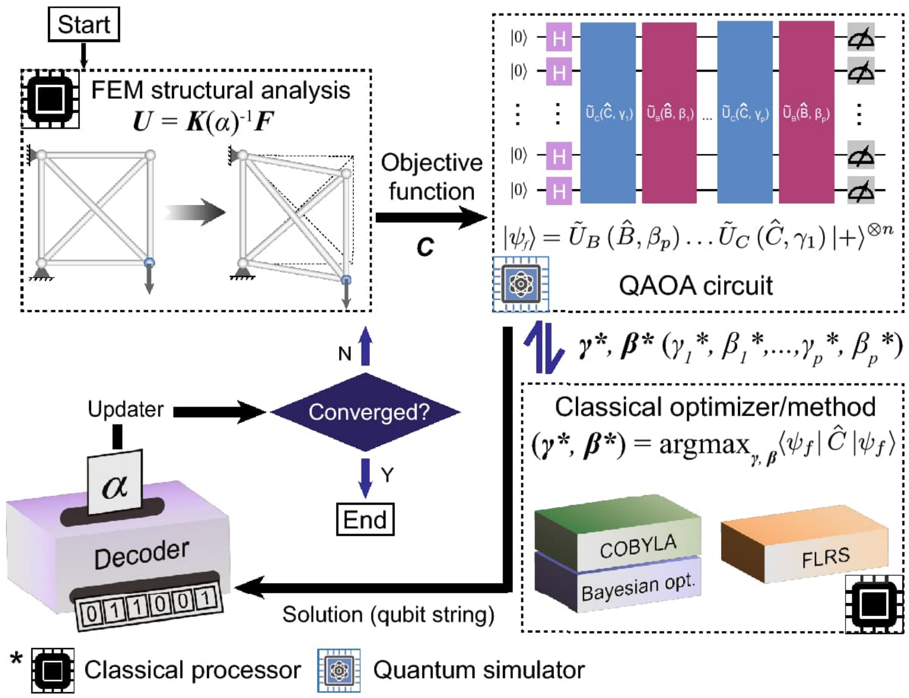


Figure 2.11.2: Quantum Finite Element Method based on QAOA (source: J. Xiao et al. 2025)

Finite Element Method (FEM) is a numerical method for solving engineering problems by breaking a large structure into smaller, simpler elements. Analysing the behaviour of these elements by means of mathematical equations allows engineers to predict how the entire structure will respond to forces, heat, etc. thus allowing for optimising a design before it is constructed physically. Quantum Finite Element Method (Q-FEM) is a hybrid quantum-classical algorithm that uses quantum computation to solve the large systems of equations that arise from the classical FEM.

Box 2.11.1: Quantum Finite Element Method (Q-FEM)

- optimise energy management in buildings equipped with battery energy storage and renewable energy generation systems, e.g. by using an adaptive quantum approximate optimisation-based Model Predictive Control (MPC) strategy, which is based on casting a QUBO problem as an Ising Hamiltonian that is solved by the gate-based quantum computing QAOA method, using Bayesian optimisation for the objective function (Figure 2.11.3);

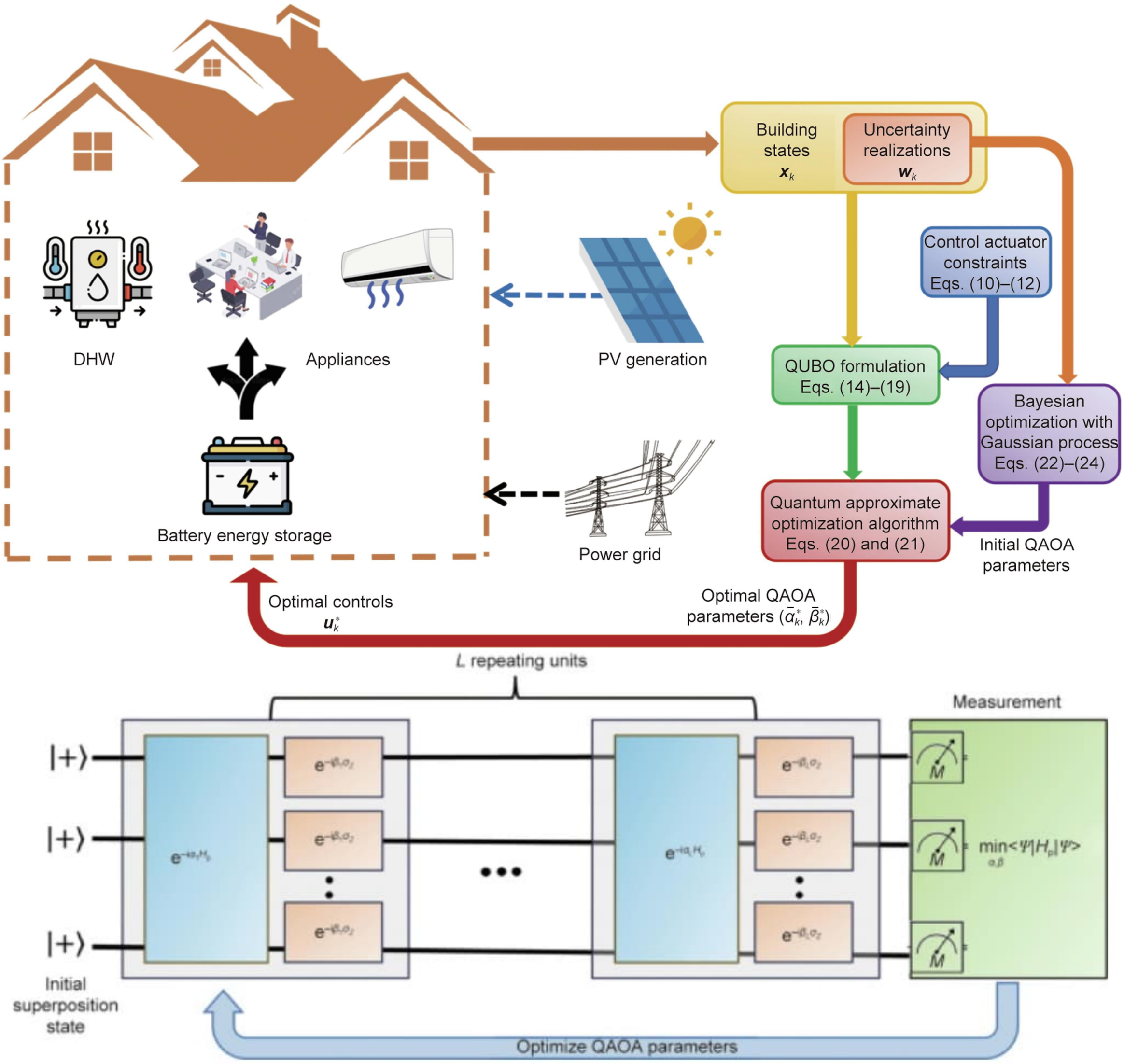


Figure 2.11.3: Quantum optimisation-based MPC (source: A. Ajagekar and F. You 2025)

- optimise cable routing, e.g. defining a QUBO formulation for the Cable Routing Optimization Problem (CROP) or solving CROP with VQE;
- optimising building construction scheduling;
- optimising roadwork scheduling;
- optimising sensor placement for road traffic systems, water distribution networks, etc.;
- optimising workforce schedules;
- improving material delivery balancing;
- quantum-enhanced energy consumption prediction (used for improving energy efficiency and reducing carbon emissions);
- reducing planning time for large-scale infrastructure projects (including smart city urban planning and development), while improving resource utilisation.

In the long term, quantum computing could revolutionise the civil engineering domain. Given the current state of quantum computer technology, practical large-scale applications are however not expected soon. Meanwhile quantum-inspired approaches are being developed and tested.

2.12. Content and media

Quantum use cases developed or proposed for content and media include:

- optimisation of TV commercials allocation;
- quantum-enabled gaming;
- creation of quantum music and quantum musical instruments (Figure 2.12.1);

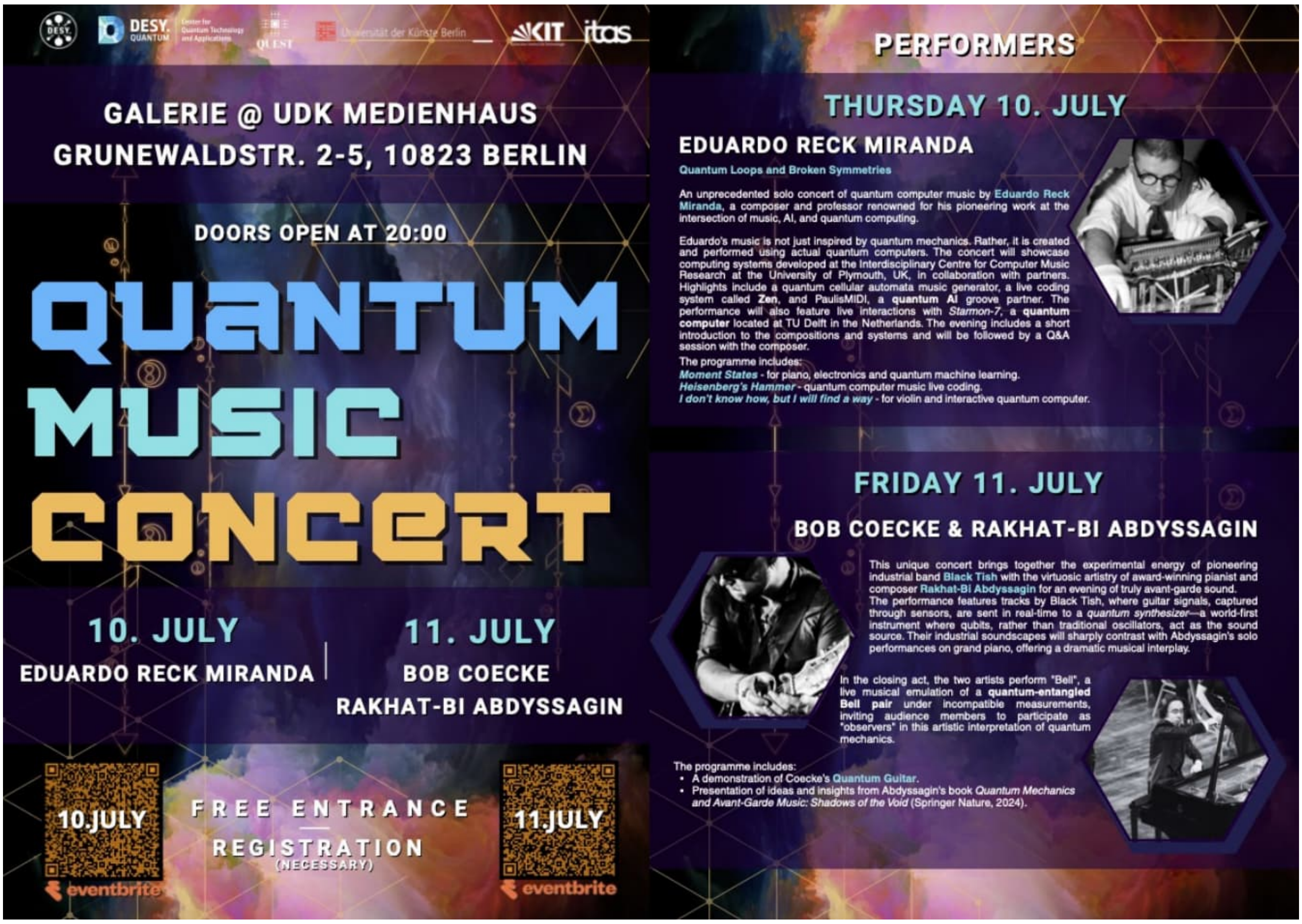


Figure 2.12.1: Quantum music concert (source: Bob Coecke[26] 2025)

- quantum-assisted video editing and rendering;
- quantum-assisted image and video compression;
- quantum-assisted dynamic adjustment of streaming content quality;

---

[26] Bob Coecke is a Belgian theoretical physicist and logician who is Chief Scientist at Quantinuum. He was Professor of Quantum foundations, Logics, and Structures at Oxford University until 2020. Bob is also a composer and musician and is one of the pioneers of employing quantum computers for music.

- quantum-enabled art creation, e.g. quantum drawings (Figure 2.12.2).

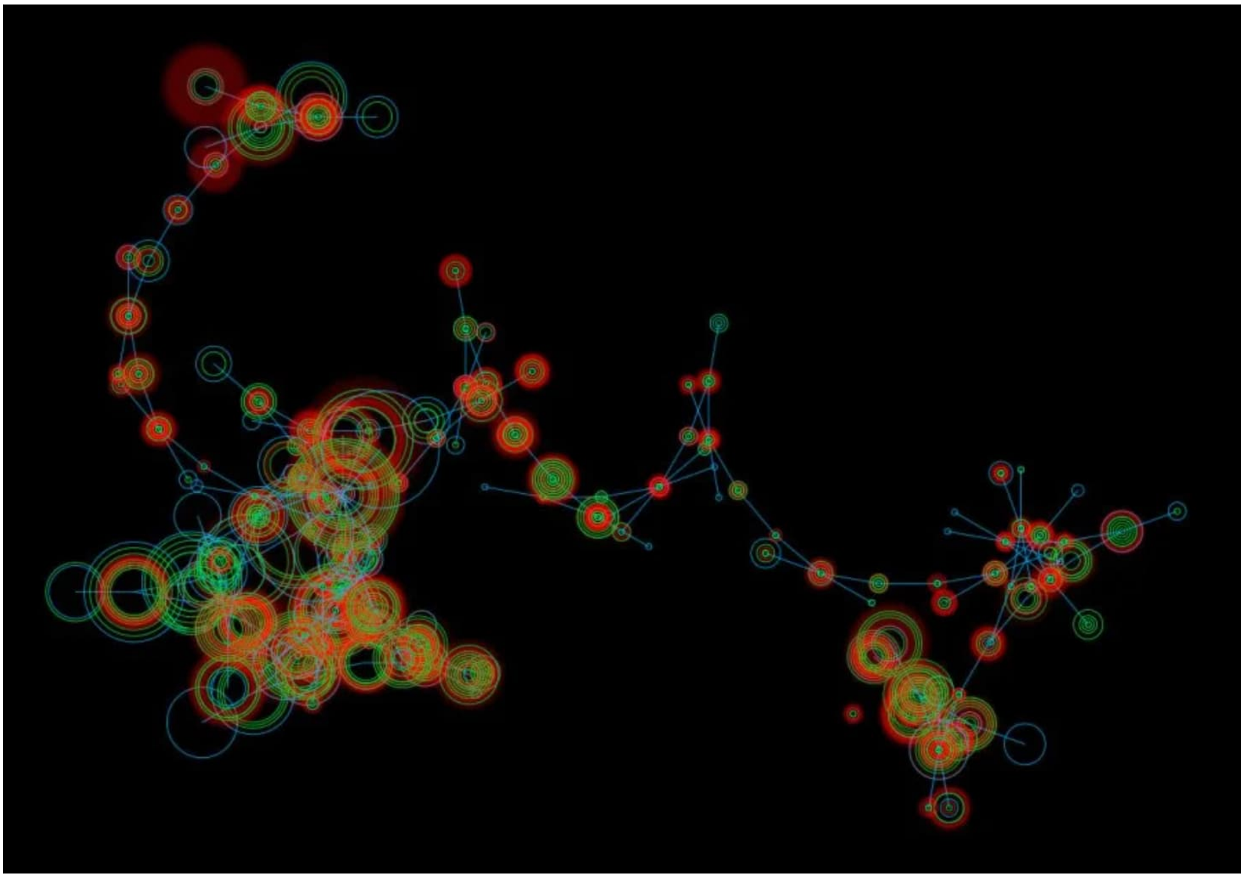


Figure 2.12.2: Quantum drawing (source: artnet 2025)

Most of these use cases are still at the early stages of development.

2.13. Agriculture

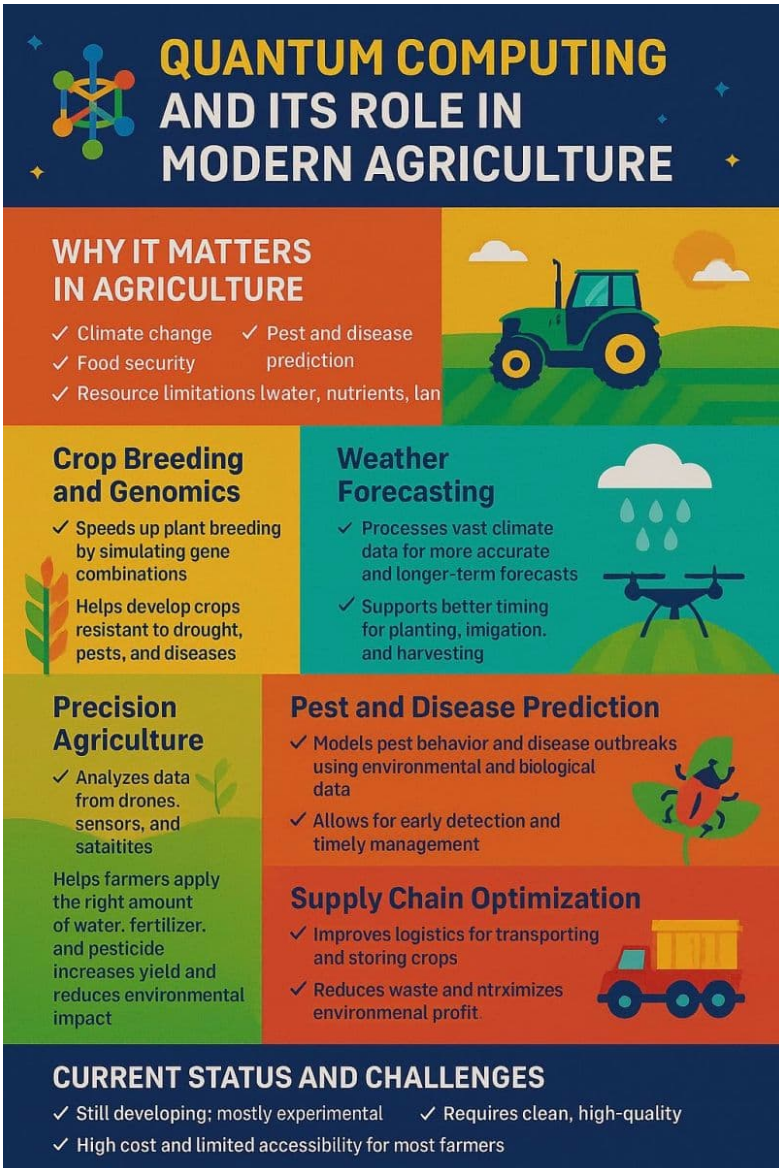


Figure 2.13.1: Quantum computing use cases for agriculture (source: Periaih Battula 2025)

Several use cases have been proposed for improving agricultural practices (Figure 2.13.1), for some of which quantum computing solutions are already under development:

- optimisation of agrifood supply chains (including post-harvest operations);
- quantum-enhanced crop modelling and optimisation;
- soil chemistry simulation;
- quantum-assisted decision making on usage of water, fertiliser, pest control, etc. (precision resource management);

- modelling (simulation) of climate change adaptation scenarios, e.g. using a combination of several quantum computing methods for climate-resilient farming (Figure 2.13.2);

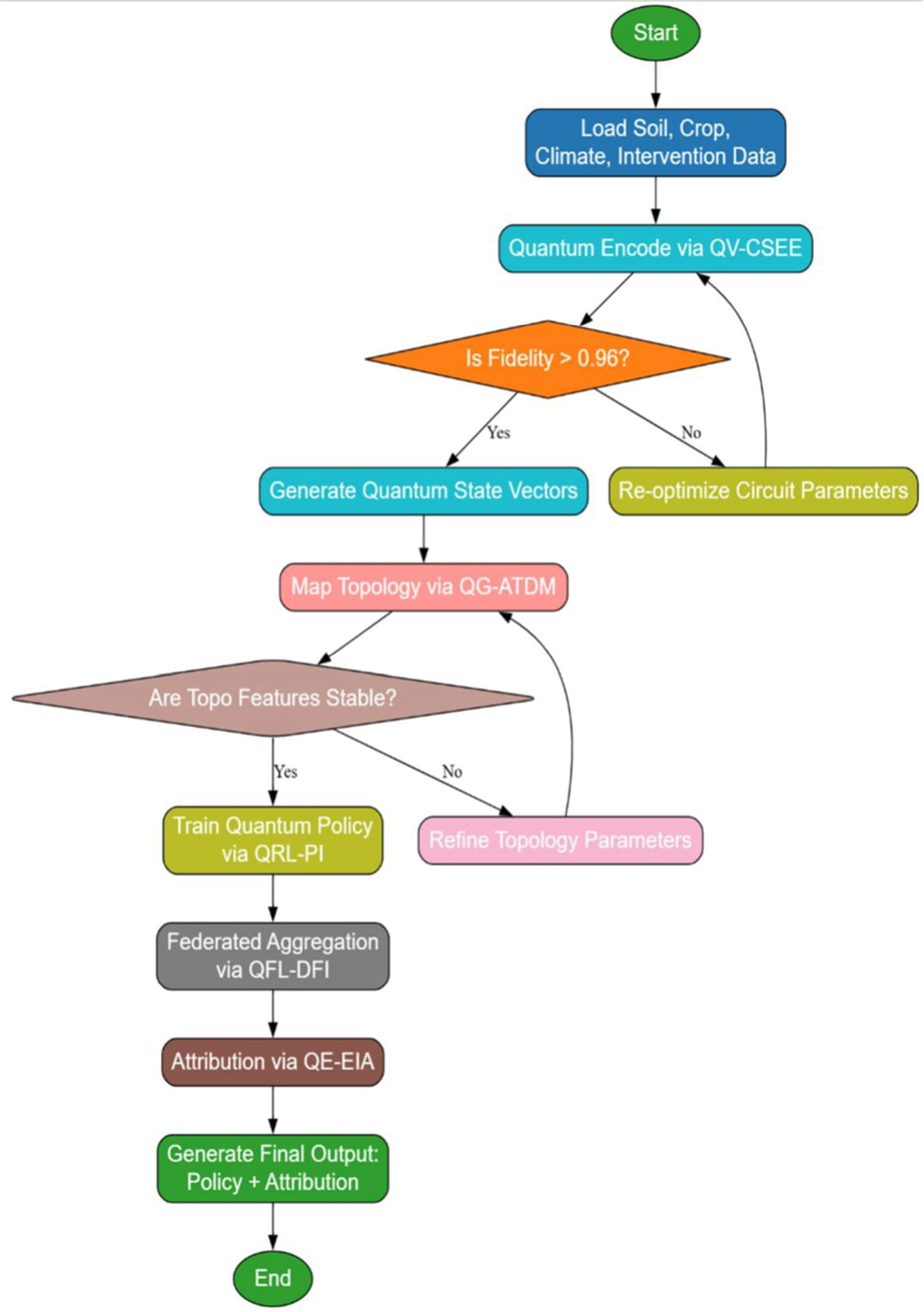


Figure 2.13.2: Quantum-enhanced climate-resilient farming (source: A.H. Khan et al. 2025)

QG-ADTM: Quantum Guided Agri-Topological Dynamics Mapping
QE-EIA: Quantum Explainability through Entropic Intervention Attribution
QFL-DFI: Quantum Federated Learning for Distributed Farm Intelligence
QRL-PI: Quantum Reinforcement Learning for Precision Intervention
QV-CSEE: Quantum Variational Crop-Soil Entanglement Encoding

- modelling (simulation) of carbon sequestration for agricultural land;
- land-surface dynamics classification of land use, vegetation, crops, deforestation, fires and other phenomena (using QML methods);
- improved food waste reduction;
- optimised resource recovery from agriculture waste streams, e.g., animal manure;
- improved estimating of genetic merits for livestock animals and genomic selection;
- optimisation of robotic movement across agricultural fields.

Given that most of the solutions for these proposed use cases (Figure 2.13.3) are still in very early stages of development and given the current state of quantum computer technology, practical use is not foreseen in the near future. However, with quantum computers becoming more reliable and performant in the future, research into quantum computing agricultural use cases presents great opportunity, potentially providing pioneering advancements for the agriculture domain.

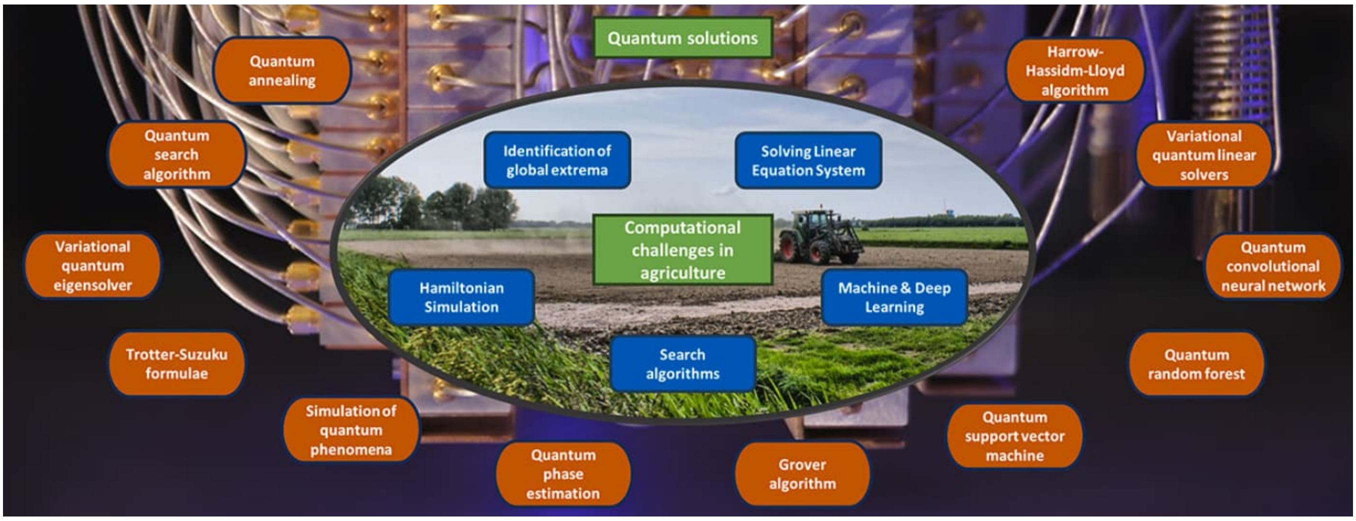


Figure 2.13.3: Quantum computing solutions for agriculture (source: Torsten Pook et al. 2025)

2.14. Space

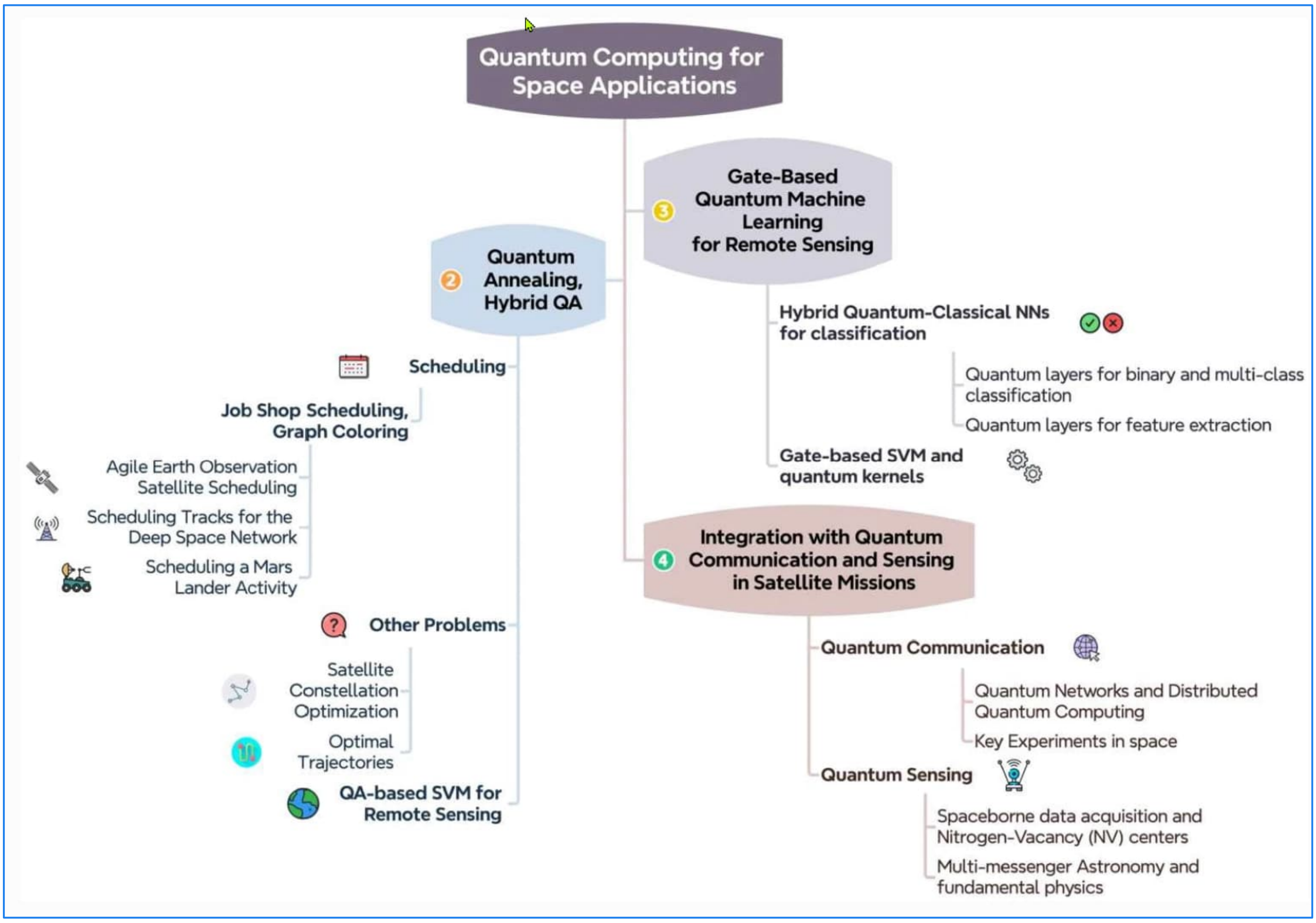


Figure 2.14.1: Quantum computing for space applications (source: Pietra Torta et al. 2025)

Quantum computing use cases that have been developed or proposed (Figure 2.14.1) include:

- Satellite constellation optimisation:

  Maximising the coverage of a targeted Earth region by splitting *n* satellites into *k* independent sub-constellations is a real-world optimisation challenge that can be formalised as an optimisation problem. This problem has been formulated as a QUBO for solving it on quantum annealers. A QAOA-based quantum algorithm has been developed for solving it on gate-based quantum computers.

- Agile Earth Observation Satellite (AEOS) scheduling optimisation:

  AEOS satellites are operated to acquire images from targeted Earth regions while obeying several manoeuvring and operational constraints. They are commonly employed for monitoring disasters, tracking environmental changes, and exploring resources. AEOS scheduling optimisation (Figure 2.14.2) involves creating an optimal satellite mission plan based on several competing requests for Earth images. A total score should be maximised while obeying constraints, accounting for the minimum time interval required to rotate optical sensors between two successive image acquisitions scheduled on the same satellite, and obeying operational constraints imposed by ground control. This problem has been formulated as a QUBO for solving on quantum annealers.

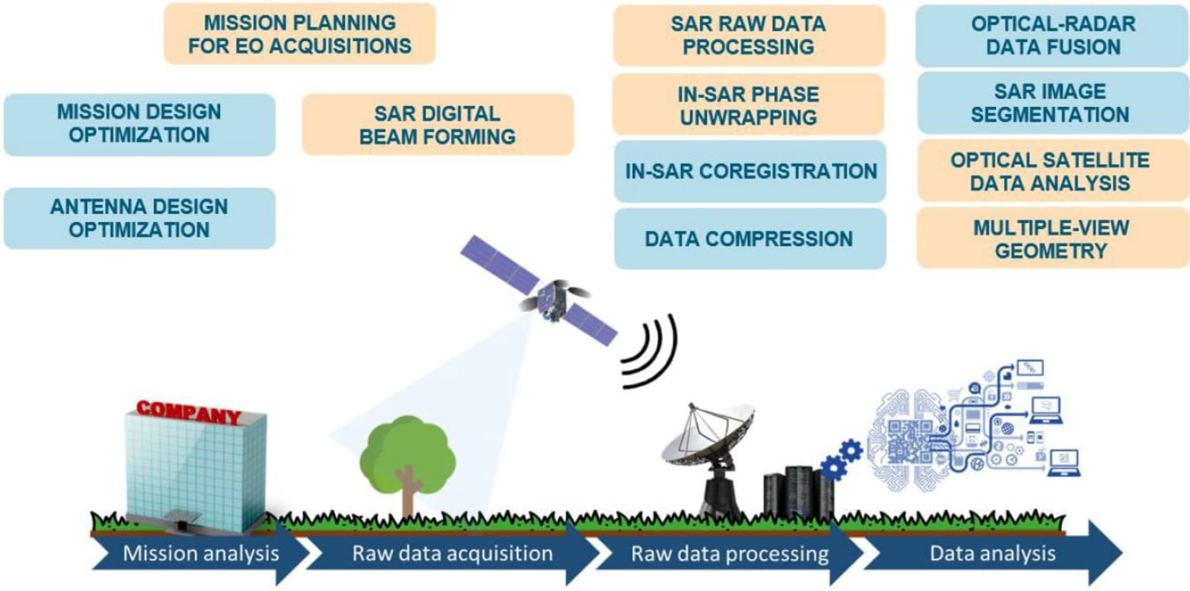


Figure 2.14.2: AEOS quantum computing candidate scenarios (source: Thales Alenia 2023)

- Scheduling track optimisation for the Deep Space Network (DSN):

  DSN is NASA's infrastructure for managing tracking and communication for deep space missions. It comprises systems located in California, Australia and Spain, each featuring several radio antennas in order to guarantee full sky coverage. The objective is to coordinate multiple antenna access requests for transmitting and receiving spacecraft data and to generate a schedule that accommodates all of these requests. This is a highly complex task for which a QUBO has been formulated for solving it on quantum annealers.

- Optimisation of trajectories for aerial and space vehicles:

  Trajectory optimisation is crucial in space exploration and satellite operations, where identifying the most efficient trajectories is critical to ensuring mission success, minimising fuel consumption and optimising available resources. A QUBO formulation has been developed for implementing this use case by means of quantum annealing.

- Quantum-enhanced remote sensing:

  Remote sensing is the process of collecting data from a distance relating to an object, an area or a phenomenon. This is typically done with sensors for detecting and measuring electromagnetic radiation (visible light, infrared or radar). The main application of remote sensing is Earth observation, which is crucial for mapping, monitoring and analysing both natural and human-made environments. A fundamental Earth observation task is the identification and classification of land use and land cover images gathered from airborne or space platforms. Cutting-edge research for Earth observation solutions has resulted in proposals which are based on quantum computing and hybrid quantum-classical computing using QAOA, QSVM and (variational) QML methods.

- Quantum-assisted development of heat resistant materials:

  Development of heat resistant materials (e.g. based on SiN) for photon propulsion engines consisting of arrays of powerful lasers, to be used by interstellar missions.

2.15. National security and defence

Information about the use of quantum computing for intelligence gathering and surveillance is often not public, but currently the main focus is undoubtedly on eavesdropping using sophisticated variants of Shor's quantum algorithms. Another important use case in this field of application is quantum-assisted intelligence analysis, e.g. by means of quantum-assisted HSI (Box 2.15.1) using QSVM methods.

Hyperspectral Imaging (HSI) is a method of capturing and processing information across hundreds of narrow electromagnetic bands. Unlike traditional RGB or multispectral imagery, which measures just a few colour bands, hyperspectral sensors detect subtle variations in reflected light. Each species of plant, mineral, or man-made object reflects light differently. Hyperspectral imaging makes it possible to identify these subtle differences, which can be crucial in for example environmental monitoring, agriculture, and defence surveillance.

Box 2.15.1: Hyperspectral Imaging (HSI)

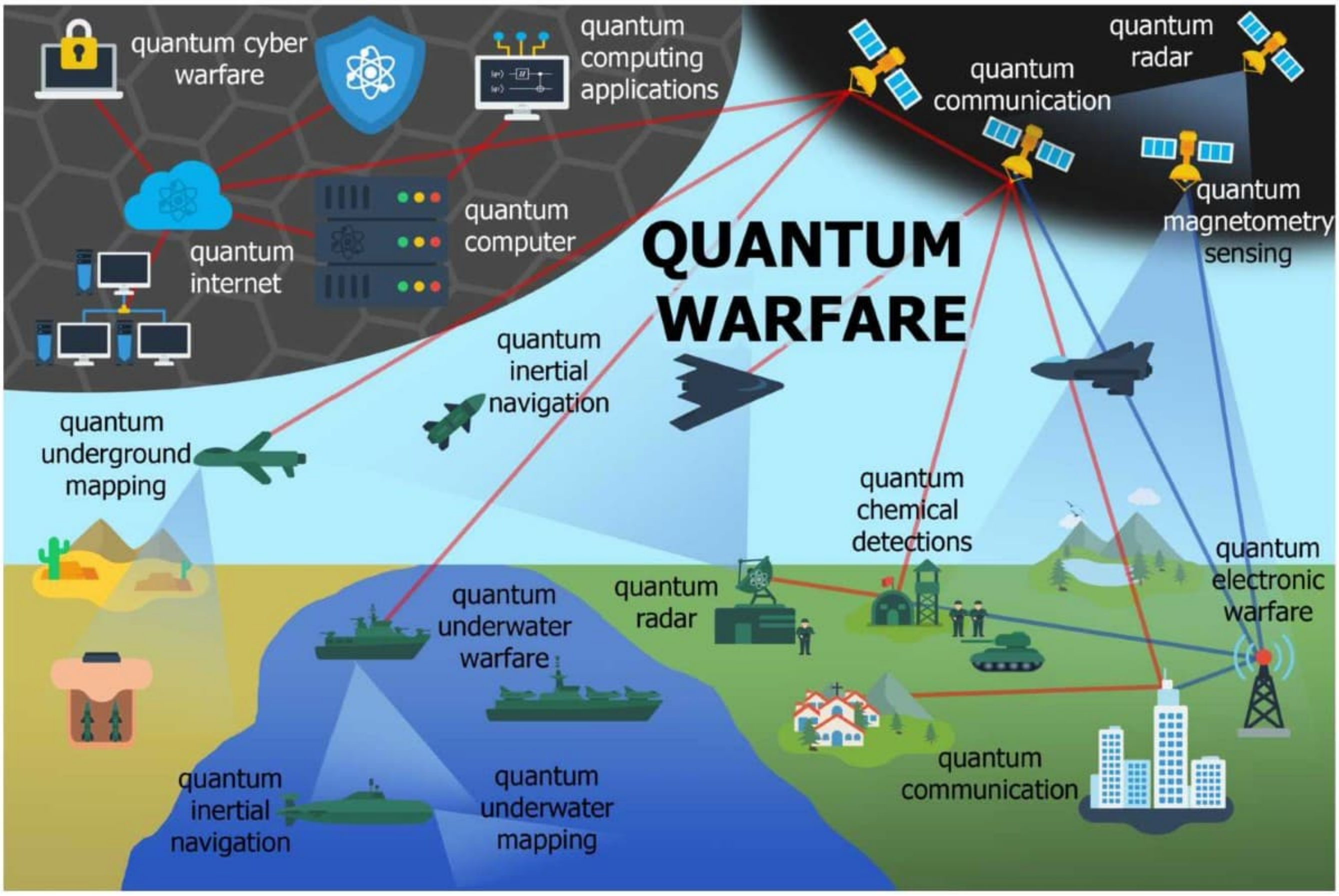


Figure 2.15.1: Quantum technology for military applications (source: npj 2021)

Other quantum use cases developed or proposed for national security and defence include (Figure 2.15.1):

- cybersecurity threat detection, analysis and response prioritisation based on variational quantum algorithms or QML methods (e.g. for critical systems and infrastructures); example: QML Intrusion Detection System (QML-IDS, Figure 2.15.2);

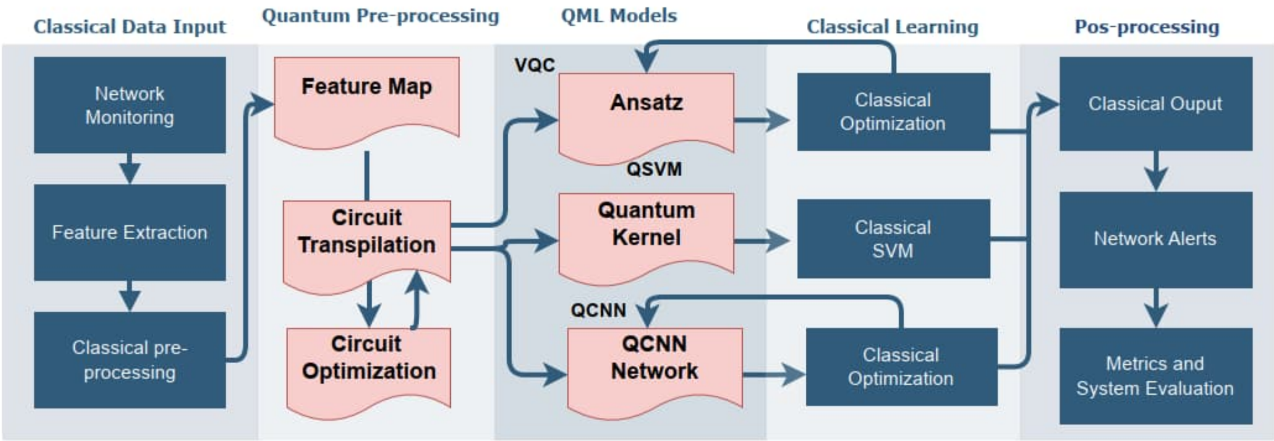


Figure 2.15.2: QML-IDS (source: Diego Medeiros de Abreu et al. 2024)

- quantum-assisted Chemical, Biological, Radiological, and Nuclear (CBRN) detection;
- simulation of complex military scenarios;
- development of quantum algorithms for bathymetry (the study of water depths), e.g. to determine possible landing sites for amphibious vehicles or the presence of sandbanks;
- optimisation of mission planning, scheduling and coordination;
- development of quantum algorithms for the analysis of drone and satellite images;
- development of quantum algorithms for object recognition;
- development of quantum algorithms to optimise radar configuration;
- optimisation of logistics and supply chains;
- QML-based health monitoring and predictive maintenance for Armoured Fighting Vehicles (AFVs) and warplanes: early detection of defects and anomalies, resulting in reduction of unplanned downtime;
- QML-based optimisation of (planned) maintenance schedules and extended asset lifetime.

Use of quantum computing could provide crucial advantages for future defence strategies. In the meantime, there is a lot of focus on developing quantum-inspired solutions.

2.16. sOther quantum computing use cases

Quantum computing has been proposed for several other use cases (of which a few are most probably to be considered "horseshit" or "bullshit"[27] [28]), including:

- Quantum-assisted discovery of complex patterns and structures within data (which is useful for certain applications in finance, biology and forensics).
- Personalized Quantum Federated Learning (PQFL) for anomaly detection (Figure 2.16.1).

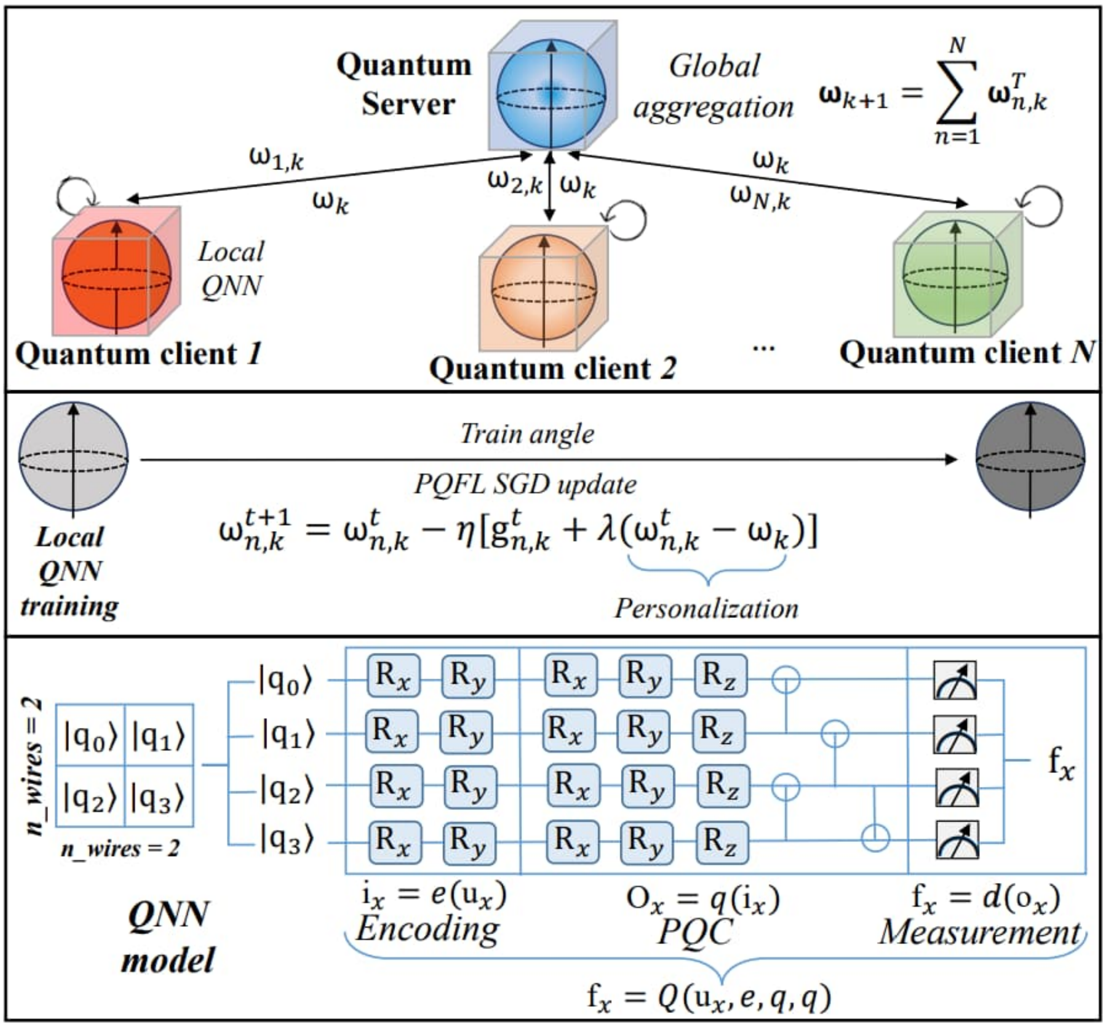


Figure 2.16.1: PFQL method (source: Ratun Rahman et al. 2025)

[27] There is a major difference between "bullshit" and "horseshit". The former implies deception while the latter stems from ignorance.

[28] Even renown scientists, including the British mathematician and physicist Sir Roger Penrose (who was awarded the physics Nobel Prize in 2020), have published what is commonly believed to be quantum technology nonsense.

- Quantum enhanced object classification, e.g. small-species classification in aquaculture using the Variational Quantum Enhanced Deep Transfer Learning (VQEDTL) method (Figure 2.16.2).

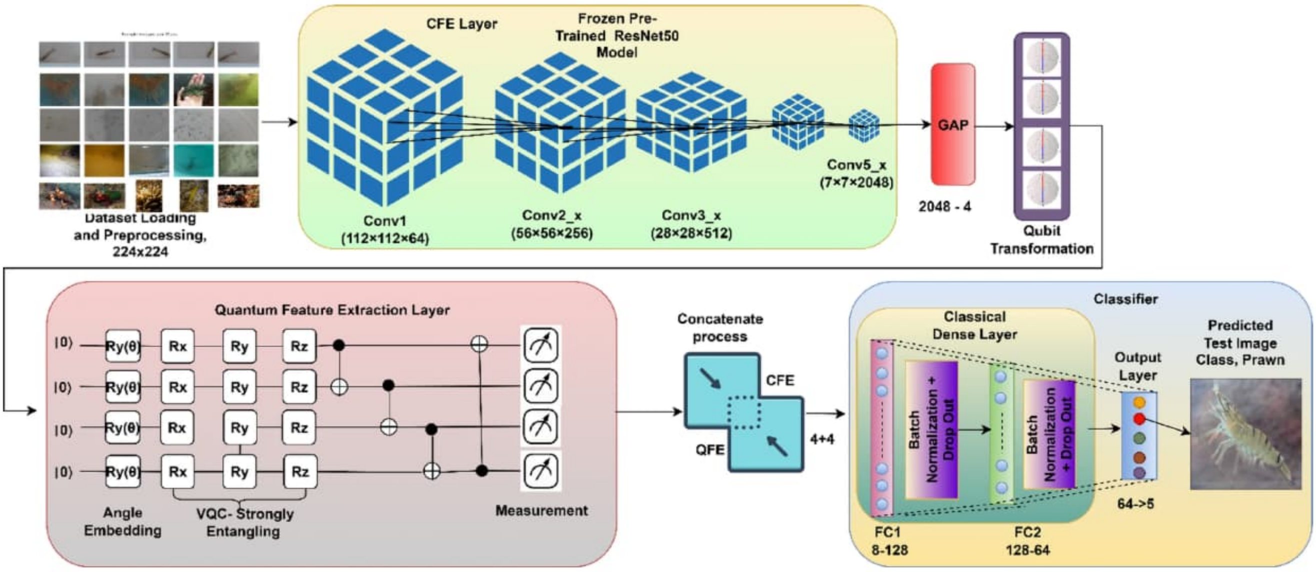


Figure 2.16.2: VQEDTL method (source: A. Sugunapriya and S. Markkandan 2025)

- Quantum computing-based economic modelling methods such as QABM (Box 2.16.1) could allow economists to to better understand complex market dynamics. This would enable them to explore scenarios and policy interventions efficiently.

Quantum Agent-Based Modelling (QABM) simulates complex systems by representing individual, autonomous agents and their interactions within an environment. By defining the rules governing individual agent behaviour, emergent system-wide behaviours are generated from the bottom up. QABM could be used in several application domains (e.g. economics and urban planning), to analyse how individual interactions create large-scale phenomena and to test hypothetical scenarios.

Box 2.16.1: Quantum Agent-Based Modelling (QABM)

- Quantum-enhanced human resource processes (predictive workforce planning, optimising employee engagement, forecasting future skill requirements, predicting employee turnover, optimising talent acquisition, etc.).

- Quantum computing methods for the generation of synthetic training data for Artificial Intelligence (AI) algorithms in fields where real-world data is scarce.

- Simulation of artificial intelligence, potentially leading to unforeseen advanced applications.

- Optimisation of cloud computing resource scheduling, load balancing and traffic routing, to increase efficiency and lower power consumption/environmental impact.

- Quantum-assisted classical software engineering, e.g. quantum-assisted compiler design, algorithm efficiency optimisation, and quantum-assisted software quality control and testing.

- Quantum-proofed certifiable deletion, i.e. verifying that a file has been deleted on all systems involved (addressing concerns about digital privacy and data permanence beyond simple deletion).

- Compiling quantum algorithms for NISQ quantum computers (accounting for the native quantum gate set, limited qubit connectivity, limited quantum circuit depth, QEM, etc.) is a major challenge and places severe restrictions on the size of the quantum algorithms that can be implemented in practice. Classical methods for solving this challenge are limited due to excessive compilation times needed for large quantum algorithms. Quantum computing based solutions could address this challenge; examples:

  - Quantum-Assisted Quantum Compiling (QAQC, Figure 2.16.3) is a variational NISQ quantum algorithm that provides exponential speedup. It primarily provides for reduction of quantum circuit depth, which enables implementing larger quantum algorithms, but it can also "learn" the noise characteristics of a given NISQ quantum computer and compensate for it during compilation.

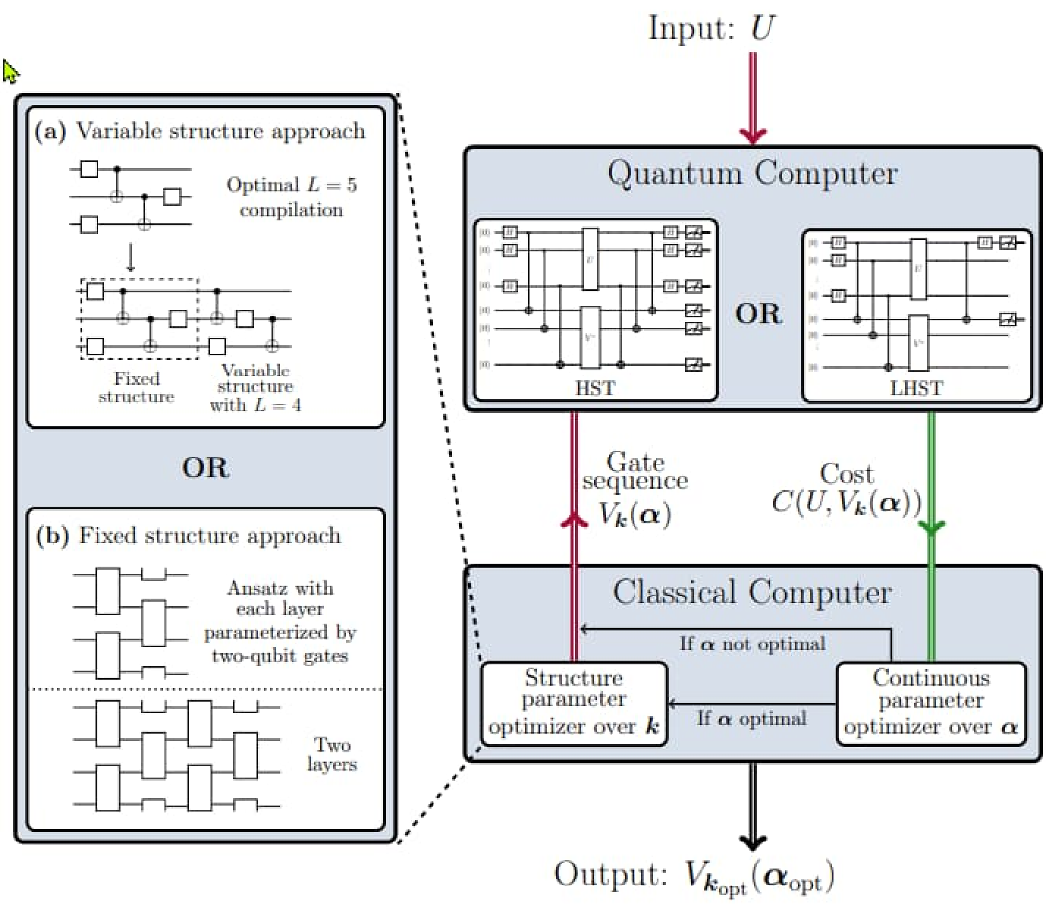


Figure 2.16.3: Variational QAQC quantum algorithm (source: Sumeet Khatri et al. 2025)

- Hybrid-Action Reinforcement Learning for Quantum Architecture Search (HyRLQAS) is a Reinforcement Learning (RL) framework that simultaneously learns how to place single-qubit gates and initialise parameters for rotation gates in variational quantum circuits. It comprises several components (Figure 2.16.4): Tensor-based Circuit Encoding (encodes the construction information of the previously built quantum circuit into a tensor, which is then flattened into a vector), Hybrid Policy Network (generates the next action, including discrete quantum gate selection, continuous rotation parameters and refinement updates), Environment (executes the constructed quantum circuit and returns feedback to the classical REINFORCE optimiser[29] in the form of an energy-based reward), and the intermediate Batch of Trajectories (stores trajectories collected across rollouts, used in batch for updating the Hybrid Policy Network).

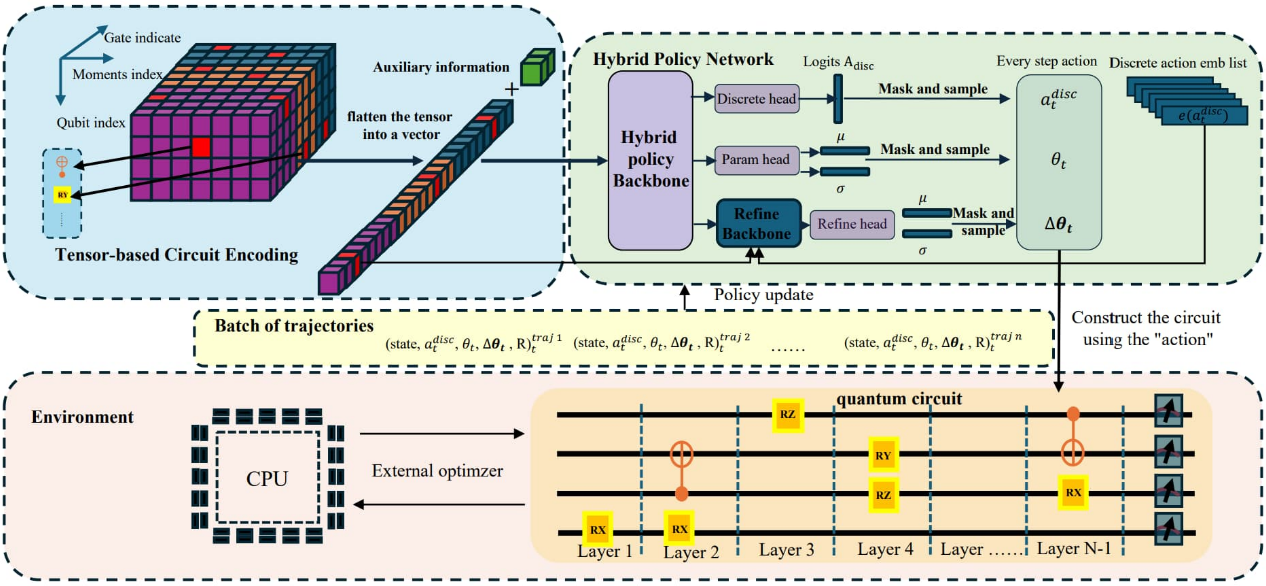


Figure 2.16.4: HyRLQAS framework(source: Jiayang Niu et al. 2025)

- Quantum computing based cryptographic schemes for confidentiality/privacy protection, including:

  - Quantum Homomorphic Encryption (QHE): enables quantum computing over encrypted data and returning the encrypted computed result, without access to the encryption key.

  - Blind Quantum Computation (BQC): blinding is a method by which an agent can provide a service to (i.e. compute a function for) a client in an encrypted form without knowing either the real input or the real output. Example: multi-server BQC protocol (Figure 2.16.5).

[29] The REINFORCE algorithm is a Monte Carlo (MC) based RL method that enables direct policy learning by optimising the parameters of the policy model (i.e. without explicitly modelling the value of each action or state).

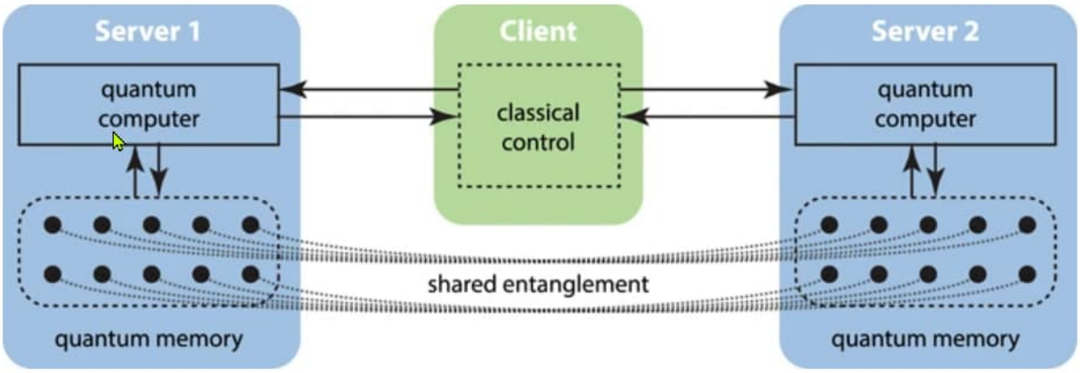


Figure 2.16.5: Multi-server BQC protocol (source: J.F. Fitzsimons 2017)

- Quantum Multi-Party Computation (QMPC): enables quantum computing parties to jointly compute a function over their inputs, while keeping those inputs private.
- Quantum Differential Privacy (QDP): ensures that the results obtained from QML algorithms do not reveal significant information about the data that has been fed into these algorithms, e.g. by adding noise to quantum computing measurements (Figure 2.16.6).

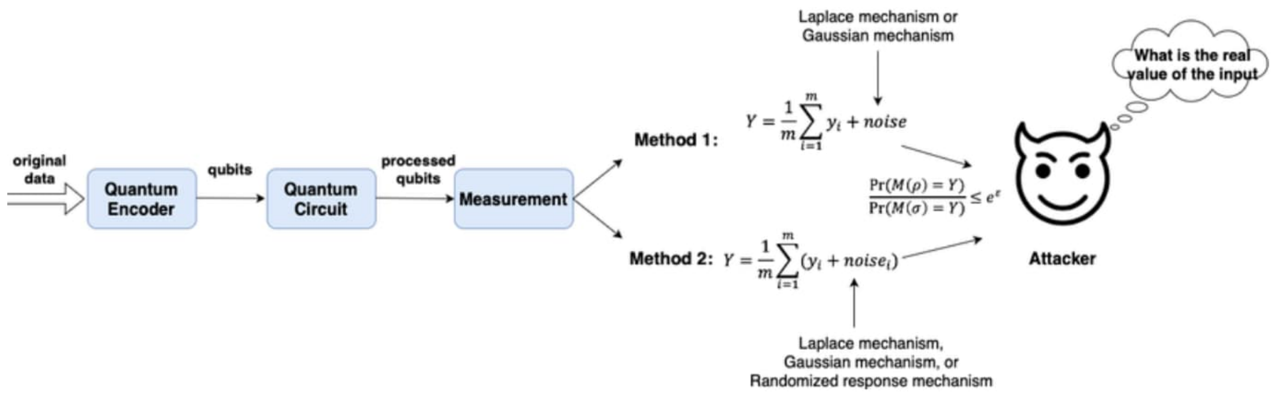


Figure 2.16.6: QDP method examples (source: B. Song et al. 2025)

Method 1: adding noise to the average value Y of m rounds of a qubit measurement
Method 2: adding noise to the value Y of each round of a qubit measurement

- Quantum Secret Sharing (QSS): provides for secure storage and reconstruction of quantum information thus enabling distribution of secrets among multiple parties.
- Quantum Digital Signature (QDS).

- Quantum algorithms for generation of truly unpredictable numbers, i.e. Quantum Random Number Generators (QRNGs).
- Quantum-enhanced secure online voting.

- Optimising resource allocation in community support systems. The goal is to optimally connect supporters (volunteers) with visitors (those needing assistance) based on their preferences and needs.

- Matching parents and experienced seniors via quantum computing optimisation, aiming to provide psychological support and improved intergenerational matching diversity to reduce parental stress.

- Modelling pedestrian stress levels from skin conductance responses (aka galvanic skin responses) in a virtual reality environment, using QSVM and a QNN.

- Optimising personal hobbies by analysing individual data from wearable devices.

- Optimising initial line-up of a soccer team (using a BQM solver on quantum annealer).

- Quantum-assisted sports betting; example: QNN based soccer match results prediction (Figure 2.16.7).

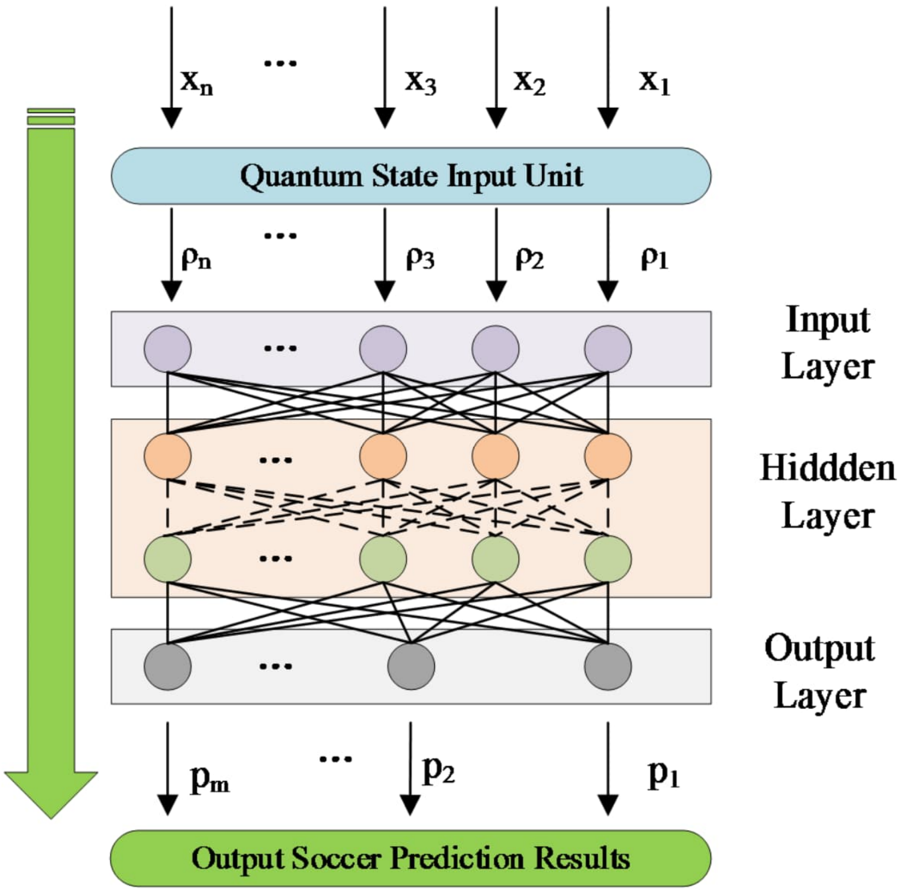
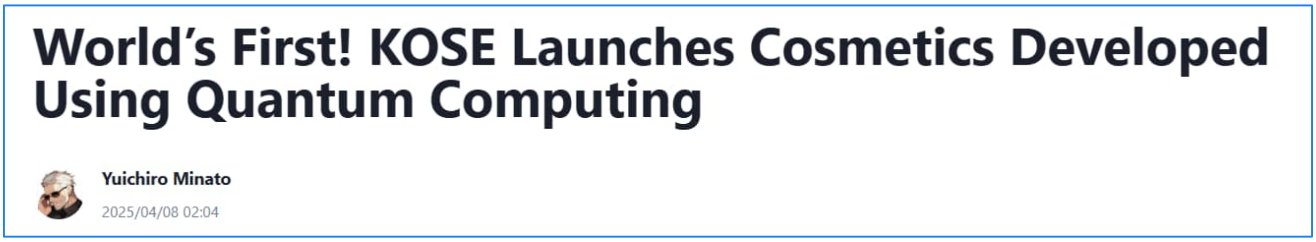


Figure 2.16.7: QNN based soccer match results prediction (source: Yan Sun et al. 2025)

- Developing optimal strategies for playing (and winning) board games by simulating countless scenarios.

- Quantum computing based development of cosmetic products (Figure 2.16.8).


World's First! KOSE Launches Cosmetics Developed Using Quantum Computing

Yuichiro Minato

2025/04/08 02:04

Figure 2.16.8: Cosmetics Developed Using Quantum Computing (source: blueqat 2025)

- Development of conscious systems based on qubit entanglement and quantum wave function collapse, e.g. human-aligned (i.e. with qualities such as intuition and empathy) AI systems and robots.

- Quantum Energy Teleportation (QET, Figure 2.16.9).

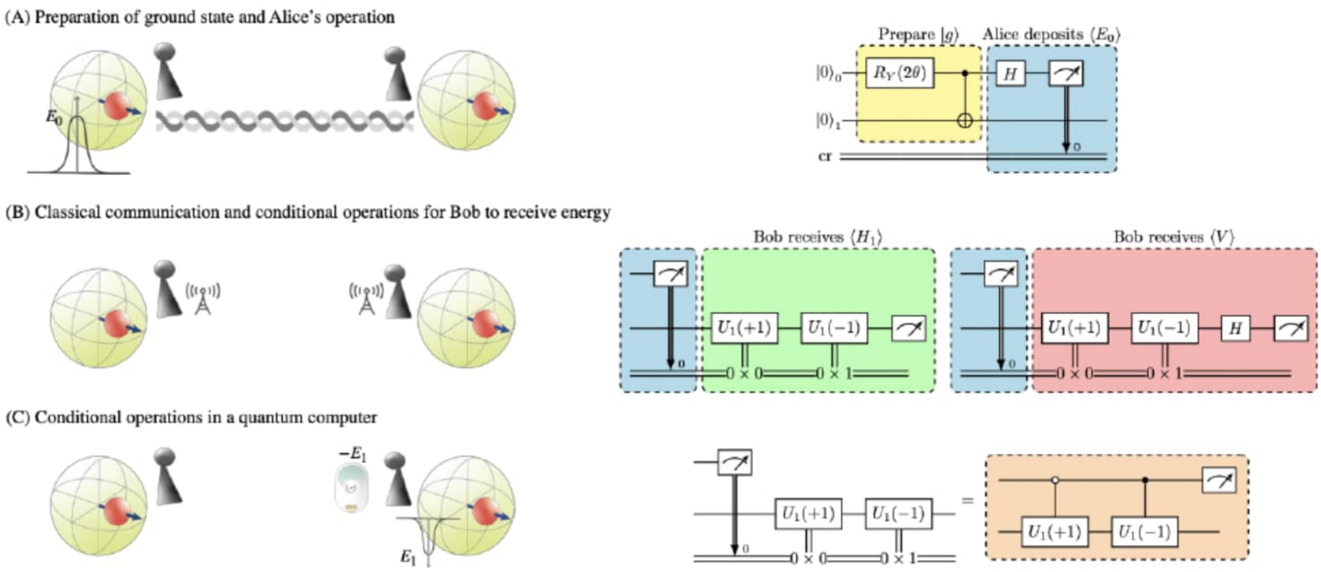
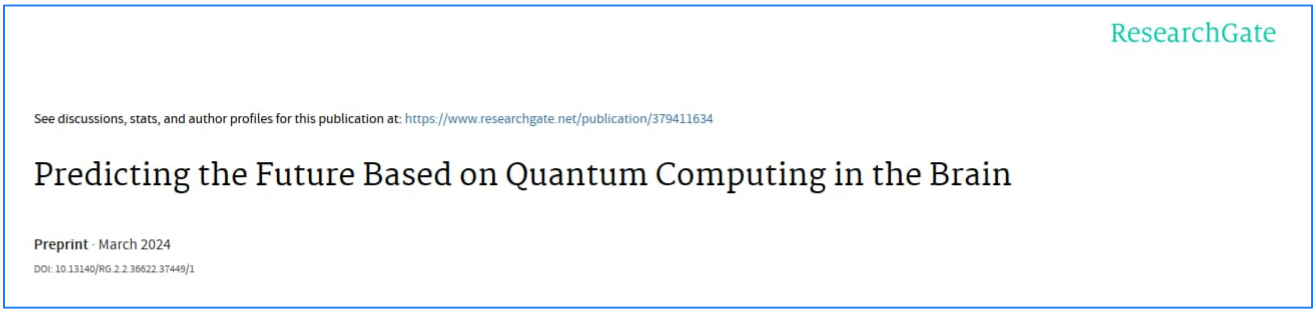


Figure 2.16.9: QET quantum circuits (source: William Brown 2025)

- Future prediction using quantum computing methods (Figure 2.16.10).


ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/379411634

Predicting the Future Based on Quantum Computing in the Brain

Preprint · March 2024

DOI: 10.13140/RG.2.2.36622.37449/1

Figure 2.16.10: Future prediction with quantum computer (source: ResearchGate 2024)

- Time reversal using quantum computing methods (Figure 2.16.11).

Figure 2.16.11: Time reversal with quantum computer (source: Newsweek 2019)

Appendix A – References

[Eisert and Preskill 2025] Mind the gaps: The fraught road to quantum advantage

[Elsevier 2024] Quantum computing for market research

[Elsevier 2025] Assessing the potential of quantum computing in agriculture

[Ezratty 2025] Understanding Quantum Computing Technologies Eighth Edition

[IBM Quantum 2023] The state of quantum computing applications in health and medicine

[ICFNDS 2023] Exploring Quantum Computing Use Cases for Critical National Infrastructures

[IEEE 2025] Quantum Computing for Finance: State of the Art and Future Prospects

[JTCT 2023] Quantum Computing for Chemistry

[Konga 2025] Quantum Computing in Materials Engineering

[L.E.K. Consulting 2025] Quantum Computing in Biopharma: Future Prospects and Strategic Insights

[Meagle 2025] Quantum Computing in Oil and Gas Industry

[NOREA 2025] Post-Quantum Migration

[NOREA 2025] Quantum Algorithms

[NOREA 2025] Quantum Annealing Explained

[NOREA 2025] Quantum Computing Explained

[Phillipson 2025] Quantum Computing in Logistics and Supply Chain Management - An Overview

[QED-C 2024] Quantum Computing for Transportation and Logistics

[Quantum Zeitgeist 2024] Quantum Computing for Chemistry and Materials Sciences

[ResearchGate 2024] Quantum Computing in Healthcare: Unlocking New Frontiers in Drug Discovery and Data Management

[ResearchGate 2025] Quantum Computing in Civil Engineering: Potentials and Limitations

[SIPRI 2025] Military and Security Dimensions of Quantum Technologies

[Springer 2023] An Overview of Quantum Computing Approach in the Present-Day Energy Systems

[Springer 2025] Quantum computing for space applications: a selective review and perspectives

[Telefónica 2025] Quantum Computing and Its Impact on the Media and Entertainment Industry

[TNO 2023] Quantum Computing in Telecommunication – A Survey

[Wikipedia 2025]

[World Wide Web 2025]

Appendix B - Acronyms and abbreviations

1dBPP	one-dimensional Bin Packing Problem
2D	2-Dimensional
3D	3-Dimensional
3dBPP	three-dimensional Bin Packing Problem
ρ	quantum state
τ	tau
μ	muon
ν_e	electron neutrino
ν_τ	tau neutrino
ν_μ	muon neutrino
γ	photon
ψ	quantum state
π	pi
$\surd$	square root
a	action
AB	Artificial Brain
ABM	Agent-Based Modelling
AdamW	Adaptive *M*oment *E*stimation *D*ecoupled Weight *D*ecay
AE	Auto*e*ncoder
AEO	Agile Earth Observation
AEOS	Agile Earth Observation Satellite
AFT	Algorithmic Fault Tolerance
AFV	Armoured Fighting Vehicle
Agri	Agriculture
AGV	Automated Guide Vehicle
AI	Artificial Intelligence
AIQ	AI for Quantum
aka	also known as
AL	Air Liquide

algo	algorithm
ALM	Asset Liability Modelling
ALO	Aircraft Loading Optimization
AM	Ante Meridiem
Amgen	Applied *M*olecular *G*enetics
AML	Anti-Mony Laundering
Anc.	Ancilla
ANN	Artificial Neural Network
AQS	Applied Quantum Software
AQT	Alpine Quantum Technologiesq
Ar	Argon
argmax	arguments of the maxima
argmin	arguments of the minima
ARP	Aircraft Recovery Problem
arXiv	*"archive"*
ASIC	Application-Specific Integrated Circuit
AT&T	American Telephone & Telegraph
ATM	Air Traffic Management
AV	Autonomous Vehicle
AZ	AstraZenica
b	bottom quark
B	Billion
B&B	Branch-and-Bound
BBS	Black Brane Systems
BCG	Boston Consulting Group
bit	binary digit
BMO	Bank of M*o*ntreal
BMW	Bayerische Motoren Werke
BN	Bayesian Network
BOC	Bank *of* Canada
BP	British Petroleum
BPP	Bin Packing Problem
BPSP	Binary Paint Shop Problem
BQ	Bloq Quantum
BQC	Blind Quantum Computation

BQM	Binary Quadratic Model
BS	Base Station
BSM	Black-Scholes Model
BT	British Telecom
c	celeritas charm quark
C	Carbon Celsius Cost function
CA	Crédit Agricole
CAD	Computer-Aided Design
CADD	Computer-Assisted Drug Design
CBM	Constraint-Based Modeling
CBRN	Chemical, Biological, Radiological, and Nuclear
CF	CogniFrame
CFD	Computational Fluid Dynamics
CFE	Classical Feature Extraction
CH_4	*methane*
Citi	Citibank
CNI	Critical National Infrastructure
CO	Carbon *Mo*noxide
CO_2	Carbon *Di*oxide
COBYLA	Constrained Optimization by Linear Approximation
Conv*n*	Conversion *n*
cos	cosine
CPS	Cyber-Physical System
CPU	Central Processing Unit
CQM	Constrained Quadratic Model
CQOA	Constrained Quantum Optimization Algorithm
CQRT	Constrained Quantum Relation Testing
CRM	Customer Relationship Management
CROP	Cable Routing Optimization Problem
CSV	Comma Separated Values
CV	Continuous Variable
CVaR	Conditional Value-at-Risk

CVRP	Capacitated Vehicle Routing Problem
d	down quark
DAG	Directed Acyclic Graph
DAM	Data Assimilation Model
DBS	Development Bank of Singapore
DDPP	Drone Delivery Packing Problem
DE	Differential Equation
DESI	Dark Energy Spectroscopic Instrument
DFJSP	Distributed Flexible Job Shop Scheduling Problem
DFT	Density Functional Theory
DHW	Domestic Hot Water
DL	Deep Learning
dlog	discrete logarithm
DLT	Distributed Ledger Technology
DMRG	Density Matrix Renormalization Group
DNA	Deoxyribo*n*ucleic Acid
DOI	Digital Object Identifier
DOM	Discrete Ordinate Method
DP	Differential Privacy
DQC	Distributed Quantum Computing
DQIM	Decoded Quantum Interferometry Method
DQM	Discrete Quadratic Model
DSGE	Dynamic Stochastic General Equilibrium
DSN	Deep Space Network
DSO	Distribution System Operator
DT	Deutsche Telekom
DTMC	Discrete-Time Markov Chain
DV	Discrete Variable
e	electron *E*uler's number
E	Energy
e.g.	exempli gratia
EDP	Electronic Data Processing
EDT	Eastern Daylight Time

EHR	Electronic Health Record
EIA	Environmental Impact Assessment
EL	Entropica Labs
EM	Exxon Mobil
emb	embedding
EMuSE	Environmental Multi-Sector *M*odel
E*n*	Edge *n*
EO	Earth Observation
Eqs.	Equations
et al.	et alia
etc.	et cetera
ETF	Exchange-Traded Fund
EV	Electric Vehicle
EV	Expectation Value
EVM	Expectation Value Measurement
f( )	function
FCI	Full Configuration Interaction
FC*n*	Feature Classification *n*
FD	Fractal Dimension
FDM	Finite Difference Method
Fe	Ferrum (Latin for “Iron”)
FE	Feature Extraction
FEA	Finite Element Analysis
FEM	Finite Element Method
FeMoCo	Ferro*m*olybdenum Cofactor
FFT	Fast Fourier Transform
FH	Fermi-Hubbard
FJSP	Flexible Job Shop *S*cheduling Problem
FL	Federated Learning
FLP	Factory Layout Planning
FLRS	Fixed Linear Ramp Schedule
FM	Feature Map
FPGA	Field-Programmable Gate Array
FT	Fourier Transform
FTA	Fault Tree Analysis

FTQC	Fault-Tolerant Quantum Computer
FU	Functional Unit
g	gluon
GA	Grover's Algorithm
GAN	Generative Adversarial Network
GAP	Global Average Pooling
GAS	Grover Adaptive Search
GBQML	Gate-based Quantum Machine Learning
GC	Graphic Coloring
GCM	General Circulation Model
GE	General Electric
GeV	Giga electronVolt
GM	General Motors
GNN	Graph Neural Network
GPU	Graphics Processing Unit
GS	Goldman Sachs
GSK	GlaxoSmithKline
GVBMP2	Generalized Valence Bond-Møller–Plesset second-order
GWAS	Genome-Wide Association Studies
H	Higgs scalar boson Hadamard quantum gate Hamiltonian Hydrogen
H_2O	*water*
HB	Haber-Bosch
He	Helium
HEA	Hardware-Efficient Ansatz
HEBM	Hamiltonian Evolution Based Method
HEP	High-Energy Physics
HF	Hartree-Fock
HHL	Harrow, Hassidim and Lloyd
HMM	Hidden Markov Model
HPC	High-Performance Computing
HQC	Horizon Quantum Computing

HQCD	Hybrid Quantum-Classical Dispatching
HQCNN	Hybrid Quantum-Classical Neural Network
HQS	Honeywell Quantum Solutions
HSBC	Hongkong and Shanghai Banking Corporation
HSI	Hyperspectral Imaging
HST	Hilbert-Schmidt Test
https	*H*yper*T*ext *T*ransfer *P*rotocol *S*ecure
HyRLQAS	Hybrid-Action Reinforcement Learning for Quantum Architecture Search
i	imaginary number
i.e.	id est
IBM	International Business Machines
ICAA	Inter-Class Attribution Alignment
ICFNDS	International Conference on Future Networks and Distributed Systems
IDS	Intrusion Detection System
IE	Industrial Engineering
IEEE	Institute of Electrical and Electronics Engineers
IN-SAR	I*n*terferometric Synthetic Aperture Radar
ion	ionised atom
IPM	Interior Point Method
IQNN-CS	Interpretable Quantum Neural Network for Credit Scoring
IS	Intesa Sanpaolo
ITS	Integrated Trading Solution
JSP	Job Shop Problem
JSS	Job Shop Scheduling
JSSP	Job Shop Scheduling Problem
JTCT	Journal of Chemical Theory and Computation
K	Kelvin
KAIST	Korea Advanced Institute of Science and Technology
KP	Knapsack Problem
L	Layer
LA	Lorenz Attractor
Lab	Laboratory

laser	light amplification by stimulated emission of radiation
LE	Lyapunov Exponent
LHST	Local Hilbert-Schmidt Test
Li	Lithium
LIGO	Laser Interferometer Gravitational-Wave Observatory
LM	Lockheed Martin
LN	Layer Normalization
LNG	Liquified Natural Gas
log	logarithm
logit	logistic unit
LQRL	Lyapunov-aware Quantum-inspired Reinforcement Learning
LSA	Logarithmic Search Algorithm
LSV	Lyapunov Stability Verifier
M	Mapping Measurement
MAC	Message Authentication Code
MAR	M*ar*ch
MATLAB	M*at*rix L*ab*oratory
max	maximum
MB	Mercedes-Benz
MBD	Many-Body Dynamics
MC	Monte Carlo
MCFP	Manufacturing Cell Formation Problem
MCI	Monte Carlo Integration
MCLP	Maximal Covering Location Problem
MCM	Markov Chain Monte Carlo
MCMC	Monte Carlo Method
MD	Molecular Dynamics
MDKP	Multi-Dimensional Knapsack Problem
MDM	Master Data Management
ME	Materials Engineering
MeV	Mega electronVolt
MF	Matrix Factorization
MIDI	Musical Instrument Digital Interface
MIMO	Multiple Input Multiple Output

min	minimum
MIP	Mixed Integer Programming
MIST	Molecular Insight SMILES Transformers
ML	Machine Learning
MLE	Maximum Likelihood Estimation
MMA	Multi-Messenger Astronomy
MMC	Modular Multilevel Converter
Mo	Molybdenum
MO	Molecular Orbit
MOF	Metal-Organic Framework
MPC	Model Predictive Control
MPS	Matrix Product State
MQS	Molecular Quantum Solutions
MS	Morgan Stanley
Mt	Megatonne
MVG	Multiple-View Geometry
MZM	Majorana Zero Mode

N	Nitrogen
NASA	National Aeronautics and Space Administration
NDP	New Product Development
NH_3	*ammonia*
NISQ	Noisy Intermediate-Scale Quantum
NLL	Negative Log-Likelihood
NLM	Natural Language Modeling
NLP	Natural Language Processing
N*nnn*	Node *nnn*
NN	Neural Network Novo Nordisk
NOREA	Nederlandse Orde van Register EDP-Auditors
NP	Nuclear Physics
npj	*N*ature *P*artner *J*ournals
NPK	Nitrogen, Phosphorus, and Potassium
NQCG	Nordic Quantum Computing Group
NR	Newton-Raphson
ns	nanosecond

NS	Navier-Stokes
NTT	Nippon Telegraph and Telephone
NV	Nitrogen-Vacancy
NWP	Numerical Weather Prediction
O	Oracle Oxygen
OCT	Optical Coherence Tomography
ODE	Ordinary Differential Equation
opt.	optimizer
OFDM	Orthogonal Frequency Division Multiplexing
OQ	Origin Quantum
OQS	Open Quantum System
OR	Operations Research
OTI	Optical Techniques Incorporated
OTSP	Open Loop Travelling Salesman Problem
p	prediction
P	Polynomial Privacy
PAPR	Peak-to-Average Power Ratio
Param	Parameter
PCA	Principal Component Analysis
pcu	primitive cubic
PDE	Partial Differential Equation
PE	Phase Estimation
PEA	Phase-Estimation Algorithm
PEC	Probabilistic Error Cancellation
PGA	Point Group Analysis
PGO	Policy Gradient Optimizer
pH	potential of Hydrogen
PM	Post Meridiem
PoC	Proof-of-Concept
PoQ	Proof-of-Quantum work
POVM	Positive Operator-Valued Measurement

PQC	Parameterized Quantum Circuit
PQFL	Personalized Quantum Federated Learning
Pr	Privacy
PSA	Pressure Swing Adsorption
PSC	Phase Space Computing
PTM	Parameter Transfer Module
PV	Photovoltaic
PVA	Photovoltaic Array
Q4RPD	Quantum for Real Package Delivery
Q-DFT	Quantum Density Functional Theory
Q-FEM	Quantum Finite Element Method
Q&A	Questions & Answers
QA	Quantum Annealing
QAA	Quantum Amplitude Amplification
QABM	Quantum Agent-Based Modelling
QAE	Quantum Amplitude Estimation Quantum Analog Ensemble Quantum Autoencoder
QAL	Quantum Application Lab
QAOA	Quantum Approximate Optimization Algorithm
QAP	Quadratic Assignment Problem
QAR	Quantum Applications and Research
QAQC	Quantum-Assisted Quantum Compiling
QBB	Quantum Branch and Bound
QBM	Quantum Barrier Method Quantum Boltzmann Machine
QBN	Quantum Bayesian Network
QC	Quantum Chemistry Quantum Circuit Quantum Clustering Quantum Communication Quantum Computer Quantum Computing Qunova Computing
QCA	Quantum Cluster Analysis

QCaaS	Quantum Computing-as-a-Service
QCC	Quantum Carnot Cycle
QCL	Quantum Chemistry Library
QD	Quantum Dynamics
QCNN	Quantum Convolutional Neural Network
QCS	Quantum Computing Simulator
QDC	Quantum Data Center *C*orporation
QDL	Quantum Deep Learning
QDP	Quantum Differential Privacy
QDS	Quantum Digital Signature
QE	Quantum Encoder
QE-EIA	Quantum Explainability through Entropic Intervention Attribution
QEC	Quantum Error Correction
QED-C	Quantum Economic Development Consortium
QEM	Quantum Error Mitigation
QET	Quantum Energy Teleportation
QFE	Quantum Feature Extraction
QFL	Quantum Federated Learning
QFL-DFI	Quantum Federated Learning for Distributed Farm Intelligence
QFT	Quantum Fourier Transform
QG-ATDM	Quantum Guided Agri-Topological Dynamics Mapping
QGAN	Quantum Generative Adversarial Network
QGBM	Quantum Gradient-Based Method
QGNN	Quantum Graph Neural Network
QHD	Quantum Hamiltonian Descent
QHE	Quantum Homomorphic Encryption
QIPM	Quantum Interior Point Method
Qiskit	Quantum *I*nformation *S*oftware *K*it
QITE	Quantum Imaginary Time Evolution
QK	Quantum Kernel
QK-means	Quantum K-means clustering
QKD	Quantum Key Distribution
QKF	Quantum Kalman Filter
QKM	Quantum Kernel Method
QKNN	Quantum K-Nearest Neighbors
QKP	Quadratic Knapsack Problem

QLE	Quantum Langevin Equation
QLS	Quantum Least Squares
QLS-SVM	Quantum Least Squares Support Vector Machine
QLSA	Quantum Linear System Algorithm
QLSTM	Quantum Long Short-Term Memory
QM	Quantum Mechanics Quantum Memory
QM/MM	Quantum Mechanics / Molecular Mechanics
QMC	Quantum Monte Carlo
QMCMC	Quantum Markov Chain Monte Carlo
QML	Quantum Machine Learning
QMME	Quantum Multi-order Moment Embedding
QMPC	Quantum Multi-Party Computation
QMWUM	Quantum Multiplicative Weight Update Method
q_n	qubit n
QN	Quantum Network
QNLP	Quantum Natural Language Processing
QNN	Quantum Neural Network
QOC	Quantum Otto Cycle
qPCA	quantum Principal Component Analysis
QPCA	Quantum Principal Component Analysis
QPE	Quantum Phase Estimation
QPF	Quantum Particle Filter
QPU	Quantum Processing Unit
QR	Quantum Regression
qRAM	quantum Random-Access Memory
QRC	Quantum Reservoir Computing
QREChem	Quantum Resource Estimation Software for Chemistry Applications
QReservoir	Quantum Reservoir
QRF	Quantum Random Forest
QRL	Quantum Reinforcement Learning
QRNG	Quantum Random Number Generator
QRNN	Quantum Recurrent Neural Network

QS	Quantum Sensing Quantum Signals Quantum Simulation Quantum-South
QSA	Quantum Search Algorithm
QSAR	Quantitative Structure–Activity Relationship
QSC	Quantum Stirling Cycle
QSM	Quantum Simplex Method
QSP	Quantum Signal Processing Quantum State Preparation
QSS	Quantum Secret Sharing
QSVM	Quantum Support Vector Machine
QSVT	Quantum Singular Value Transformation
QTDA	Quantum Topological Data Analysis
qubit	quantum bit
QUBO	Quadratic Unconstrained Binary Optimization
QV-CSEE	Quantum Variational Crop-Soil Entanglement Encoding
QVA	Quantum Variational Algorithm
QVAE	Quantum Variational Auto*e*ncoder
QW	Quantum Walk
R_x	R phase shift (around the x-axis) quantum gate
R_y	R phase shift (around the y-axis) quantum gate
R_z	R phase shift (around the z-axis) quantum gate
radar	radio detection and ranging
RAM	Random-Access Memory
Reg.	Register
ReLU	Rectified Linear Unit
REM	Readout Error Mitigation
ResNet50	50-layer Residual Network
RGB	Red, Green, Blue
RL	Reinforcement Learning
RM	Risk Management
RMQKP	Required Multiple Quadratic Knapsack Problem
RNA	Ribo*n*ucleic Acid
ROI	Return *o*n Investment

RQA	Reverse Quantum Annealing
RR	Rolls-Royce
RS	Remote Sensing
RTM	Relative Transfer Model
RVE	Representative Volume Element
s	second strange quark
S	Step
S&L	Shipping and Logistics
SA	Saudi Aramco Search Algorithm
SA-OO-VQE	State-Averaged Orbital-Optimized Variational Quantum Eigensolver
SA-OO	State-Averaged Orbital-Optimized
SA-VQE	State-Averaged Variational Quantum Eigensolver
SAR	Synthetic Aperture Radar
SB	Simulated Bifurcation
SCM	Supply Chain Management
SCO	Satellite Constellation Optimization
SGD	Stochastic Gradient Descent
sin	sinus
SiN	Silicon Nitride
SIPRI	Stockholm International Peace Research Institute
SM	Spectral Method
SMILES	Simplified Molecular-Input Line-Entry System
S*n*	Step *n*
sonar	sonic navigation and ranging sound navigation and ranging
SotA	State-of-the-Art
SQA	Simulated Quantum Annealing
SVM	Support Vector Machine
sys	system
t	top quark
T	Temperature

t-SNE	t-distributed Stochastic Neighbor Embedding
T&L	Travel and Logistics
TA	Thales Alenia
TAP	Tail Assignment Problem
TCO	Total Cost of Ownership
TDVRPTW	Time-Dependent Vehicle Routing Problem with Time Windows
TE	Total Energies
tech	technology
TNO	*N*ederlandse *O*rganisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TNS	Tensor Network Simulation
Topo	Topological
TQ	Terra Quantum
TQC	Tokyo Quantum Computing
TSP	Thermal State Preparation Travelling Salesman Problem
TTN	Tree Tensor Network
TU	Technische Universiteit
TV	Tele*vi*sion
TWh	TeraWatt-hour
u	up quark
U	Unitary
UAV	Unmanned Arial Vehicle
UC	Use Case
UCA	Unsupervised Cluster Analysis
UCC	Unitary Coupled Cluster
UDK	Universität der Künste Berlin
UH	United Healthcare
UK	United Kingdom
UKRI	UK Research and Innovation
UQ	Universal Quantum
US	United States
UV	Ultra*v*iolet

V	Velocity Verifier
val	validation
VaR	Value-at-Risk
VDE	Vehicle Dynamics Environment
VQA	Variational Quantum Algorithm
VQC	Variational Quantum Circuit Variational Quantum Classifier Variational Quantum Computing
VQE	Variational Quantum Eigensolver
VQEDTL	Variational Quantum Enhanced Deep Transfer Learning
VQLS	Variational Quantum Linear Solver
VQRS	Variational Quantum Recommendation System
VRP	Vehicle Routing Problem
VW	Volkswagen
W	W vector boson W quantum gate
WAN	Wide-Area Network
WF	Wells Fargo
WGS	Water–Gas Shift
www	world wide web
WWW	World Wide Web
X	Pauli X quantum gate
Y	Pauli Y quantum gate
Z	Pauli Z quantum gate Z vector boson
ZNE	Zero-Noise Extrapolation
ZZ	ZZ quantum gate